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The Geographical Sciences During 1986—2015

From the Classics to the Frontiers

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Foreword I

The terrestrial system is a perplexing complex, jointly composed of human factors and physical elements, i.e. water, soil, air, etc. The land surface, as a crucial research field of macro-science, has evolved into one of the core areas of geoscience, drawing extensive attention from both academia and society as a whole. Along with constant rapid social and economic development, a series of dramatic changes in human activities have occurred, including more diversified activity modes, more intense activity strength and a wider activity range, giving rise to increasingly acute pressure on the land surface and environment. Meanwhile, a series of social problems have emerged owing to different levels of ecological degradation caused by excessive agricultural exploitation, environmental pollution resulting from extensive industrial production and various onerous challenges to public service provision brought by rapid urbanisation. Integrating natural and social sciences, research relating to the land surface thus finds its motivation in far-flung social needs and has developed into one of the most prominent subjects along with the flourishing earth system sciences.

Over the last few decades, land surface research has made great progress, and Chinese scientists have made numerous achievements in this area, which have received a great deal of attention from the international academia. For a long time, National Natural Science Foundation of China (NSFC) has made major contributions to this field by providing stable funding and paying close attention to the development of research, helping promote high-quality research and significant international cooperation. Issues concerning how to document research progress in a comprehensive and accurate way, how to evaluate the key features and contributions of Chinese terrestrial research, how to capture the driving forces of disciplinary development, how to assess the contribution of a funding agency, and how to identify the opportunities and challenges faced by disciplinary development, have become common components of an appraisal of the evolution of a discipline. In order to increase funding efficiency and support this research field more purposively, it is crucial for NSFC to grasp objectively and accurately the intrinsic nature of these issues to formulate proper development and funding strategies. This book series entitled *Reviews and Prospects of Land Surface Research*, the first volume *The Geographical Sciences During 1986–2015*: *From the Classics To the Frontiers* have provided some important methods and meaningful conclusions to understand and further explore the above-mentioned questions.

This book series, aiming at demonstrating disciplinary development and research progress, fully explores the multiple factors affecting disciplinary advancement. It pays close attention to the support for talented researchers in the terrestrial research field. It also conducts comparative analysis of representative educational institutions at home and abroad, in terms of their organisational structure, curriculum development, professional background, laying the foundations for a full comprehension of the *status quo* and evolving tendency of interdisciplinary research in this subject area. Besides, focusing on international cooperation, it discusses and delineates the changing role and status of major countries and identifies China's advantages and international standing in different branches of land surface research.

Mainly employing bibliometric analyses, authors of this book series identify the evolving history and achievements acquired at different scales in various research fields. Publications are the most important outputs of scientific research, while bibliometric analysis is the most effective way to comprehensively review achievements in scientific research. Using a database of publications in both English and Chinese, at home and abroad, as well as NSFC grant applications and funded projects, this book series summarised land surface research's key features and research progress in various stages over the past 30 years. Within the detailed analyses of disciplinary development, land surface studies are divided into assorted sub-disciplines, including Physical Geography, Human Geography, Geographical Information Science, Environmental Geography, Soil Geography, Soil Physics, Soil Chemistry, Soil Biology, etc. Contributors further identify nine strategic issues and 28 research fields, and elaborate on their development and progress, and their development motivations, opportunities and challenges using bibliometric and qualitative analyses. Meanwhile, contributors re-categorise the funding sources for different research outputs, and objectively evaluate NSFC's contributions to the development of land surface studies.

As a complex mega-system and an important research field in geosciences, the land surface has received varied financial support from NSFC. A large cohort of dedicated and courageous researchers have been actively engaging in international cooperation, and showcasing China's academic achievements in the international academic community. Based on publication records, research outputs sponsored by NSFC had increased exponentially in the past three decades. And both the absolute and relative quantity of influential outputs funded by NSFC show a stable yearly increment.

As one of the most important tasks of NSFC, a comprehensive and objective assessment on disciplinary development summarises work efficiency for the previous period, and also lays the foundation for future funding plans. Constantly innovating and refining assessment methods is the only way to achieve effective scientific funding management and bolster basic research and disciplinary development in China.

November 2015

Changqing Song
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Vice Director of Department of Earth Science, NSFC

Foreword II

Geography is devoted to the study of the spatial distribution and pattern of variation, spatial–temporal processes and regional characteristics of geographical elements and geographical complexes. The research foci of geography cover the interaction mechanism and regulatory approaches between the human and epigeosphere. This research involves the coupling of the physical properties of Earth's surface and the functioning of human societies spreading across the earth surface, and makes geography a comprehensive and cross-cutting discipline divulging humanistic substances while probing into the laws of the nature. In recent decades, along with the emergence of pressing issues relating to global population, resources, environment and development, etc., sustainable human development faces great challenges. Geography has played a significant role in the studies of global environmental change and economic integration, while geographical theories, methods and techniques have laid a solid scientific foundation for resolving problems concerning human society's sustainable development. Contemporary geographical research methods have shifted from traditional methods, i.e. survey, observation, recording, and cartography, etc., to spatial statistics, earth observation, geographical information system, indoor and outdoor simulation, modelling, decision support systems, and other modern scientific methods, which tend to be more comprehensive and quantitative. Facing the increasing complexity of research questions, geographical research becomes more diversified and comprehensive, drawing attention from other disciplines. Given that geographical perspectives become more and more important in a wide range of areas, geography is entering a new epoch full of golden opportunities. China is a perfect testing ground for studies of the sustainable development of human society, which meet the strategic needs of the internationalisation of geographical research and national economic and social development, and will therefore create great opportunities for innovative and groundbreaking research.

The development of geography in China is tightly bound up with national development. Chinese geography fully embraces cutting edge international geographical research while closely attending to China's natural environment and social economy condition. Geography in China has hitherto evolved into a systematic and distinctive discipline achieving a series of innovative research outputs and playing an increasingly significant role in China's national economy and social development. Accordingly, geography in China has captured extensive attention from both governments and the society, projecting considerable influence far beyond disciplinary boundaries.

In the last three decades, with the support of National Natural Science Foundation of China (NSFC), Ministry of Science and Technology, Chinese Academy of Sciences and other institutes, Chinese geographers had made more meticulous contributions to the studies of the pattern of natural environment and human economy on epigeosphere. With sufficient data acquired in extensive field observations and empirical socio-economic surveys, along with the development and application of new technologies and new methods such as geographical information system, geography in China has gradually acquired its own distinctive features in physical geography, human geography and regional integration studies. At the time of the 30th anniversary of NSFC and the 33rd International Geographical Union Congress, a group of young and middle-aged geographers, motivated by enthusiasm and responsibility for the development of geography in China, compiled this book *The Geographical Sciences During 1986-2015*: *From the Classics To the Frontiers.* Based on rich sources of information and data relating to higher education and scientific research and the outputs of geographically relevant sciences, and using quantitative analysis, international comparisons and synthesis, this book systematically summarised the main strategic research issues and areas in Physical Geography, Human Geography, Geographical Information Science and Environmental Geography in the past 30 years, and pointed out several issues and frontiers that deserve further exploration in future geographical studies.

This book incorporates the following features:

(1) Well-founded arguments
It presents a comprehensive analysis of disciplinary development, higher education, international cooperation and relevant strategic issues for the development of geography in China over the past three decades. Equipped with different perspectives of disciplinary evaluation and supported by analysis of specific database, this book provides ample evidence and abundant information and covers a range of issues.
(2) Variety of methods
Based on published English and Chinese papers, NSFC funding projects, Geography Schools and Departments in higher education institutions, employing bibliometric analysis, statistical analysis, questionnaires and web searches, it vividly demonstrates the disciplinary development trend priorities, frontiers, funding structure and main achievements of scientific research using quantitative methods and providing abundant graphical and textual documentation.
(3) International comparison
Conducting comparative studies by putting the development of China's geography into an international context and summarising the progress and main features of domestic research, this book highlights the unique development path and distinctive outcomes of China's geographical research. Through international comparison, it uncovers the characteristics of China's geography in terms of research, education, international communication and cooperation, key issues and research fields, and identifies main ways in which Chinese geography differs from the international mainstream.
(4) Research prospects
Comprehensively analysing the major issues, areas and progresses in China's geographical research, international trends, and China's national conditions and national demands, it discusses areas where there are prospects of potential breakthroughs and future innovative development. Identification of these prospects has significant reference values for geographical researchers and administrative officers from home and abroad.

This book, which summarises 30 years of development of China's geographical research and sets up a new starting point for it, not only provides a knowledge base for overseas scholars wishing to understand China's geographical research, but also a knowledge base for Chinese domestic geographers to recognise gaps and identify future research directions. Considering a series of realistic demands, such as promoting the new type urbanisation, industrial upgrading and optimisation, reducing the pressure on limited resources and the environment, optimising the use and conservation of land and resources, implementing sustainable development and ecological construction strategy, etc., and facing numerous new challenges, i.e. global environmental change, economic globalisation, and the transformation of global geopolitics, the future development of China's geographical research needs to pay close attention to more synthetic issues and strengthen the understanding of the man–earth complex to realise the coupling of elements, patterns, processes and systems to advance its theoretical and practical capabilities. Chinese scientists should seize these opportunities, promote innovation, cope with the challenges, actively lead or participate in major international research projects, and strengthen research on global issues to achieve new breakthroughs. By doing so, China can transform itself from a country with a large number of geographers to a country with high quality geographical research. This book attempts to strengthen the geographical sciences in China, improve their capacity to explain geographical phenomena and processes with the help of advanced techniques, and thereby to realise their social service value. These are the high hopes and the vision of the editors.

November 2015

Bojie Fu
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Preface

Traditional geography mainly focuses on the occurrence and development, as well as regional differentiation patterns of geographical factors on the epigeosphere, paying more attention to the evolving rules and regional differences of a sole geographical element such as soil, hydrology, vegetation, climate or humanity. It thus often employs descriptive research methods. Based on the inheritance of traditional geographical thought, modern geography gradually became more comprehensive and quantitative by borrowing research methods from other disciplines. The aims of modern geography are not only limited to explain the past but also to solve current problems concerning resources, the environment and sustainable regional development and to improve the capability to predict future development trends.

In recent decades, the development of remote sensing, geographical information system and spatial orientation systems technology has greatly improved the possibilities for the visualisation, observation and calculation of geographical phenomena. Ecosystem orientation tests, indoor physics and chemical simulation experiments have significantly deepened the knowledge of geographical processes and dynamics. Earth system model coupling with multi-spherical elements has promoted the development of geographical virtual experiments, and descriptive geography has been transformed into quantitative geography, which plays an indispensible role in promoting the development of earth science.

Geography in China has a long historical tradition, albeit deeply inspired by geographical studies in Western Europe, Northern America and Russia. In post-reform China, motivated by the demands of national economic development and disciplinary development, a team of talented geographical researchers at various levels had emerged and a distinctive geographical disciplinary system had been formed, featuring reasonable organisational structure and abundant research outputs. The development of China's geographical research had experienced different stages, and each stage had pronounced features in terms of research objects, methods and topics.

Similar to the development trajectories of other basic research disciplines, the development of China's geography discipline had benefited immensely from the National Natural Science Foundation of China (NSFC). The year of 2016 marks the 30th anniversary of NSFC and coincidently the 33rd International Geographical Congress will be held in Beijing in the same year. To celebrate these two great events and summarise three decades' development of geography in China, a group of young and middle-aged geographers formed the editorial board in September 2014 and eventually completed this book on schedule after more than one year's preparation, under guidance of Mr. Changqing Song, Vice Director of Department of Earth Science, NSFC, and academic committee director of the Geographical Society of China, who named this book *The Geographical Sciences During 1986–2015*: *From the Classics To the Frontiers*.

The debate on "what is geography" has a long history and has provoked various answers and thoughts, which however does not challenge the disciplinary validity and scientific nature of geography at all. All geographers need to think about the discipline's position, research scope and development directions, with a vision to strengthen the role of geography in the scientific community. To quote Academician Bingwei Huang, "All sciences need to be restructured, the contents of geography should be adjusted accordingly. There is no way out standing still and refusing to make progress". Yet, he also emphasised "Choosing the wrong way will also bring huge losses. Therefore, I urge every geographer in China to further discuss these issues".[1] The geographical society in United States published *Rediscovering Geography*: *New Relevance for Science and Society*[2] in 1997 and *Understanding the Changing Planet*: *Strategic Directions for the Geographical Sciences*[3] in 2010 respectively, which showed potential opportunities for future development while reviewing and reflecting on its evolution and subject characteristics. Both books provide a vast number of case studies for readers to gain a better understanding of "what is geography and how it develops". The aim of this book is not to generalise the characteristics, research content and evolution of geography, but to uncover international and domestic changes in the field of geography in the past 30 years. The purpose is to make current research and education in Geography more clear, and offer some inspiration for future geographical studies by using statistical databases and compiling information about numerous publications, projects, questionnaires, etc.

This book includes an introduction and four parts. In order to give readers a better understanding of the authors' research ideas, the introduction details the data assembly, analytical methods and perspectives. The first part outlines the overall development of the geographical sciences, elaborating on development trends and international cooperation, as well as relevant background of China's geographical sciences. The second part mainly focuses on the development conditions of sub-disciplines of geography, examining four geographical sub-disciplines, in terms of publications, evolution of hot research topics, features of NSFC-funded projects and research teams. The third part is about strategic issues in the geographical sciences, explaining the evolution, research situations, research progresses and achievements in relation to nine strategic issues. These nine issues are the common concerns of the international geographical society and have significant implications for the construction of theoretical and methodological systems of comprehensive integration and simulation analysis in geography. The fourth part presents reviews and prospects for several areas of geographical research under NSFC's funding schemes, explaining the evolution, research situations, research progresses, achievements, problems and research prospects in nine research fields. These nine key areas reflect the development commitments of NSFC, covering international frontiers, domestic advantages or highlights, or underdeveloped yet indispensable basic research fields.

This book employs various methods, including bibliometric analysis, statistical analysis of NSFC-funded projects, geographical education questionnaires and geographical distribution analysis, qualitative literature analysis, synthetic judgments from experts, etc., to acquire basic conclusions on disciplinary development rules and trends. Data for bibliometric analysis is from reputable citation index databases including Web of Science, created by the United States of America (USA) Institute for Scientific Information, and the Chinese Science Citation Database (CSCD), initiated by the National Science Library, Chinese Academy of Sciences. The ISI Web of Science database mainly includes publications from Science Citation Index (SCI) and Social Sciences Citation Index (SSCI). The first two parts are based on SCI/SSCI-indexed publications retrieved in July 2015 and CSCD-indexed publications retrieved in May 2015; and the third and fourth parts are based on SCI/SSCI-indexed

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[1]Editorial board of Collected Works of Bingwei Huang: "Comprehensive Work and Interdisciplinary Research of Geography", In: *Comprehensive Study of Geography*: *Collected Works of Bingwei Huang*, Page XI. Beijing: The Commercial Press, 2003 (in Chinese).

[2]Geoscience and Resources Bureau, Environment and resources committee, US National Research Council (NRC), translated by Runhua Huang: *Rediscovering Geography*: *New Relevance for Science and Society*. Beijing: Academic Press, 2002 (in Chinese).

[3]The National Research Council of the US National Academies, translated by Yi Liu, Weidong Liu, *Understanding the Changing Planet*: *Strategic Directions for the Geographical Sciences*. Beijing: Science Press, 2011 (in Chinese).

publications retrieved in November 2014. First, on the basis of expert assessments, we identified publications from SCI/SSCI and CSCD that can well reflect the scientific outputs of geographical sciences. Then we manually handled problems such as authors with the same name, varied expressions for the same institution or different names for one institution at various development stages and manually verified the research funding organisations and project reference numbers extracted by computer programs. Last, we used the literature analysis software CiteSpace and TDA (Thomson Data Analyzer) bought from Thomson Reuters to process and analyse these datasets. Network analysis of authors and corresponding institutes generally adopts the current names of institutes and authors' current affiliations. NSFC project analysis data include all kinds of applications and funded projects in the geographical sciences (application code D01, excluding soil science D0105) from 1986 to 2015. Apart from project leaders, research institutes, project categories and funding amounts, other information including keywords, references, collaborators, case study areas were extracted through computer programming. Geographical education analysis data mainly come from questionnaire surveys and data downloaded from the Internet, containing organisational structure and curriculum development in the geographical sciences in higher education institutions in the USA, the UK, Germany and China, as well as the distribution of geography departments or colleges within China. Geographical distribution analysis uses maps to convey information relating to particular geographical positions, such as the locations of project leaders or research institutes, study areas of funded projects, and the distribution of geographical elements investigated in funded research projects. The basic map information are provided by the National Geomatics Center of China and Nanjing Hydraulic Research Institute. Qualitative literature analysis identifies the major academic contributions for each of the nine strategic issues and the nine research fields, based on specialists' reading and experts' judgment of representative publications.

The bibliometric analysis database comprises selective publications, mainly based on journal classification or keywords extraction. Some disciplinary categories have a good match with journal sorting, which is convenient for obtaining publications by using existing matching relations or constructing corresponding relations. Some research fields can be represented by a small number of explicit keywords; therefore relevant papers can acquired from journals through searching keywords. For the geography discipline, in which research objects and questions are also shared with other disciplines, and research outputs are extensively published in multidisciplinary journals, there are no clear corresponding relations between disciplines and journals. Publications cannot be extracted by keywords, which is a great challenge for the authors of this book and also a problem that needs to be solved to guarantee the reliability of bibliometric analysis outcomes. According to the research needs and part characteristics, the first and second parts obtain publications mainly from journal and discipline classifications, while the third and fourth parts acquire publications through a combination of keywords and journal classification method and conduct sample evaluations of publication extraction results to ensure that selected papers are comprehensive, representative and interdisciplinary as far as possible. Together, this book selected 307 "mainstream" or "core" SCI/SSCI journals covering four geographical sub-disciplines through many rounds of cross-assessments by more than 30 experts in different research fields. Among them, 118 journals are considered as "comprehensive journals", on the grounds that their research themes are relatively comprehensive. According to our estimation, among the 307 mainstream journals, more than 50 % of papers are closely related to geographical sciences, and authors funded by NSFC account for 38.9 % of all authors from China (first authors or corresponding authors); the overwhelming majority of papers from the 118 comprehensive journals are closely correlated with the geographical sciences, and authors funded by NSFC account for 43.4 % of all authors from China (first authors or corresponding authors). The above results show that the 118 comprehensive journals can totally represent the research directions of geography, but the number of publications in the geographical sciences will be seriously underestimated. On the other hand, the 307 mainstream SCI/SSCI journals contain some professional journals relating to geographical sciences sub-disciplines, which also publish a lot of multidisciplinary studies. For instance, the *Journal of Quaternary Science* publishes papers from both geomorphology and geology, resulting in the overestimation of geographical publications. For the sake of fully representing the research outputs and development trends of geography and making bibliometric analysis results more accountable, the first and second parts compute the paper amount and total citation frequency according to the 307 mainstream SCI/SSCI journals. In the third and fourth parts the number of journals is increased to satisfy the need to analyse corresponding strategic issues and fields based on the 307 journals and compute the total paper amount and citation frequency in particular areas by retrieving specific terms in titles, keywords and abstracts. Chinese authors in SCI/SSCI journals are extracted if the first author's or corresponding author's address contains "China". Papers from other countries (regions) are calculated in the same way. Non-first and non-corresponding authors' papers are not counted in a country's article number but are used in the construction of co-occurrence network of keywords in Sino-USA (UK or Germany) cooperation articles.

The selection of Chinese geographical journals was first based on the Chinese core periodicals catalogue indexed by CSCD, and then referred to the journal ranking from the *Annual Report for International Citation of Chinese Academic Journals*, *CAJ-IJCR*, *2014,* developed by the International Academic Literature Evaluation Research Center of China and Tsinghua University Library, and published by China Knowledge Resource Integrated Database (CNKI). Most CAJ-IJCR indexed journals are from overseas and are chosen to examine the impact of China's journals from international perspectives. The selection indicator used is the Clout Index (CI), which takes both total citation frequency and impact factors into consideration. Through a consecutive analysis from 2012 to 2014, it was shown that the total international citation frequency of journals ranked in the top 10 % in terms of their international influence had experienced a dramatic increase in three consecutive years since 2012. Considering the authority of CAJ-IJCR, this book chooses the top 10 % of Chinese journals selected by the *Annual Report for International Citation of Chinese Academic Journals*, *CAJ-IJCR*, *2014*. In the light of the widespread geographical research outputs, several important comprehensive Chinese journals and professional Chinese journals which are not within the top 10 % were added, yielding 29 journals altogether.

To solve the problem of overestimating the number of geographical papers caused by contributing researchers with a multidisciplinary background, we identified geography authors by using the reference numbers of NSFC-funded projects and information relating to project leaders' names and corresponding institutes. In this way non-geography researchers were largely removed. Actually for multidisciplinary journals, the research objectives and questions with which different disciplines are concerned are almost the same, so it is nearly impossible to distinguish geographical studies from studies in other disciplines and neither it is possible to recognise authors' disciplinary background one by one. Therefore statistical error cannot be totally avoided, even if NSFC funding information is used. But the clustering results of research directions and themes should be more precise than the statistics of total publications.

The authors of this book are all young and middle-aged Chinese geographers, which makes systematically generalising 30 years development of the geographical sciences a really big challenge. Motivated by the sincere enthusiasm for geography and a strong sense of responsibility for disciplinary development, the authors of this book pay a lot of attention to the data sources, refining the structure of the book, exchanging views on the contents, optimising graphical methods and eventually accomplished the writing with lots of hard work on top of their daily research, teaching and administrative obligations.

Building upon a large volume of literature, finding new methods of data acquisition and developing new analytical methods is the first priority of this book. Fully aware of the unverified conclusions obtaining from previous bibliometric analysis, this book constructs a unified database by strictly controlling data quality at every stage, including methods of data acquisition, conditions of data retrieval, methods of data analysis and graphical representation to guarantee that the conclusions of this book are well-founded. We have applied for a national invention patent for our approach to accessing literature automatically from the Web of Science. To allow readers to verify the authenticity of our analysis results, we tried to introduce the data source as explicitly as possible.

During the process of writing, the authors of this book also consulted many Chinese geographers for advice. Accordingly, we categorised authors into three groups, i.e. lead authors, authors and contributors, and introduce all of the authors in each chapter to enable readers to further communicate with them. Lead authors are mainly responsible for the conception and major writing tasks, authors are responsible for at least one complete chapter (equivalent to the content under a fourth-level heading) and contributors are those who provide data and empirical materials. Limited by authors' experience, ability and time constraints, mistakes and improper argument are inevitable. We welcome readers' invaluable criticism and comments!

In fact, apart from all the authors listed in the book, there are a lot of geographical institutions and geographers deeply concerned about this book. At the point of publication of this book, we extend our cordial gratitude to all the colleagues who have given us encouragement. The emotional and moral support from them played an important role in the completion of this book! Special thanks go to the Geographical Society of China, Institute of Geographic Sciences and Natural Resources Research of Chinese Academy of Sciences, The Faculty Geography Resource Science of Sichuan Normal University and the Key Laboratory for Virtual Geographical Environments of the Education Ministry of China at Nanjing Normal University, for sponsoring editorial committee working conferences! We also thank the China Knowledge Resource Integrated Database, CNKI and Ms. Junhong Wu, the vice director of the Research Centre for the Quantitative Evaluation of Scientific Papers in China for their significant help! And we would like to express our gratitude to Academician Chenghu Zhou, the director of the State Key Laboratory of Resources and Environmental Information System, Institute of Geographic Sciences and Natural Resources Research of Chinese Academy of Sciences for his support for database management! Thanks also go to Academician Jianyun Zhang and Director Jiufu Liu from Nanjing Hydraulic Research Institute for providing the hydrology and geography database! We are grateful to Mr. Zhigang Li, the chief engineer of the National Administration of Surveying, Mapping and Geoinformation of China, Mr. Jun Chen, chief engineer of the National Geomatics Center of China and Ms. Jie Jiang, director of MapWorld, National Geomatics Center of China for providing the fundamental geographical information database! Last but not least, we wish to present our special thanks to the Commercial Press of China and German Springer Publishing Company for their deep concerns in the development of the discipline of geography!

We dedicate this book to all the people who had contributed to the development of geography in China in the past 30 years and those who make unremitting endeavours to promote the development of geography at international level!

November 2015

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Introduction: Interpreting the Geographical Sciences from a Perspective of Bibliometric Analysis

Tao Pei, Xizhang Gao, Shenjing He and Xiaoqian Liu

This book aims to summarise in a comprehensive way the development of the geographical sciences over the past 30 years, to evaluate the position of the geographical sciences research in China and the role of NSFC in its development based on a comparison between domestic and foreign research and to provide an outlook for future development. Adopting bibliometric methods in analysing and predicting the development of the geographical sciences in China is one prominent feature of this book. In order to have a better understanding of the methods used in the book, this part will focus on the following issues relating to bibliometric analysis: data sources and data selection criteria; methods of data acquisition and verification; types of graphs and tables used in bibliometric analysis and their meanings; and the content of bibliometric analysis in the geographical sciences.

Rationale for Adopting Bibliometric in the Geographical Sciences

Characteristics of the Geographical Sciences

As the major branch of the geosciences, the geographical sciences have a strong characteristic of comprehensiveness defined by the following three features. The first feature is the complexity of research objects which not only consists of the physical movement rules within the earth surface system, but also the relationship between nature and human beings. The complexity makes the geographical sciences interdisciplinary. Second, the research objects have multi-scales. From the perspective of spatial scale, research in the geographical sciences incorporates both global macro-scale and local micro-scale analysis. In terms of temporal scale, geographical research not only covers environmental changes during the Quaternary geological historical period, but also contemporary global change. Therefore, the diversity of scales leads to great differences in research methods and ways of thinking. The variety of research methods is the third feature of the geographical sciences, which mainly includes field research, laboratory analysis, computer simulation, remote sensing observation, etc. The large span of literature and blurred disciplinary boundaries, resulting from these characteristics of the geographical sciences, have led to great difficulties in adopting bibliometric methods.

The Logic of Bibliometric Methods

The general idea of the bibliometric methods is to find out the evolution of the research questions, the progress of research methods and means, the fabric of research and its trends, and to explore the differences in the development of domestic and international research and their influencing factors through statistical analysis of the literature. Based on the characteristics of geographical sciences, authors of this book construct a four-step literature analysis framework. Step 1 is the selection of literature sources in which fundamental literature (i.e. journals relating to geographical sciences) of targeted discipline can be determined. Step 2 is the acquisition and verification of data of literature: selecting literature corresponding to research topics (i.e. determine the search query); downloading journal articles; checking and affirming the data carefully. Step 3 is to produce figures and tables that are needed in bibliometric methods, which requires that all statistical characteristics and interrelationships of each attribute are reflected directly. Step 4 is to analyse the trend of development of the discipline by making the comparison between domestic and international situation and their influencing factors (in this book the factor is the contribution from NSFC). The concepts, principles and meanings of each step will be introduced in following sections.

Literature Sources and Selection Criteria of Bibliometric Methods

Before the bibliometric analysis is conducted, the sub-disciplines of geographical sciences need to be identified such that all representative journals of each sub-discipline can be determined in the subsequent process. In this section, the contents of the data and the meaning of each field will be introduced first, followed by the method of determining the representative journal of each sub-discipline of geographical sciences.

Data Sources

Data used for bibliometric methods in this book come from three sources: the Science Citation Index (SCI) and Social Sciences Citation Index (SSCI) from Web of Science; the Chinese Science Citation Database (CSCD) provided by China Knowledge Resource Integrated Database (CNKI); and the database from National Natural Science Foundation of China (NFSC) which consists of all the information relating to project applications and research funding in the discipline of geography. The following text provides a detailed introduction to the three different databases, the properties of each and its significance.

(1) **SCI/SSCI**
The Web of Science, owned by Thomson Reuters, but that Thomson Reuters plans to sell, is a citation index database created by the Institute for Scientific Information (ISI). SCI/SSCI is one of the three major citation databases of Web of Science. SCI contains 8,659 journals and SSCI contains 3,154 journals.[4] SCI/SSCI has a comprehensive coverage of the most important and influential research in various disciplines. Besides, as a retrieval tool, SCI/SSCI also has a unique citation index which can explain the interrelationships between articles and shows the influence of the early literature by analysing citations data. These characteristics of SCI/SSCI make it not only a retrieval tool, but also a widely recognised scientific evaluation tool.

(2) **CSCD**
China Science Citation Database (CSCD) was founded in 1989. It includes over one thousand Chinese and English core journals in mathematics, physics, chemistry, astronomy, geoscience, biology, agriculture science, medicine, engineering and environmental science. The CSCD database (2015–2016) has 1,200 journals, of which 194 journals are published in English and 1006 journals are published in Chinese. CSCD comprises a core database (872 journals) and an extended database (328 journals).

(3) **NSFC**
The database of NSFC projects, provided by the Division of Geography, Department of Earth Science of NSFC, contains a total of 48,899 projects from 1986 to 2015, of which 38,909 projects belong to the geographical sciences.

[4]http://admin-apps.webofknowledge.com/JCR/JCR.

Data Structure and Attributes of SCI/SSCI

Each journal article within the citation index database of the Web of Science has 37 fields. The most frequently used and important attributes are the following fields.

(1) **Author, Country and Institution**
SCI/SSCI includes three types of authors: first author (first line of C1), corresponding author (RP) and co-author (referring to authors excluding the first and corresponding authors of C1). Both C1 and RP fields contain information about the country and institution of authors. To determine the total number of published articles for a certain country, which country the paper belongs to must be identified. Hence, this book defines the country of the article by using the nationality of the first author or the corresponding author. For example, the number of published works of Chinese scholars is defined as the number of articles for which the first author or corresponding author is Chinese. Similarly, in the calculation of the total number of published works of a certain research institutions, this book uses the institution of the first author or the corresponding author.

(2) **Keywords**
There are three types of keywords: keywords defined by authors (DE field), keywords defined by the system (ID field) and keywords in the title (TI field). The first type enables the author to define the scope and characteristics of a paper, which reflects directly the highlights and classification of the paper. The second type, given by the Web of Science based on the features of the paper, can only present the classification information of the paper. The third type of keyword, generated from the matches of texts between the title and a preset keywords list (i.e. keywords defined by authors and the system), presents the core contents of the paper. It should be noted that not all articles contain keywords defined by authors and the system in Web of Science, some articles have both of them, while others only have one type.
Because of the different research objectives, the selection of keywords in bibliometric analysis can also be different. For instance, a combinational analysis involving three types of keywords is needed if someone wants to understand the overall development of a discipline. While for the analysis of research highlights, keywords defined by authors and keywords in titles are enough (in some cases, analysing keywords defined by authors alone is also suitable). The shortcoming of the former example, although it involves a comprehensive consideration of the three types of keywords, is that the highlights of a paper may be diluted due to the excessive generation of keywords defined by system (e.g. geography and remote sensing) which can only provide information on classification. As for the second example, the information is often not comprehensive if the analysis only concerned keywords defined by authors and keywords in title, especially when there is a missing value in keywords defined by authors.

(3) **Funding Agency and Sources**
Funding agencies and sources refers to the information provided by the FU field of the SCI/SSCI. It contains information about project funding agencies (e.g. NSFC) or funding sources (such as NSFC projects) and detailed research project titles (such as the Continental Drilling Program). Funding agencies and sources are mainly used to evaluate the contribution of scientific research funding agencies to the outputs of scientific research. Due to the lack of annotation standards, the annotations of funding information are not uniform. For example, there are at least 10 types of annotations for NSFC (e.g. the Chinese Natural Science Foundation, National Natural Science Foundation, National Funds, NSFC, etc.). In this book, various NSFC annotations needed to be unified before calculating publications funded by NSFC.

(4) **Number of Citations**
The number of citations (TC field), defined by the times a SCI/SSCI paper is cited by other SCI/SSCI-indexed articles before the retrieval date, reflects the degree of attention

from peers. In a certain period of time, papers with the highest number of citations are defined as highly cited papers. For this book, two parameters must be decided before highly cited papers are determined: the time frame, and the threshold for ranking citations. This book defines those top 5 % of papers as highly cited papers. For example, the highly cited papers of 2010–2014 are defined as articles that were published between 2010 and 2014 and that are within the top 5 % of cited papers before the retrieval date.

(5) **Titles of Journals**
Titles of journals (JI field) record the name of the journal in which the article was published. The bibliometric analysis in this book primarily relies on the search scope, which requires a precise selection of journals in related disciplines. Then, we can choose publications that match the research topics by using academic search queries. It should be explained that, due to the potential mismatch of research content and journals, all the journals need to be carefully screened and filtered.

Data Structure and Attributes of CSCD

Each journal article within the CSCD has more than 20 fields. The following fields are used for bibliometric analysis in this book.

(1) **Author and Institution**
In CSCD there are two types of authors, i.e. the first author (listed first in the author list) and the co-author. As for the institution field, it contains all the information about the authors' institutions which in general is specified at the school/faculty or laboratory level. In this book we adopt this rule in determining the institution: in the case of a university, we collect statistics at university level (for instance, College of Urban and Environmental Sciences of Peking University will be simplified as Peking University); for all kinds of scientific institutes, we collect statistics at institute level (for instance, the State Key Laboratory of Urban and Regional Ecology at Environment and Ecology Institute of Chinese Academy of Sciences will be simplified as Environment and Ecology Institute of Chinese Academy of Sciences).

(2) **Title, Keywords and Abstract**
Each journal article within the CSCD contains title, keywords and an abstract. Unlike SCI/SSCI, CSCD only includes keywords provided by authors to indicate the content and features of a paper. The keywords co-occurrence network, used for identifying research hotspots, in four sub-disciplines of the geographical sciences in this book are generated from cluster analysis based on the keywords provided by authors. It is very common that, due to different writing habits, there are abbreviations and synonyms in the keywords; therefore, these keywords should be standardised before the cluster analysis.

(3) **Agency and Sources**
Funding information refers to the data relating to funding agencies (e.g. NSFC), funding for research projects and research proposals (e.g. Major Scientific Research Plan (MRP) on "Global Change and Its Regional Response"). The funding information of CSCD is mainly used to evaluate the contribution of scientific research funding agencies (e.g. NSFC, the Ministry of Science and Technology of People's Republic of China) to the outputs of scientific research. As in the case of SCI/SSCI, the annotations of funding information are not uniform in CSCD. As a result, various annotations in Chinese were also unified.

(4) **Number of Citations**
Number of citations, defined by the number or times a CSCD paper is cited by other CSCD articles before the retrieval date, reflects the degree of attention the paper receives from Chinese peers. In this book, the number of citations of CSCD is mainly used to compare the average citation score of papers funded by NSFC compared with those not funded by NSFC.

(5) **Codes of Themes**
In the CSCD citation database, each article is labelled with a special code to identify the research direction of the article. There are more than 140 codes in the CSCD relevant to the geographical sciences. In this book, the codes of themes are helpful in deciding the sub-discipline of a certain paper in an interdisciplinary or comprehensive journal (e.g. *Acta Geographica Sinica* and *Acta Ecologica Sinica*). For instance, the code J153_3 in *Acta Geographica Sinica* represents tourism resources which belongs to human geography, and the code A008_12 represents geomorphology which can be classified as physical geography. Although *Acta Ecologica Sinica* has been seen as a journal of physical geography, most papers are about ecology or the interdisciplinary study of ecology and geography. Hence, based on the codes of themes, this book excludes papers that are not closely related to physical geography, for example articles with the labels A006_02 (General Biology), D043_6 (Soil Science) and D049_19 (Forest Biology) are not included.

(6) Titles of Journals
Titles of journals record the name of the journal in which the article was published. When this book uses the CSCD to conduct bibliometric analysis, the selection of articles in different sub-disciplines of geography is mainly determined by the journal title.

Data Structure and Attributes of NSFC

Each item in NSFC project database contains more than 20 fields, and the major fields used in this book are as follows:

(1) **Applicant and Participant**
This field includes the applicant's name, gender, date of birth, title, nationality, education, etc., as well as the participant's name and title. This information is mainly used to analyse the distribution by age and title of project applicants. At the same time, by combining the SCI/SSCI and CSCD data in different sub-disciplines of the geographical sciences, we can evaluate the contribution of NSFC to supporting the development of talented researcher. Since some applicants have the same name, it is necessary to distinguish these applicants based on dates of birth and institutions.

(2) **Title, Keywords and Abstract**
Titles, keywords and abstract mainly reflect the research content and direction of the project, based on which, the projects can be categorised into different types in the process of bibliometric analysis. Then, the result can be used to evaluate the effect of NSFC on the development of the geographical sciences. Also, variations in the temporal sequence of keywords indicate changes in the direction of NSFC-funded projects in different periods. As in the case of the CSCD, standardisation of abbreviations and synonyms in keywords is necessary before the data are analysed.

(3) **Application Institution and Cooperative Institution**
The application institution is the institution which the applicant comes from and the cooperative institution is the institution where the collaborator is based in. This information is mainly used to figure out those institutions that perform better in project applications, as well as the spatial distributions of funded projects and applicants.

(4) **Classifications of Projects**
This information mainly indicates the category of funded projects and the codes of disciplines. Projects can be divided into three types: the first is Programmes for Research Promotion, including General Programme (GP), Key Programme (KP) and Major Programme (MP); the second is Programmes for Talent Training, mainly including Young Scientists Fund (YSF), Excellent Young Scientists Fund (EYS Fund) and National Science Fund for Distinguished Young Scholar (scholars with foreign citizenship included) (DYS Fund); the third is Programmes for Infrastructure Construction, covering

Joint Funds and International/Regional Cooperation and Exchange. The codes of disciplines designed by NSFC for project applications generally contain three levels. D01 is the code for geography, while the sub-disciplines of geography are identified by second-level and third-level codes. For example, the code for physical geography is D0101; as a subtype of physical geography, hydrology is coded as D010102. This classification system not only can be used to analyse the overall picture of project applications and funding of different sub-disciplines and programmes, but is also helpful in identifying the project applications and funding of certain third-level disciplines.

(5) **Funding**
This data contain funding status (funded or not), the amount of funding, the reference number of projects, project execution time and other useful information. This information is used to summarise the number of funded projects, the amount of funding, funding rate and the relative importance of various disciplinary branches in different time ranges.

Confirmation of Literature Sources

(1) **Classifications of SCI/SSCI Journals and Selection Criteria**
An accurate bibliometric analysis relies on the quality of the data sources. If the selected data do not accurately reflect the content of the discipline, the analysis results may be misleading. The primary task of the literature source selection is to select journals which reflect the content of the discipline. According to NSFC system, the geographical sciences have four sub-disciplines: physical geography; human geography; geographical information science; and environmental geography. Therefore, journals selected as data sources from the Web of Science should correspond to the above four sub-disciplines.
Although journals in the Web of Science are categorised into 232 disciplines, of which the SCI and SSCI contain 176 and 156 disciplines, respectively, the complexity of geographical sciences makes it difficult to align this classification with the discipline of geographical sciences. Therefore, drawing of different disciplinary perspectives, the following text considers the extent to which the Web of Science meets the needs of this book.
In the case of Physical Geography, the Web of Science has designed a periodical classification system, which includes not only 46 journals (e.g. *Progress in Physical Geography*) that are strongly relevant to the research content of physical geography, but also contains a few journals (such as *International Journal of Digital Earth*) which involve only in part studies in physical geography.
Human Geography, as a subcategory of Geography in the SSCI, contains 76 journals. As in the case of Physical Geography, the classification system for Human Geography in the Web of Science contains both journals that are closely related to human geography (e.g. *Progress in Human Geography*) and those having weak connections with human geography (e.g. *International Journal of Geographical Information Science*).
The Web of Science does not include a specific category called geographical information science. Remote Sensing is the closest category, but it only contains remote sensing journals, excluding journals in geographical information system. Furthermore, most geographical information system journals are grouped with other disciplines like Computer Science, Information Systems and Physical Geography.
Also, there is not an environmental geography category in Web of Science. Environmental Sciences (containing 223 journals) is the closest, but many of the journals included are not connected with environmental geography (e.g. *Applied Catalysis A-General*).
In summary, the Web of Science classification system for the geographical sciences does not meet the requirements of bibliometric analysis. For this reason, this book combines traditional methods and expert knowledge to select journals for different sub-disciplines.

First of all, based on a literature analysis and the classification of Web of Science, we proposed journal lists for different parts of the discipline. Second, we collected the views about the proposed journal lists from experts familiar with international journals to examine and revise these lists. Third, after two rounds of discussions and assessments, we assigned 307 core or mainstream journals to different sub-disciplines, with major considerations of the coverage, representativeness and comprehensiveness of sub-disciplines/fields. Account was also taken of the number of publications and research themes. Fourth, based on statistical analysis of sample papers, these core journals were divided into two categories: comprehensive journals and professional journals. There are 307 core journals used to analyse the number of publications in the first and second parts. Of these journals comprehensive journals are used to analyse research themes in the first and second parts. As for professional journals, they are used as complementary materials for the studies in Part III (on strategic issues) and Part IV (on specific areas). Finally, we identified 39 comprehensive journals and 95 professional journals for Physical Geography; 38 comprehensive journals and 46 professional journals for Human Geography; 24 comprehensive journals and 13 professional journals for Geographical Information Science; 21 comprehensive journals and 45 professional journals for Environmental Geography. A total of more than 900,000 SCI/SSCI journal articles were analysed in this book.

(2) **Classifications of CSCD Journals and Selection Criteria**
Chinese journals selected for bibliometric analysis contain two categories: the top 10 % of Chinese journals related to the geographical sciences (including professional journals in the geographical sciences and other related journals that published research findings in geography) announced in the *Annual Report for International Citation of Chinese Academic Journals* (*2014*) by CNKI; and professional journals in the geographical sciences outside of the top 10 % of Chinese journals. Because more than 90 % of our selected journals is covered by CSCD, we use the abbreviation "CSCD" to represent all of the selected core journals. Therefore, a total of 29 journals was selected from CSCD, of which 19 journals belong to Physical Geography, 12 to Human Geography, 4 to Geographical Information Science and 3 to Environmental Geography. It should be noted that there are 9 comprehensive journals that publish papers both in Physical Geography and Human Geography. Meanwhile, we had to identify the discipline for each paper based on the codes of themes. A total of more than 110, 000 CSCD journal articles were analysed.

(3) **Classifications of NSFC Projects and Selection Criteria**
Codes of disciplines are used to identify the projects of NSFC for each disciplinary branch. Projects labelled with D0101 (Physical Geography), D0103 (Landscape Geography) and D0104 (Environmental Change and Prediction) were assigned to Physical Geography. Projects labelled with D0102 (Human Geography) was assigned to Human Geography. Those coded with D0106 (Remote Sensing Mechanism and Methodology), D0107 (Geographical Information System) and D0108 (Surveying and Mapping) were assigned to Geographical Information Science. Projects labelled with D0109 (Fate, Process and Effects of Environmental Pollutants), D0110 (Quality and Security of Regional Environment), D0111 (Natural Resource Management) and D0112 (Regional Sustainable Development) were assigned to Environmental Geography. The projects used for the analysis in Parts III and IV were determined by the codes of disciplines, keywords and experts' opinions.

Acquisition and Verification of Data

Acquisition of Data

The process of acquiring data from SCI/SSCI was divided into two steps: the first step was to determine the data source (refer to Sect. "Confirmation of Literature Sources"); and the second step was to determine the academic search query. The academic search query is composed of keywords or phrases, Booleans and wild cards. The Web of Science provides two kinds of retrieval methods: the first one is Topic retrieval, namely to find papers matched with a given query by searching within titles, keywords (including keywords defined by authors and keywords defined by the system) and abstract; the second one is Title retrieval aiming to identify papers whose titles matched with the search syntax. Once the data source and search query were decided, articles could be retrieved. In order to conduct data analysis in this book, a huge amount of information on articles had to be downloaded from the Web of Science.

With the cooperation of CNKI, we obtained CSCD citation data. As in the case of SCI/SSCI, CSCD also has two types of retrieval method: the first one is Topic retrieval, namely to find articles matching a given query by searching within titles, keywords and abstract; the second one is Title retrieval designed to find articles whose titles match with a search query.

As for the acquisition of NSFC project information, we collected the full text for each application proposal based on the application coding system compiled by Division of Geography, Department of Earth Science of NSFC and then verified the results manually.

Verification of Data

This process mainly includes the verification of authors, institutions, etc. Chinese authors use names in *pinyin* in their English papers, which results in many same-name authors or different names for the same author. Therefore, the verification of authors in SCI/SSCI data was mainly targeted at Chinese authors. In order to accomplish this task, manual verification was the major method and involved comparing the data relating to institutions and names. The major task of institutional verification was to unify different names for a single institution in SCI/SSCI, and for institutions whose names have changed or which have been restructured. An additional function of institution verification was to identify the research results of Chinese Academy of Sciences at institution/unit level, which makes the bibliometric analysis in this book more concrete, purposive and precise.

Explanation of the Graphs in Bibliometric Methods

Graphs used in this book are mainly divided into four categories. These categories relate to keywords, authors, nationalities and institutions. Each category has several subtypes. The rest of this chapter outlines the meaning and significance of each category and subtype as well as their locations in this book.

Co-occurrence Graph

(1) **Co-occurrence Network of Keywords**
The co-occurrence network of Keywords can be used to analyse hot topics in a certain research field. The co-occurrence networks of Keywords in this book were generated by CiteSpace, a programme developed by Dr. Chaomei Chen. Each node represents a keyword in this graph and each link between two nodes indicates that two keywords

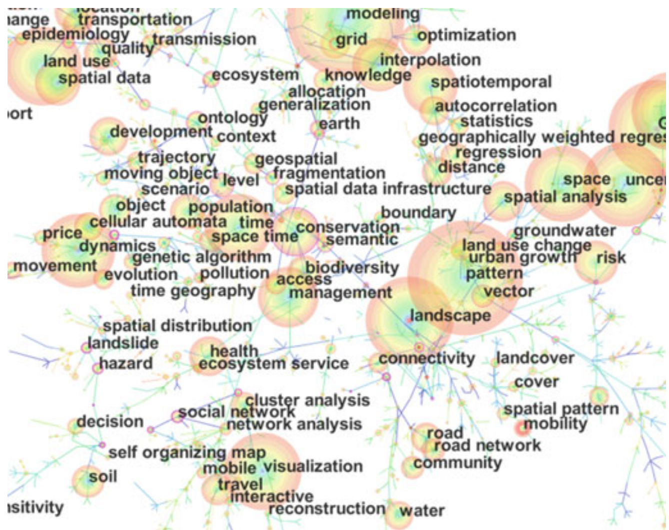


Fig. 1 Co-occurrence network of keywords

appear in the same paper. The weight of each link equals to the frequency of coexistence of two keywords. According to this logic, the Co-occurrence network of Keywords can be produced for a body of literature.[5]

As shown in Fig. 1, the nodes in the graph represent different keywords. The radius of the node represents the overall frequency for each node (and equals the number of papers that contain the keyword concerned). The annual rings for each node indicate the evolution of the keywords in different time periods. The width of each ring represents the frequency with which a keyword occurs in a specific year. The inner rings represent earlier years and the outer rings represent most recent years. In addition, if a ring of a certain node (e.g. the node "mobility" in the lower right corner of Fig. 1) is red, it means there was a burst in a certain time period, suggesting that this node belongs to a research frontier. The node "social network" in the lower left corner of Fig. 1 is surrounded by purple rings, indicating that the node has high Betweenness Centrality. Betweenness Centrality shows that this node was at the center of a keywords network and acted as a transitional element among various parts of the network. A cluster, defined by those close and connected nodes, represents a hot research topic. For instance, the cluster composed of land use change, urban growth, pattern and vector represents the application of spatial analysis in urban studies, while the cluster composed of cluster analysis, social network and network analysis shows the application of network modelling in social network analysis.

The co-occurrence networks of Keywords in this book are used to describe the following content. The first group (entitled "Co-occurrence network of keywords in *** journals of *** during the period ***") includes the general characteristics of the research topics in the four branches over the past 30 years (in Part II, Sect. *.1), changes of research topics in various periods in the four branches from 1986 to 2015 (Part II, Sect. *.2). The second group (entitled with "Co-occurrence network of SCI/SSCI-indexed article keywords on *** during the period 2000–2014) includes key research topics of the nine strategic research issues (Part III, Sect. *.1) and the key research topics of the nine research fields (Part IV, Sect. *.1). The third group (entitled with "Co-occurrence network of keywords

[5]Chen Y, Chen C M, Hu Z G, Wang X W. (2014) *Principles and Applications of Analyzing a Citation Space*. Beijing: Science Press (in Chinese).

in Sino-*** cooperation", Part I, Sect. 2.3) includes the series of co-occurrence networks showing the Sino-USA, Sino-UK and Sino-Germany academic cooperation in different areas.

(2) **Collaborative Networks of Chinese Authors**
In this case, the node represents the author, the width of node shows the number of publications of a certain author in a specific year and the burst of a ring indicates a sharp rise in the publication of a certain author. A link shows that two authors publish papers together. This graph is used to describe the cooperation networks among different research teams as well as to identify outstanding scholars. The existence of a group of authors who all published many papers clustered in the graph indicates the existence of an important research team in a certain area of research. In Sect. *.3.1, Part II of this book, graphs of collaborative networks of Chinese authors were produced based on SCI/SSCI and CSCD data respectively to describe developmental trends for different disciplines and research teams in China.

(3) **International Cooperation Graphs**
This graph appears in the part dealing with global cooperation network (Sect. 2.1). A node represents a country and the size of node shows the degree (number of publications involving global cooperation). The width of the link between two countries represents the number of publications involving mutual cooperation. In addition, if one country has stronger and broader cooperations with other countries, it is more likely to be the center of the graph (i.e. the colour of the node is red, otherwise it is green). This type of graph can be used to describe the degree and position of different countries in global academic cooperation.

Keywords Temporal Trajectory Graph

(1) **Comparative Diagram on Hot Topics between China and Others**
Using high-frequency keywords from the SCI/SSCI data set, this book makes comparisons between China and other countries (regions) to describe the differences between and changes in hot research topics in four branches of the geographical sciences (Part II) and different research areas (Part IV). This diagram shows changes in the ranking of keywords arranged in descending order in terms of frequency. Each node in this diagram represents a keyword. This diagram has two parts: the left side represents the frequencies of keywords in different time periods in foreign countries; while the right side shows the frequencies for China. Keywords used both in China and foreign countries are shaded in the same colour. In Part II, the area of each node indicates the proportion of the frequency with which a certain keyword was used in a specific period of time, while in Part IV it indicates the proportion of the frequency of a certain keyword in the total number of articles in a specific year. The former is used to study "Changes of research topics in different periods" in Sect. *.2, Part II; the latter is used to study "Research advances and problems" in Sect. *.2, Part IV.

(2) **Keywords Temporal Trajectory Graph of Research Topics in SCI/SSCI**
In order to study the evolution of research topics, keywords from SCI/SSCI data that are similar in meanings were merged into several topics in this book. By comparing the number of papers of a certain research topic in different periods, the trends in research hotspots and trends in the study of strategic issues can be described. These diagrams are used in Sect. *.1, Part II and Sect. *.1, Part IV.

(3) **Keywords Temporal Trajectory Graph of Research Topics in NSFC**
In order to analyse the characteristics of NSFC-funded projects and the contribution of NSFC, this book keywords from NSFC data that are similar in meanings were merged into several topics. By comparing the number of NSFC-funded projects on a certain research topic in different periods, we can find the changes in research topics that NSFC has funded. These diagrams are used in Sect. *.1, Part III and Sect. *.1, Part IV.

Statistical Chart of the Number of Publications

Based on the SCI/SSCI and CSCD data, the number of publications was calculated in four sub-disciplines, on nine strategic issues and in nine areas, respectively in the book. Constructed for different research sub-disciplines/issues/areas, these charts can be divided into five types: descriptive analysis of the number of publications of different countries (regions); the percentage of publications of different countries (regions); the percentage of papers funded by NSFC; the number of publications of different institutions; the funding agencies for highly cited papers. Since these charts are very easy to understand, nothing more really needs to be explained on the subject.

Explanation of Tables in Bibliometric Analysis

Tables used in this book mainly include the following four types: The World Ranking of Closeness Centrality; the World Ranking of Publications in the Geographical Sciences; the Countries (Regions) Ranking of Average Cites Per Paper for Highly Cited Papers in Branches of the Subject; the Statistical Table of NSFC-funded projects and SCI/SSCI-indexed articles.

World Ranking of Closeness Centrality

This indicator is used to evaluate the position of each country (region) in international academic cooperative networks. The higher the closeness centrality is, the closer the county will be to the center on the network. In network analysis, the closeness centrality of one node is defined as the reciprocal of the sum of its distances from all other nodes. The formula can be expressed as follows:

$$C_C(i) = \frac{n-1}{\sum_{i=1,(i\neq j)}^{n} d(i,j)}$$

where *i*, *j* are the sequence numbers of two nodes in the network, n is the total number of nodes and d(*i*,*j*) represents the distance between node *i* and node *j*.[6] Section 2.1 discusses the "Global cooperation networks", of which the closeness centrality of each country (region) is created by Pajek and the mapping of closeness centrality is created by Gephi. For the detailed ranking of closeness centrality of different countries, please refer to Table 2.1.

World Ranking of Publications in the Geographical Sciences

Section 2.2 of Part I provides two tables to describe the number of publications in the geographical sciences and the number of highly cited papers in different countries (regions) between 2000 and 2014. Table 2.2 is used to evaluate the overall capability in the geographical sciences of different countries (regions), while Table 2.3 can be used to describe the innovative ability of different countries (regions). These tables contain indicators like the year, the number of independent research papers in 2000 and 2014 and the number and percentages of international cooperative papers. Independent research refers to a paper whose authors all come from the same country (region), and international cooperative articles refers to article whose authors come from different countries (regions). Remember that this book defines the country (region) of a paper by considering the nationality of the first author or the corresponding author.

The overview of Sect. *.1 in Part III and of Sect. *.1 in Part IV mainly present the overall number of SCI/SSCI publications, the overall citations and the number of highly cited papers and the position and progress of China in international research over the past 15 years (see

[6]Okamoto K, Chen W, Li X Y. Ranking of closeness centrality for large-scale social networks. Frontiers in Algorithmic, 186～195, Berlin Heidelberg: Springer, 2008.

Table *.1 in Part III or Table *.1 in Part IV). Table names are presented as "Top 20 countries (regions) with the number and citations of SCI/SSCI-indexed articles on **** during the period 2000–2014.

Countries (Regions) Ranking of Average Cites Per Paper for Highly Cited Papers in Branches of the Subject

For each of the four sub-disciplines identified in the second part, the average number of cites per paper for SCI/SSCI highly cited papers from 1986 to 2015 was computed, and the top 20 countries (regions) were ranked to analyse their influence in that field (see Table *.1 in Part II). Table names are presented as "To 20 countries (regions) of average cites per paper for highly cited SCI/SSCI–indexed articles in ****". Average cites per paper of highly cited articles are defined as: Total citation frequencies for the 100 top cited papers divided by 100. Highly cited papers refer to those with total citations ranked in the top 100 for each country (region) in a period of 5 years.

Statistical Table of NSFC-funded Projects and SCI/SSCI-indexed Articles

In Parts III and IV, Chinese authors' funding information and outputs were examined to analyse NSFC's funding features and contributions in different strategic issues and fields. The statistical information consists of two parts, i.e. SCI/SSCI-indexed articles and NSFC-funded projects, including time periods, number of articles, proportion of articles by Chinese authors, proportion of articles with NSFC funding by Chinese authors, proportion of Chinese authors' articles simultaneously funded by NSFC and MOST (Ministry of Science and Technology), the number of funded projects, funding amount, the number of funding project leaders, the number of funded institutions. The table will be presented as "NSFC-funded projects and SCI/SSCI-indexed articles on*** during the period 2000–2014 in Sect. *.1 "Overview" in Part III and Sect. *.1 "Overview" in Part IV.

Content of Bibliometric Analysis in the Geographical Sciences

This book attempts to adopt methods of bibliometric analysis to clarify the hot research topics and trends in the development of the geographical sciences and to uncover the underlying influencing factors, to compare current status of research in China and abroad, and to analyse NSFC's contribution to the development of China's geographical sciences.

Comments on Hot Research Topics and Development Trends

(1) **Hot Research Topics in the Geographical Sciences**
This book summarised the changes in the geographical sciences over the past 30 years from four angles, including the overall geographical sciences, four sub-disciplines, nine strategic issues and nine research fields. In terms of hot topics, the analysis is mainly based on Keywords Co-occurrence Relations, identifying hot topics by the cluster nodes shown in the graphs of high-frequency keywords.

(2) **Development Trends of the Geographical Sciences**
For the four sub-disciplines, we generally used the area chart (comparative diagram) of hot keywords to conduct analysis, illustrating the change in different research fields by comparing the changing features of keyword frequencies in different periods. For the nine strategic issues and nine research fields, the analysis was mainly based on the temporal trajectory graph of research themes in SCI/SSCI journals. This analysis examined the evolution of research hotspots relating to the strategic issues and research fields by comparing variations for each research theme in different periods. Trends in the

development of the discipline and the evolution of research teams in China are mainly reflected in the changing number and proportion of NSFC applications and funded projects, the topics selected for NSFC-funded projects, the changing number of research institutes, the changing average number of SCI/SSCI papers published by research institutes, author collaboration networks in SCI/SSCI or CSCD papers and institutes and NSFC funding information relating to highly cited papers.

(3) **The Role of the Geographical Sciences**
The geographical sciences have played a significant role in the research progress made in relation to the nine strategic issues. We aimed to refine and summarise the contributions of the geographical sciences in terms of research perspectives, approaches and research teams based on a careful reading of a wide range of literature, on the basis of analysing the number of SCI/SSCI-indexed articles, citations, number of highly cited papers and authors' background information for SCI/SSCI-indexed articles.

(4) **International Comparison and Problems of Domestic Studies**
The nine strategic issues in Part III and nine research fields in Part IV are important areas of interdisciplinary research and play an important role in strengthening NSFC funding strategies for geography as a discipline. Based on bibliometric analysis, we revealed the problems of domestic studies, put forward recent development goals and NSFC key funding priorities and predicted China's future role on the basis of examination of differences in research questions, perspectives, progress, quality and research team as reflected in representative papers.

Comparative Analysis of Scientific Research Capability

In describing the scientific research capability of China and other countries, the overall number of publications is the major indicator. In detail, the following tables are used in this book: the overall numbers, percentages and ranking of publications in different countries (regions). As for the evaluation of original research outputs, the number of highly cited papers is the major indicator. In addition, authors in this book analysed the keywords of highly cited papers in China in Part II, aiming to identify the problems in four sub-disciplines of the geographical sciences and to identify the positions of research teams.

International Cooperation

International cooperation reflects the openness of scientific research and can be seen as one of the factors that influences the development of a discipline. This book discusses international cooperation in two dimensions: the first dimension focuses on the depth of international cooperation at a national level and includes the analysis of the international cooperation in mainstream SCI/SSCI-indexed geographical sciences' journals (Figs. 2.1 and 2.2), the closeness centrality of international cooperation networks (Table 2.1) and the independent research and international cooperation of different countries (regions) (Tables 2.2 and 2.3); and the second dimension involves identification of hot topics in international cooperation, i.e. to compare the hot topics in China with those in other countries (regions) which have strong connections with China in academic research (e.g. the USA, the UK and Germany).

Characteristics and Functions of NSFC

In describing the characteristics of NSFC funding, this book focuses on these topics: research directions of projects, keywords of projects, research objects of projects, etc. As for the functions of NSFC, the analysis was divided into two aspects: the outputs (research papers) of the fund and the contribution to nurturing talented researchers. The measurement of the outputs of scientific research involves the overall number and percentage of papers funded by

NSFC, the percentage of highly cited papers funded by NSFC and changes in funding directions in different periods. When it comes to nurturing talented researchers, we mainly referred to the number and spatial differentiation of institutions and researchers, the number of authors, the nodes within collaborative networks, the number of authors who contributed to highly cited articles and leading research institutions, etc.

Part I

An Overview of Development in the Geographical Sciences

Abstract

Part I consists three chapters: (1) general trends in the geographical sciences at home and abroad; (2) international research cooperation and (3) the background to the development of the Chinese geographical sciences. Using CiteSpace and TDA as analysis tools and high frequency keywords in 307 SCI/SSCI geographical sciences' journals as source materials, this chapter summarizes the general research trends in the geographical sciences in terms of hot issues relating to global change, globalization and sustainability. It then describes the supporting role of remote sensing and geographical information system in regional research and the role of field observation and experiment in physical geographical process research, and points out that simulation and prediction have become important directions in geographical research. The number of published articles in SCI/SSCI journals and their citations provide an opportunity to see the pattern of independent and cooperative research in the top 20 countries. The results show that major research fields in which cooperation has been carried out with the USA, the UK and Germany are environmental pollution and global change. The curricula and the background of faculty in geographical universities in China, the USA, the UK and Germany have been examined with the help of internet data searching and questionnaires. Finally, this part outlines the background to the development of geographical sciences including the NSFC funding for the geographical sciences, research and teaching in geography faculties and departments in Chinese universities, the development of the Geographical Society of China and the construction of academic platforms.

Keywords

Development trends in the geographical sciences • International cooperation of the geographical sciences • Geographical faculty • Geographical sciences in China • NSFC geographical sciences

General Trends in the Geographical Sciences

1

Shuying Leng, Wenxiang Zhang, Siyuan He, Canfei He, Desheng Xue, Linwang Yuan, and Qiuhong Tang

Abstract

In this chapter, major geographical issues examined in 307 SCI/SSCI mainstream journals in the geographical sciences are identified to describe general trends in the geographical sciences in the past 30 years, both at home and abroad. The geographical sciences play an increasingly important role in solving global and regional hot issues such as global change, globalization and sustainability. Research into geographical processes is deepened as well as integrated, with field observation and experimentation contributing greatly to research on physical geographical processes and mechanisms. The geographical sciences as a discipline are now improving their ability to simulate and predict the future evolution of the earth surface and environment, assisting with the development of ways of mitigating and adapting to environmental change. Adaptation, vulnerability, uncertainty and resilience have become new frontiers in global change studies. In addition, the development situation of geography education in three developed countries has been analysed based on questionnaire and internet data.

Keywords

Trend of the geographical sciences • Geographical education • RS and GIS • Simulation and prediction • Field observation and experiment

In this chapter, major geographical issues examined in 307 SCI/SSCI mainstream journals in the Geographical Sciences (see Appendix A) have been identified to describe general trends in the Geographical Sciences in the past 30 years. The number of publications by Chinese authors was counted by the appearance of “China” in the mailing address of either the first author or the corresponding author. The number of publications by authors from other countries (regions) was the total number of publications minus the number with Chinese authors. In addition, the development situation of geography education in three developed countries has been analysed based on questionnaire and internet data.

1.1 Global Hot Issues Propose New Entry-Points for Research

Global hot issues are problems that attract all people, including scientists globally. They are closely related to human survival and development, and at the same time are problems scientists in different fields of expertise hope to be involved in solving. Global hot issues are usually complex, and demand systematic research at different spatial and temporal scales. These features provide a suitable platform for Geography. This section focuses on global change, globalisation and sustainable development, taking 307

S. Leng et al., *The Geographical Sciences During 1986–2015*,
Springer Geography, DOI 10.1007/978-981-10-1884-8_1

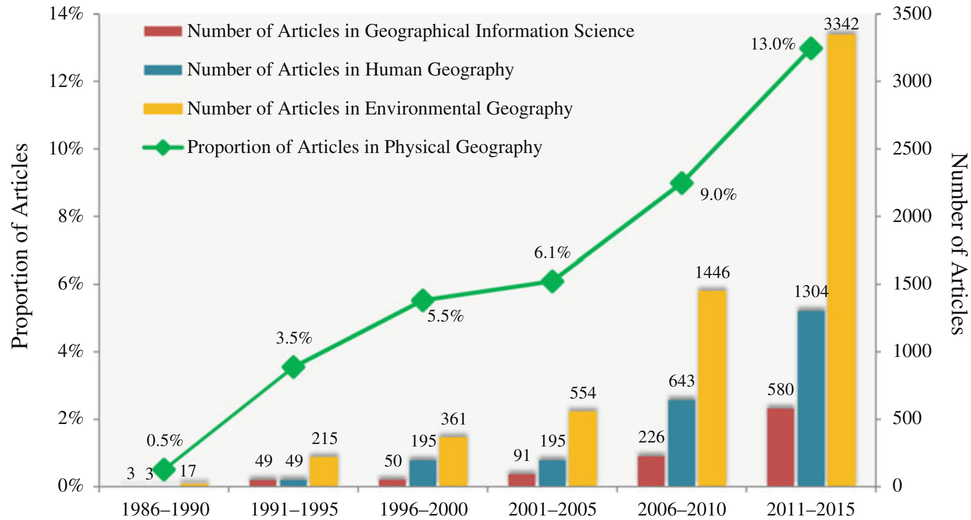


Fig. 1.1 Number/proportion of articles on "Climate Change/Global Change" in mainstream SCI/SSCI-indexed geographical sciences' journals

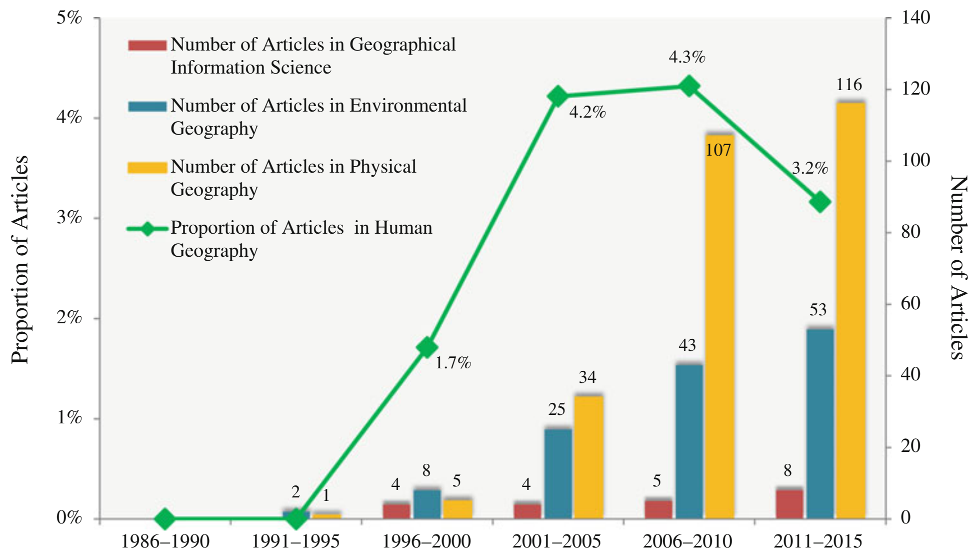


Fig. 1.2 Number/proportion of articles on "Globalization" in mainstream SCI/SSCI-indexed geographical sciences' journals

mainstream SCI/SSCI-indexed geographical journals as research objects to search for "global change" (or "climate change"), "globalisation" and "sustainability" within article title, keywords and abstract. The results (Figs. 1.1, 1.2 and 1.3) show that the number of articles with the three keywords has increased in amount (or proportion if the number is too large), indicating an increasing concern with these global hot issues where Geographical Sciences can provide some unique perspectives.

The two most important representative keywords for global change should be "climate change" and "global change", with different emphases. "Global change" contains both "climate change" and changes in atmospheric composition and land use change. "Climate change" mostly represents changes in the climate system itself, such as changes in temperature and precipitation. Climate change may be due to the internal natural processes of the climate system or external forces, or the constant changes of atmospheric composition and land use caused by human activities.[1] In this section, these two keywords are the representative words for statistical analysis of global change. Data show that in the past 30 years all the four branches of the Geographical Sciences have touched upon "climate change" and the number of articles has kept increasing. Among them, most research occurred in physical geography, with the proportion of articles in all articles increasing by 12.5 % between the period 2011–2015 and 1986–1990, and by 6.9 % between 2011–2015 and 2001–2005 (Fig. 1.1). The frequencies of "climate change" and "global change" as keywords were 9687 and 736. Other keywords with a co-occurrence frequency of over 200 included "adaptation", "Holocene", "temperature", "global warming", "drought", "precipitation", "climate",

[1]Qin D H (chief editor) (2014) *Glossary of Cryosphere Science*. Beijing: China Meteorological Press. P122 (in Chinese).

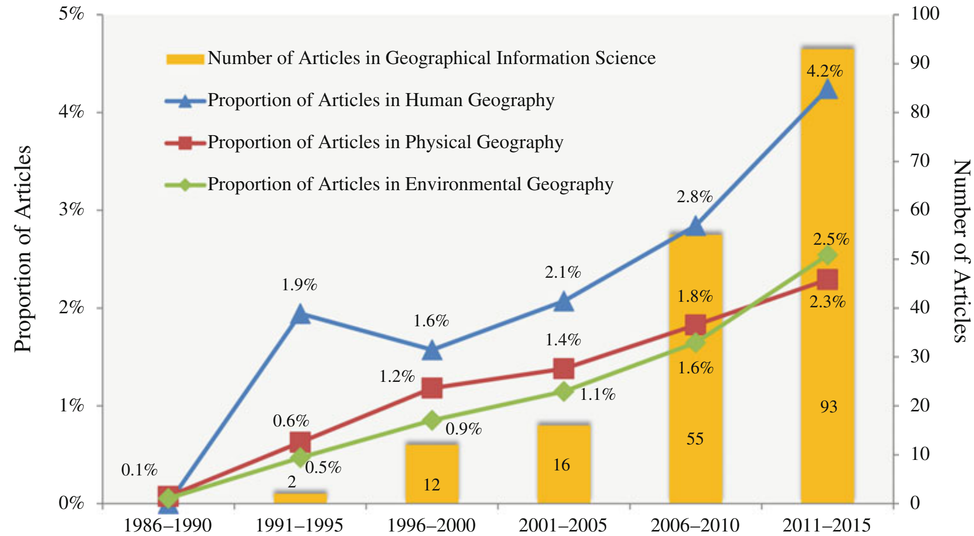


Fig. 1.3 Number/proportion of articles on "Sustainability" in mainstream SCI/SSCI-indexed geographical sciences' journals

"remote sensing", "vulnerability", "biodiversity", "uncertainty", "agriculture", "Phenology", "Arctic", "climate variability", "land use", "resilience", "pollen", "China", "carbon dioxide", "Hydrology", and so on. From these patterns we found that "Holocene" and "pollen" were hot spots for research on global change in the past; "Arctic" and "China" were hot spots for regional research; research on the climate system itself focused on "temperature", "global warming", "precipitation", "drought" and "climate variability"; interaction between global change and the earth surface (including human activities) concerned "biodiversity", "agriculture", "Phenology", "land use", "carbon dioxide", and "Hydrology"; while "adaptation", "vulnerability", "uncertainty" and "resilience" indicated the focus on scientific problems closely related to human survival and development. With further analysis we found that within the 21 keywords, the last four keywords were among the top 10 hottest keywords in 2011–2015, indicating that these were at the recent frontier and were current hot spots. The five-year re-occurrence (2011–2015) of these keywords, and of "climate variability", "China", "water resources", "remote sensing", "drought" and "precipitation" as a proportion of their 30-year re-occurrence all were between 60 and 64 %, indicating their popularity in the recent years. Keywords representing research into paleoclimate and past global change, such as "Holocene" and "pollen" occurred a lot in the last five years; however, the current five-year re-occurrence proportion has only increased by less than 10 % compared to the previous five years, which was much lower than for the above-mentioned keywords.

Data show that of the four branches of geography research on globalisation has increased most in Human Geography in the last 30 years. The proportion of articles in all mainstream human geography journals has increased by 2.6 % between the period 2006–2010 and 1996–2000, but has decreased by 1.1 % between the period 2011–2015 and 2006–2010 (Fig. 1.2). Research on globalisation appeared from the early 1990s. Since then, the frequency of the keyword "globalisation" in SCI/SSCI mainstream journals was 596, with an increasing trend based on the five-year sum from the period of 1991–1995 to 2001–2005; the number peaked 222 in 2006–2010 and decreased to the lowest number of 154 in 2011–2015. Thirty five other keywords have a frequency of co-occurrence higher than 20. These keywords included *China*, *Neoliberalism*, *scale*, *India*, *governance*, *development*, *regional development*, *urbanization*, *migration*, *climate change*, *trade*, *global production networks*, *Latin America*, *inequality*, *institutions*, *Mexico*, *networks*, *Economic Geography*, *gender*, *poverty*, *vulnerability*, *environment*, *foreign direct investment*, *sustainability*, *transnationalism*, *world cities*, *Africa*, *adaptation*, *agriculture*, *Political Economy*, *global city*, *place*, *tourism*, *Europe*, *urban development*. Of these keywords 17 reached a peak frequency in 2006–2010 and then decreased. The greatest decreases were for *poverty* (−48.3 %), *inequality* (−46.7 %), *tourism* (−33.3 %), *neoliberalism* (−21.2 %) and *gender* (−20.7 %), indicating a faster fall against the background of a downward interest in *globalisation*; however, *neoliberalism* was still among the top 10 high-frequency keywords. By contrast, the frequencies for *India, governance, climate change, trade, global production networks, sustainability, world cities, adaptation, agriculture, Political Economy, global city, and Europe* reached a peak in 2011–2015, of which *global production networks, adaptation* and *governance* are the hottest recent topics, with the proportion of the five-year re-occurrence to the 30-year re-occurrence standing at 65.5, 56.5 and 53.4 %. This indicates that research on globalisation was closely linked to adaptation to global change. In addition, concern with political economy, urban and sustainability increased.

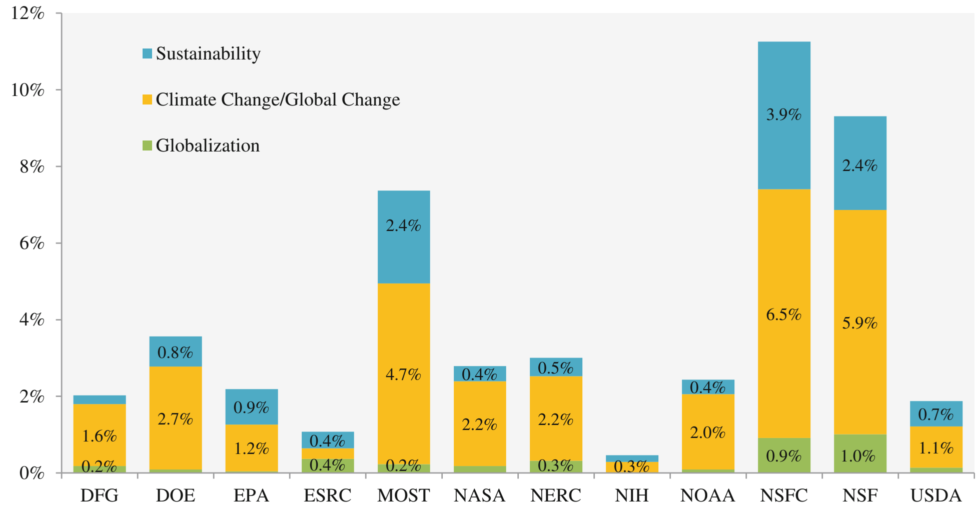


Fig. 1.4 Representative funding agencies for research articles on global hot issues published in mainstream SCI/SSCI-indexed geographical sciences' journals

Data show that research on sustainability has increased in the past 30 years with the greatest increases in Human Geography and the smallest in Geographical Information Science. The proportion of articles in the mainstream journals of Human Geography, Environmental Geography and Physical Geography has increased by 2.3, 2.0 and 1.7 %, respectively, between the periods 1991–1995 and 2011–2015. The number of articles in Geographical Information Science in 2011–2015 was 46.5 times that in 1991–1995, and 5.8 times that in 2001–2005 (Fig. 1.3). The frequency of the keyword "sustainability" in the mainstream SCI/SSCI-indexed Geographical Sciences' journals was 1719 in 1986–2015. It has kept increasing and reached the peak of 689 in 2011–2015, which was 40.1 % of its total times re-occurrence in the past 30 years. Twenty other keywords had a co-occurrence frequency higher than 80, including *sustainable development*, *climate change*, *life cycle assessment*, *China*, *ecosystem services*, *resilience, biodiversity*, *indicators*, *agriculture*, *governance*, *land use*, *environment*, *conservation*, *ecological footprint*, *sustainability assessment*, *environmental sustainability*, *GIS*, *environmental management*, *sustainability indicator and vulnerability*. Their frequencies all reached a peak in 2011–2015 and the proportion to the total times re-occurrence in the past 30 years of "sustainability assessment", "life cycle assessment" and "ecosystem services" were as high as 73.7, 72.0 and 71.3 %, suggesting that they were core research topics. Keywords with an above-mentioned proportion between 60–70 % included "climate change", "environmental sustainability", "ecological footprint", "China", indicating that they were major foci where environmental sustainability and ecology were closely interwoven with global change and human activities. Furthermore, keywords including "resilience", "governance", "vulnerability", "environmental management", "indicators" and "sustainability indicators" were also among those with high proportions (50–60 %), indicating the popularity of topics relating to the evaluation of environmental and ecological sustainability (Fig. 1.4).

Directions supported by international funding agencies represent the base and cutting-edge of science. This section summarizes the statistical characteristics of research funded by DFG, DOE, EPA, ESRC, MOST, NASA, NERC, NIH, NOAA, NSFC, NSF, USDA (see Appendix B), the major research funding bodies of the USA, the UK, Germany and China. The analysis includes all articles published in 307 journals in 2006–2015 with the keywords "climate change", "global change", "globalisation" and "sustainability". Within all the 23,880 articles on global change, those funded by the 12 agencies accounted for 17.7 % in 2006–2010 and 37.3 % in 2011–2015. The overall ratio in the decade was 30.6 %, indicating a great interest from these funding bodies in these topics. In total, 7308 articles were funded by the 12 agencies and 80.2 % of them were published in 2011–2015. Of them 1549 articles (6.5 %) were funded by NSFC, which was slightly more than those funded by the NSF (USA) (1398, 5.9 %). Articles supported by MOST (China), DOE (USA), NASA (USA), NOAA (USA) and NERC (UK) all accounted for more than 2 % of the total; articles supported by DFG accounted for 1.6 % (386). In all of the 7888 published articles on sustainability, those funded by the 12 agencies accounted for 7.2 and 16.6 % in the former and latter five years of 2006–2015, and the overall decadal ratio was 13.2 %. In total, 1040 out of 7888 articles were supported by the 12 agencies and 80.1 % of them were published in 2011–2015. Major funding bodies were NSFC (304, 3.9 %), NSF (193, 2.4 %) and MOST (191, 2.4 %). As for "globalisation", of all the 2180 published articles those funded by the 12 agencies account for 2.2 and 5.2 % for the two five-year periods respectively, and the overall decadal ratio was 3.6 %. Seventy eight out of the 2180 articles were supported by the 12 agencies with 66.7 % published in 2011–2015. Major funding bodies were NSF (22, 1 %) and NSFC (20, 0.9 %). Of the three topics with which world funding bodies were particularly greatly concerned, "global change" attracted far more funding opportunities than "sustainability" and "globalisation".

1.2 RS and GIS Provide Essential Methods and Tools for Area Studies

One of the features of the Geographical Sciences is area studies, which is determined by the heterogeneity of the components of the earth surface. From the analysis of the statistical characteristics of research articles in area studies, we could see the role of Remote Sensing (RS) and Geographical Information System (GIS) in area studies at different periods. The object of analysis was 307 SCI/SSCI mainstream journals with the search conditions ("Asia" OR "America" OR "Europe" OR "Africa" OR "Oceanica" OR "Oceania" OR "China" OR "USA" OR "United States" OR "Russia" OR "Australia" OR "Brazil" OR "Canada" OR "plateau" OR "plain" OR "river basin" OR "watershed" OR "hill" OR "mountain" OR "highland" OR "lake" OR "glacier" OR "ice sheet" OR "icesheet" OR "flatland") applied to article title and keywords. The number of papers published by Chinese authors and foreign authors were calculated (Fig. 1.5). Another search condition was ("remote sens*" OR "remotely sens*" OR "imageries" OR "imagery" OR "RS" OR "geographical information system" OR "GIS" OR "geographic information system" OR "geographical-information-system" OR "geographic-information-system") applied to the title, keywords and abstract of the articles gathered from the former step, so that articles using Remote Sensing and Geographical Information System methods could be calculated regarding Chinese and foreign authors.

Search results show that in the past 30 years Chinese and foreign scholars have a total of 162,950 papers published on area studies, which was 25.2 % of all the papers in the geographical sciences. The number of articles in 2011–2015 was 18.1 times higher than in 1986–1990, and 2.4 times higher than in 2001–2005. Chinese authors accounted for 13.8 % which was also 16 % of foreign scholars' articles. Of these 63.9 % were published in 2011–2015 and 25.4 % in 2006–2010 (Fig. 1.5). The increase in the number of articles on area studies indicates a growing concern with comprehensive issues in research in the Geographical Sciences. The 47 keywords with a ratio of co-occurrence higher than 600 included *China*, *Australia*, *Africa*, *Brazil*, *Europe*, *South Africa*, *Canada* and *Asia*, indicating that these countries (regions) received considerable attention. Of the 47 keywords excluding these countries (regions), the top 14 keywords with a ratio of co-occurrence higher than 1000 were *climate change*, *remote sensing*, *Holocene*, *water quality*, *GIS*, *sediment*, *mercury*, *precipitation*, *land use*, *biodiversity*, *nitrogen*, *heavy metals*, *conservation* and *climate,* which involved comprehensive research issues at different geographical scales from the global to the continental and the local, at important temporal scales and using popular research methods. The other 26 keywords with high frequencies included *phosphorus*, *agriculture*, *drought*, *Hydrology*, *eutrophication*, *fish*, *temperature*, *air pollution*, *pollen*, *runoff*, *soil*, *fire*, *groundwater*, *disturbance*, *urbanization*, *nutrients*, *vegetation*, *risk assessment*, *stable isotopes*, *watershed*, *species richness*, *MODIS*, *soil erosion*, *monitoring*, *and restoration*, mainly suggesting research

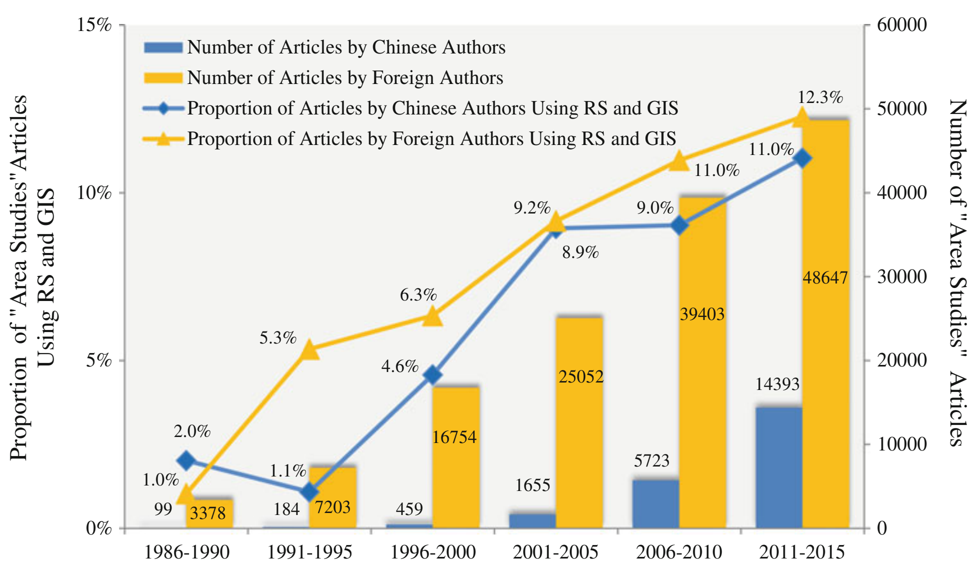


Fig. 1.5 Proportion of area studies' articles using RS and GIS in mainstream SCI/SSCI-indexed geographical sciences' journals

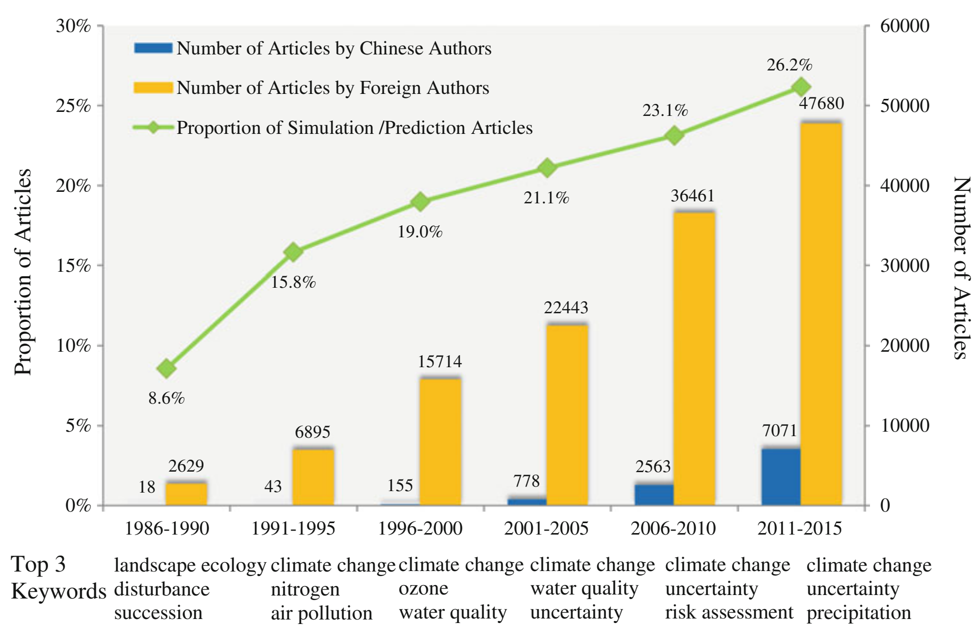
interest in the complexity of these issues at national and local scales. Examples included non-point pollution and lake eutrophication under highly intensive agriculture, air and underground water pollution, fire and disturbance and their impact on species richness and vegetation restoration, and runoff and soil erosion. In addition, growth in area studies also shows that the acquisition of regional data has been promoted and analytical abilities have been enhanced, especially in relation to the role of Remote Sensing (RS) and Geographical Information System (GIS). These two phrases were among those with a high frequency in area studies, ranking 3rd and 7th respectively, indicating their indispensable role. In the past 30 years, research assisted by these two methods has accounted for 10.1 % of all those published in area studies. The respective ratio for Chinese authors and foreign authors was 11.0 and 12.3 % in 2011–2015, increasing by 9.0 and 11.3 % compared to 1986–1990, and 2.1 and 3.1 % compared to 2001–2005.

1.3 Simulation and Prediction Become Crucial Aspects of Geographical Science Research

The core research theme in the Geographical Sciences is human-land relationships, which could happen in the past, present or future, so that the research scale spreads from the past to future. Traditional geographical research focuses explain phenomena that have happened in the past, and aim to propose solutions to current resource and environment issues. The cutting-edge however is to predict the evolving direction of each surface environment in the future and to identify measures to tackle and adapt to possible outcomes. This research trend could be detected through searching for research on simulation and prediction. With the searching condition ("model" OR "modeling" OR "models" OR "simulation" OR "quantitative" OR "spatial analysis" OR "spatial data" OR "spatial statistics" OR "virtual" OR "virtualization" OR "decision" OR "scenario" OR "policy") in article title and keywords, we calculated the number of papers on simulation and prediction research published by Chinese and foreign authors (Fig. 1.6), and the proportion of the number of papers to the total number of papers published in the 307 mainstream SCI/SSCI-indexed Geographical Sciences' journals (Fig. 1.6, line chart).

In the past 30 years, research articles on simulation and prediction have kept increasing, as a proportion of all articles in 307 mainstream geographical journals of 26.2 % in 2011–2015, 20.7 times that in 1986–1990 and 2.4 times that in 2001–2005. Chinese authors contributed 7.5 % of all the articles which equals 8.1 % of those published by foreign authors (Fig. 1.6). The six highest frequency keywords with a ratio of co-occurrence higher than 1000 were *model*, *climate change*, *remote sensing*, *GIS*, *uncertainty*, and *simulation*, indicating the importance of RS and GIS in simulation and prediction and the great concern with the uncertainty of climate change modelling. Other keywords with a rate of co-occurrence higher than 500 included *China*, *risk assessment*, *sensitivity analysis*, *air pollution*, *groundwater*, *precipitation*, *policy*, *Hydrology*, *soil moisture*, *land use*, *spatial analysis*, *runoff*, *ozone*, *agriculture*, *biodiversity*, *temperature*, *climate*, *optimization*, *sustainability*, *evapotranspiration*, *nitrogen*, *conservation*, and *MODIS*, showing that climate and hydrological models, atmospheric pollution

Fig. 1.6 Proportion of articles on "Simulation and Prediction" in mainstream SCI/SSCI-indexed geographical sciences' journals



models, risk assessment, decision making support, sensitivity analysis, spatial analysis and optimisation were all critical issues in simulation and prediction. The most frequent keywords among the above-mentioned ones were "climate change" (57.9 %) and "China" (57.1 %); this proportion increased by 31.9 and 29.2 % from 2006–2010 to 2011–2015, respectively, indicating that climate change was a frontier and hot spot. The next ranking keywords were "precipitation" (52.4 %) and "uncertainty" (52.4 %), indicating growing concern with the uncertainty of precipitation in climate change modelling. If "model" was the single search condition, the most linked words were *simulation*, *climate change*, *water quality*, *GIS*, *Hydrology*, *groundwater*, *nitrogen*, *remote sensing*, *uncertainty*, *runoff*, and *optimization*, which further show that climate change simulation, hydrology and water environment models, uncertainty analysis and optimisation were the foci of the past 30 years' research on simulation and prediction. By contrast, some keywords associated with "model" had declined in importance in 2011–2015 compared to the previous period, including "nitrate", "nitrogen" and "groundwater".

1.4 Field Observation and Experimentation Become Important Methods in Physical Geography

Analysis of processes and mechanisms has been the foundation of integrated research in the Geographical Sciences, as well as the base on which to explain geographical phenomenon and to build models. Research in Physical Geography often targets different types of ecosystems or natural surface elements, and these studies of processes and mechanisms are usually realised through field observation and experiment. 134 out of 307 journals were Physical Geography journals. To their titles and keywords we applied the search condition ("ecosystem" OR "eco-system" OR "environment" OR "environmental": OR "water" OR "soil" OR "atmosphere" OR "forest" OR "grass" OR "farmland" OR "lake" OR "mountain" OR "desert" OR "wetland") to calculate the number of papers in Physical Geography published by Chinese and foreign authors (Fig. 1.7, bar chart). Additional condition ("site" OR "sites" OR "situ" OR "field laboratory" OR "field station" OR "observation" OR "experiment" OR "experiments") was applied to identify articles on field observation and experiment in the previously obtained list. The number and proportion of papers on field observation and experiment published by Chinese and foreign authors was calculated (Fig. 1.7, line chart).

It was found that research articles on physical geographical processes and mechanisms had kept increasing to reach a proportion of 59.5 % in all the 134 Physical Geography journals in 2011–2015, which was 11.6 times that in 1986–1990 and 2 times that in 2001–2005. In the past 30 years, Chinese authors have published about 7.1 % of all the obtained articles, which equals to 7.6 % of all those published by foreign authors. 64.6 % of these papers were published in 2011–2015 and 25.4 % in 2006–2010 (Fig. 1.7). Field observation and experiment are important means to carry out research into processes and mechanisms. Some hundreds of years of data have been accumulated in some world famous observation stations. Overall, research based on field observation and experimentation conducted by Chinese scientists was no less than that by foreigners as a proportion (ca. 43 %) in the past 30 years. However, there is difference in the level of development in different time periods. The research peak abroad came earlier than in China. Research carried out by foreign scientists accounted

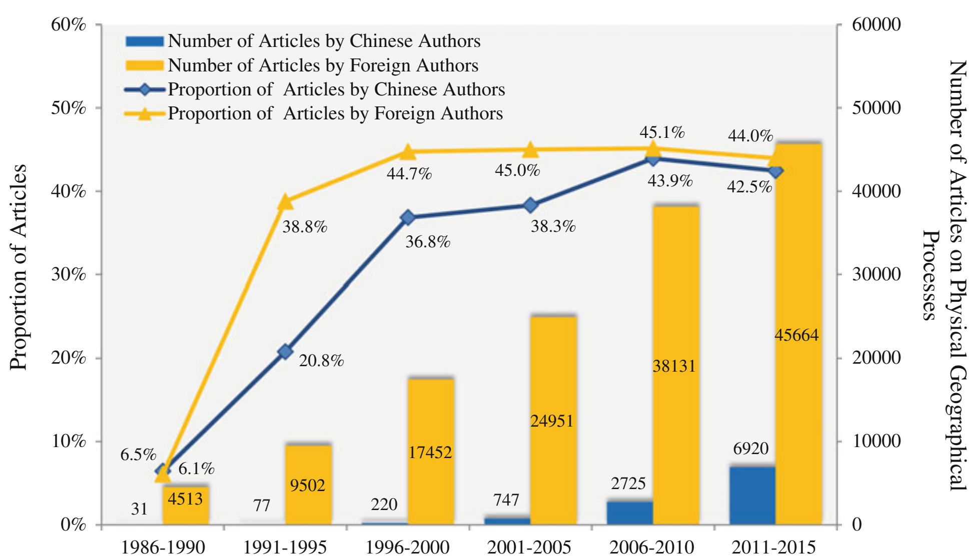


Fig. 1.7 Proportion of articles on physical geographical processes using field observation and experiment in mainstream SCI/SSCI-indexed physical geography's journals

for 6.1 % in 1986–1990 and has increased to 38.8 % in 1991–1995. China did not reach a proportion of 38.3 % until in 2001–2005. The proportion had already reached 44.7 % abroad in 1996–2000 and stabilised at around 45 % in the following 15 years. It took China 10 more years to reach a proportion of 43.9 % in 2006–2010, with generally no difference in the last five years. However, although China started late, it caught up fast. In this research field, there were 25 keywords with a rate of re-occurrence higher than 3000, including *climate change*, *vegetation*, *model*, *water*, *dynamics*, *management*, *ecosystem*, *climate*, *biodiversity*, *conservation*, *soil*, *diversity*, *variability*, *forest*, *patterns*, *growth*, *nitrogen*, *temperature*, *land use*, *precipitation*, *communities*, *United States*, *carbon*, *flow and runoff*. Of these keywords nine were related directly to vegetation and ecosystems with a word frequency of 36 %; eight keywords were related directly to global change with a word frequency of 30 %; others were related to water and soil, as well as research on modelling and management. This pattern shows the importance of global change as a driving factor in physical geography research and the essential position of ecological processes in physical geographical processes.

By a further analysis of articles directly related to vegetation and ecosystems, we found 28 keywords with a word frequency higher than 700, including *ecosystem*, *biodiversity*, *conservation*, *diversity*, *species richness*, *disturbance*, *vegetation*, *restoration*, *management*, *dynamics*, *fire*, *patterns*, *communities*, *climate change*, *forest*, *Ecology*, *rain forest*, *land use*, *landscape*, *growth*, *soil, nitrogen*, *succession*, *habitat*, *abundance*, *grassland*, *responses*, *productivity*. There was change of ranking for the first 10 keywords in the past 30 years, but *ecosystem*, *biodiversity*, *conservation*, *diversity*, *disturbance*, *vegetation* have always been among them, indicating a constant focus on ecosystem diversity, especially plant diversity and conservation. In the above-mentioned 28 keywords, those with a decrease in the five-year re-occurrence as a share of the 30-year re-occurrence between 2006–2010 and 2011–2015 included “habitat”, “succession” and “fire”. In 2006–2010, the word frequency of “management” increased rapidly. The word frequency in 2006–2010 was 2.1 times that in 2001–2005, with a five-year re-occurrence proportion of 30.8 %. In 2011–2015, this proportion increased to 46.6 %. Until in 2011–2015, keywords ranking in the 28 keywords did not include “climate change” and “community”. The word frequency of “climate change” (950) was 2.1 times that in 2006–2010, and the proportion reached 57.8 %. The word frequency of “community” in 2011–2015 (650) was 1.2 times that in 2006–2010, and the proportion reached 37.4 %. “land use” and “response” were words with increasing frequency in 2011–2015. The frequencies of them were 578 and 302, which were both 1.5 times that in the previous five years. With more details explored, this pattern shows that the response of ecosystems to global change, ecosystem conservation and management, field observation and experimentation in ecosystem research and research on community were the research frontiers and hot spots.

Chinese authors affiliated to the Chinese Academy of Sciences (CAS) have contributed 52.1 % of all the articles on physical geographical processes and mechanisms. Of those supported by field observation and experiment, CAS accounted for 56.5 %. In the articles in which the name or address of any of the 44 Chinese ecosystem observation stations could be identified, 76.3 % came from CAS affiliated authors. For all these CAS published articles, 61.8 % came in 2011–2015, 28.4 % in 2006–2010 and 7.1 % in 2001–2005. It all indicates that the development of the Chinese Ecosystem Research Network (CERN) since 1988 including 44 stations, five sub-centres and one synthesis research centre, has greatly facilitated interdisciplinary work in the Geographical Sciences and Ecology, raised the research level of Chinese research into physical geographical processes and mechanisms, and will definitely continue to play an important role in the development of physical geography in China.

1.5 Higher Education Adapts to the Development of the Geographical Sciences

Higher education institutions, curriculum, disciplinary system and faculty matter to the future development and vitality of geography. Creating an education system that reflects development trends is an important way to promote the healthy and sustainable development of geography in higher education in China. We have examined the top universities in Geography in countries famous for geography education, including the USA, the UK and Germany. In China, we chose Peking University, Beijing Normal University and East China Normal University as representatives. All three have geography as a key national discipline. From the perspective of organisational structure, curriculum, subject and major setting and faculty, we have analysed the characteristics of geography education at both home and abroad in order to contribute to the development of geography in higher education in China.

1.5.1 Organisational Structure and Subject/Major Setting

Organisational structure and the subject/major setting of Geography in higher education have been affected by running mode, subject positioning, discipline development and resource allocation, and to a large extent reflect the basic concept of higher education and major features of education and teaching. Higher education institutions in all four countries have a deductive organisational structure for teaching and management (Table 1.1). "Geography" was a School of Studies in six institutions (26 % out of 23 of the cases studied), including University of Cambridge, University of Oxford, Durham University, University of Göttingen, Beijing Normal University and East China Normal University. No American university adopted this mode. Institutions with a department of geography under a school of Earth Sciences included University of Bonn, Heidelberg University and University of Cologne. All were German universities. Institutions with a department of geography under School of Environment include University of Exeter, University of Leeds and University of Freiburg, which are all Britain or German universities. Institutions with Geography in a School of Art and Sciences, Natural Sciences or Behavioural and Social Sciences are Bristol University, Humboldt University of Berlin, Boston University, University of California St Barbara, University of Maryland College Park, University of Colorado Boulder and University of California Los Angeles, most of which are American universities. There are also institutions where geography is a key national discipline but does not appear in the name of faculties/schools, such as College of Urban and Environmental Sciences in Peking University, College of Resources Sciences and Technology in Beijing Normal University (geography has been restructured), School of Environment in Beijing Normal University and School of Urban and Regional Science in East China Normal University. It is not difficult to see that geography relies on Earth Sciences and interacts largely with Environmental Sciences, Biology, Chemistry, Social Science and Liberal Arts.

As far as the sub-disciplines were concerned, the institutions in the four countries all have Physical Geography and Human Geography. All countries besides the UK included Geographical Information Science. It reflects the fact that the three traditional sub-disciplines remain being accepted internationally. Geographical Information Science is becoming essential knowledge for students to understand and master. Based on this tradition, University of Exeter, Boston University, University of Maryland College Park, University of Colorado Boulder, University of California Los Angeles, Beijing Normal University and Peking University have also added Environmental Science, reflecting the emphasis on environmental education and research in the three countries.

In the setting of further subjects, the UK was similar to China, without clear further subjects. By contrast, in Germany and the USA there were very detailed subjects. Traditional research areas, such as Geomorphology, Hydrology, Climatology and Economic Geography, have received great deal of attention in Germany and the USA. Subjects including Biogeography, Landscape Ecology, Land Science, Soil Science, Urban and Regional Planning, Spatial Planning, Social and Cultural Geography, Development Geography and Historical Geography were set up as specialities in some German universities. American universities not only pay attention to traditional disciplinary divisions, but also focus on global hot issues, thus their teaching subjects are related to global change, nature conservation, resources, energy, the environment, marine and sustainable development. Some also established courses/programmes in polar studies, cognitive geography, behavioural geography and transportation related subjects. All four countries lay emphasis on broadening the scope of knowledge so that students have the ability to carry out interdisciplinary research and analyse complex environmental problems.

1.5.2 Curriculum and Specialisation

According to statistics for different types of courses[2] (Fig. 1.8), among the four countries the number of courses in China was far greater than in the other countries. The average number of courses in the three Chinese universities was 2 or 3 times that of universities in the other three countries. Even within a country, the number of courses was quite different. For example, the number of the University of Exeter was 3 times that in the University of Cambridge and Durham University; the number of courses in University of Colorado Boulder was 2 times that in the University of California, St Barbara. However, the number is quite balanced in Germany for the three subjects, possibly because diverse types of degree, including science, arts and education could be awarded to undergraduates. From the perspective of different subjects, there was no Geographical Information Science major in the UK universities included in this study, but it was a support tool for Physical and Human Geography where the related courses were mostly about methodology. For example, there are courses in Applied Geographical Information Science for Physical Geographers, Geographical Information Science and Systems and Remote Sensing for Environmental Management in a programme in Physical Geography and Environmental Sciences and courses in Research Methods for Geographers in a programme in Human Geography in the University of Exeter; there were Statistical Methods, Cartography and Geographical Information Science, Working with Geographical Databases as

[2] Non-specialised courses in the three Chinese universities have included non-compulsory public geography-related courses. For lectures and seminars, there are explicit schedules in Boston University, University of Colorado Boulder, Humboldt University of Berlin, University of Bonn and Beijing Normal University, but schedules for other universities without fixed and specific information are not listed.

Table 1.1 Subject classification of the geographical sciences in representative countries and universities

Country	University	Colleges /Departments (1st Level)	Majors (2nd Level)	Academic areas (3rd Level)	Country	University	Colleges /Departments (1st Level)	Majors (2nd Level)	Academic areas (3rd Level)
UK	University of Oxford	Faculty Board of Anthropology and Geography (School of Geography and the Environment)	Geography	–	Germany	University of Cologne	Department of Geoscience (Geography Institute)	Physical Geography; Human Geography; Geographical Information Science	Coastal Geomorphology, Quaternary Sciences and Applied Geomorphology, Geochronology, Soil Science; Economic Geography, Urban and Regional Development, Social Geography, Economic Geography in Global South; GIS and Remote Sensing
	University of Leeds	Faculty of Environment (School of Geography)	Human Geography; Physical Geography; Geography with Transport Studies; Geography-Geology	–		Heidelberg University	Department of Chemistry and Geo-science (Institute of Geography)	Human Geography; Physical Geography; Geographical Information Science	Human Geography, Economic Geography; Geomorphology, Hydrology and Climatology; GIScience, 3D Spatial Data Processing
	University of Cambridge	Faculty of Earth Sciences and Geography (Department of Geography)	Human Geography; Physical Geography	People, Place and Political Difference; Environmental Process and Change		University of Göttingen	Faculty of Geoscience and Geography (Institute of Geography)	Geography; Geography Education	Human Geography; Physical Geography; Geographical Information System; Middle School Geography Teaching; Didactics of Geography; Non-School Geography Teaching
	Durham University	Department of Geography	Human Geography; Physical Geography	–		University of Freiburg	Faculty of Environment and Natural Resources (Institute of Geography)	Physical Geography	Geographical Development Research, Geographical Regional Studies, Geo-communication, Global Change, Climate Change and Historical Climatology, Landscape Interpretation, Ecological Plan and Environmental Assessment
	Bristol University	Faculty of Science (School of Geographical Sciences)	Geography; Geography with Quantitative Research Methods			University of Bonn	Department of Geo-science (Institute of Geography)	Human Geography; Physical Geography; Geographical Information Science	Development Geography, Regional Planning and Development, Economic and Social Geography, Historical Geography; Climatology and Landscape Ecology, Hydrology and Water Resources Management, Geomorphology; Remote Sensing and GIS
	University of Exeter	College of Life and Environmental Sciences (Geography)	Human Geography; Physical Geography; Environmental Science; Human Science			Humboldt University of Berlin	Faculty of Mathematics and Natural Sciences II (Geography Department)	–	Cultural and Social Geography, Economic Geography; Biogeography, Geography of Soils and Quaternary Morphology, Climatology, Landscape Ecology; GIScience; Didactics of Geography; Applied Geography / Town Planning
China	Beijing Normal University	School of Geography (Department of Geographical Sciences)	Geographical Sciences (Normal); Geographical Information Science; Human Geography and Urban and Rural Planning; Physical Geography and Resource Environment	–	USA	Boston University	College of Arts and Sciences (Department of Earth and Environment)	Human Geography; Physical Geography; Environmental Science; Remote Sensing and Geographical Information System (GIS); Environmental Analysis and Policy	Economic, Political, Cultural Geography; Vegetation Science, Hydrology, Climate Change; Biology, Oceanography and Geology; Remote Sensing and GIS; Environmental Science, Resource, Energy and Environmental Analysis
		College of Resources Science and Technology (Department of Resource)	Resource Science and Engineering	–		University of Maryland College Park UM	College of Behavioral and Social Sciences (Department of Geographical Sciences)	Geography; Geographical Information System; Environmental Science and Policy	Development and Sustainability, Environment Systems and Natural Resources; GIS, Cartography, Remote Sensing; Land Use, Coastal and Marine Environments, Environmental Change
		School of Environment (Institute of Environmental Sciences; Department of Environmental Planning and Management; Department of Environmental Ecological Engineering; Department of Environmental System Engineering)	Environmental Science; Environmental Engineering; Environmental Ecological Engineering	–		University of Colorado Boulder	College of Arts and Sciences (Department of Geography)	Physical Geography; Human Geography; Environment-Society Relations; Geographical Information Science	Climatology, Geomorphology, Biogeography, Arctic and Alpine Systems, Hydrology, Global Change; Population, Political, Urban, Social, Cultural Geography; Human Dimensions of Environmental Change, Natural Resources, Conservation Behavior; GIS, Cartography, Remote Sensing
	Peking University	College of Urban and Environmental Sciences (Department of Research and Environmental Geography; Department of Ecology; Department of Physical Geography; Department of Urban and Economical Geography; Department of Urban and Regional Planning)	Environmental Science, Ecological Science, Physical Geography and Resource Environment, Human Geography and Urban and Rural Planning; Urban and Rural Planning	–		University of California, Santa Barbara	College of Letters and Science (Department of Geography)	Human Geography; Physical Geography; Geographical Information Science	Cognitive and Behavioral Geography, Human-Environment Relations; Biogeosciences, Climatology; Ocean Processes; Remote Sensing, Geographical Information Science, Transportation
	East China Normal University	School of Geographic Sciences (5 Innovation Teams)	Geographical Sciences (Base, Normal); Geographical Information Science	–		University of California, Los Angeles	Social Sciences Division (Department of Geography)	Physical Geography; Human Geography; Geographical Information System and Technology; Environmental Science; Natural Systems	Climatology, Geomorphology, Resource Conservation, Biogeography; Economic Geography, Regional Economics, Urban Economics; Geographical Information System, Remote Sensing
		School of Urban and Regional Science (Department of Human Geography)	Human Geography and Urban and Rural Planning	–					

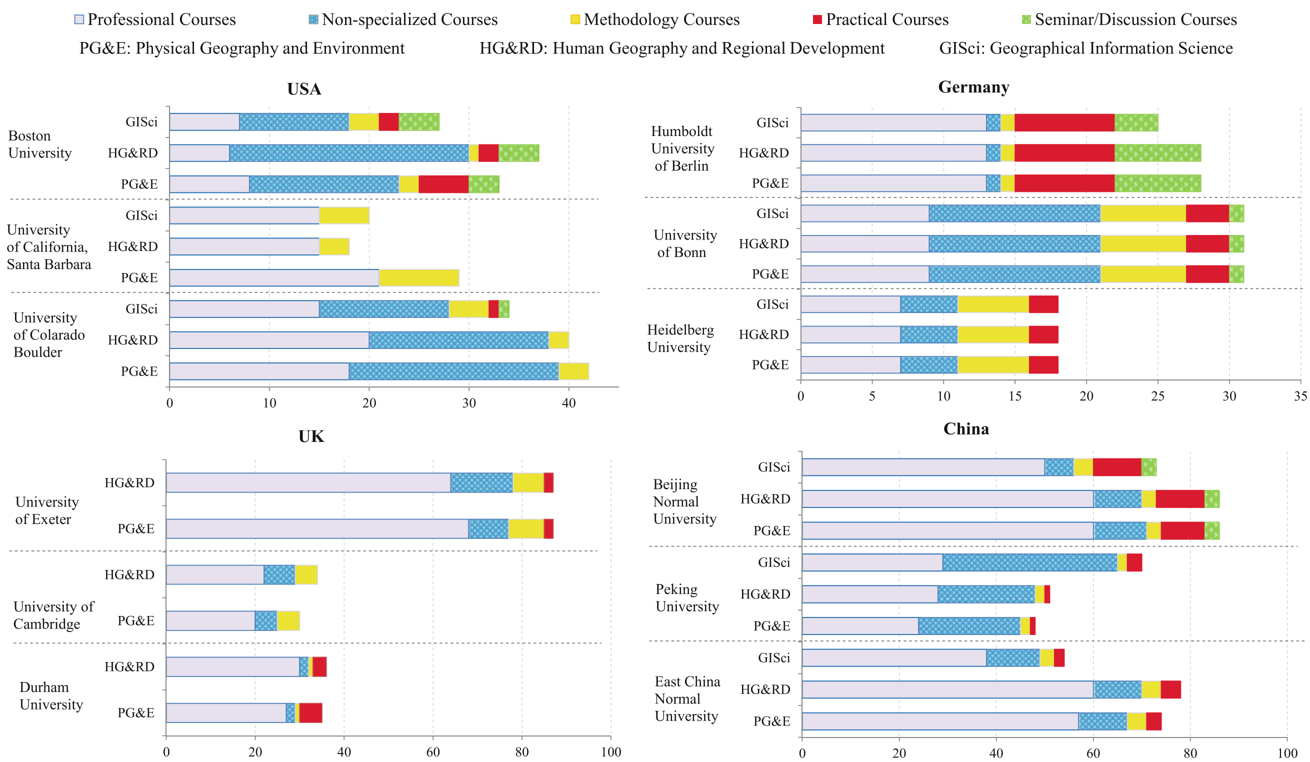


Fig. 1.8 Geographical sciences' courses in representative countries and universities. *Note* There is no geographical information science as a major in the UK universities, but it is a support tool for physical and human geography and the related courses are mostly about methodology

methodological courses in the University of Cambridge, including indoor courses for first-year students and field work for second-year students; there were Geographical Information Science and Remote Sensing courses under Physical and Human Geography in Durham University. From the perspective of types of courses, the proportion of major-related courses was especially low in the USA and Germany but relatively high in the UK and China. German universities paid more attention to research methods, so as to foster the students' ability to apply knowledge. Therefore, proportion of courses about methodology, practical courses and seminar and discussion was higher.

Similarly, in American universities, there were topics on marine and earth science, environmental sciences and experimental technology in Physical Geography and Environmental Sciences, and political science and culture and natural resource management in Human Geography. Courses sought to guide students so that they focused on academic frontiers and interdisciplinary trends, and master and apply geo-information technology. Chinese universities also offered special courses such as Instrumental Analysis in Physical Geography, Social Science in Human Geography, Computer Science and Cartography in Geographical Information Science, and Physics and Chemistry in Environmental Sciences. These courses could improve the practical ability of students and broaden their knowledge. However, they were mainly employment-driven and lacked connection with basic geography courses, so they failed to pay attention to the geographical tradition and its concern with solving nature-society problems. Therefore, the connections between courses needed to be strengthened.

1.5.3 Background of Professors

The background of professors has an impact on curriculum design, the expansion of the discipline and academic communication and cooperation. As a discipline across natural science, humanities and engineering, Geography needs professors from different backgrounds to facilitate disciplinary integration and development. Statistics of professors in the above-mentioned universities show that the ratio is 2.1:1 for professors with and without a geographical background, but the situation varies among countries (Fig. 1.9). In the six German universities the ratio of professors with a geographical background to those without was the highest (5.5:1), followed by American and British universities (2:1). In the three Chinese universities the ratio was 1.7:1 and the individual ratios were 3.4:1 (East China University), 3.1:1 (Peking University), and 1:1 (Beijing Normal University). Considering only the core subject of Geography, the ratio in the School of Geography in Beijing Normal University was

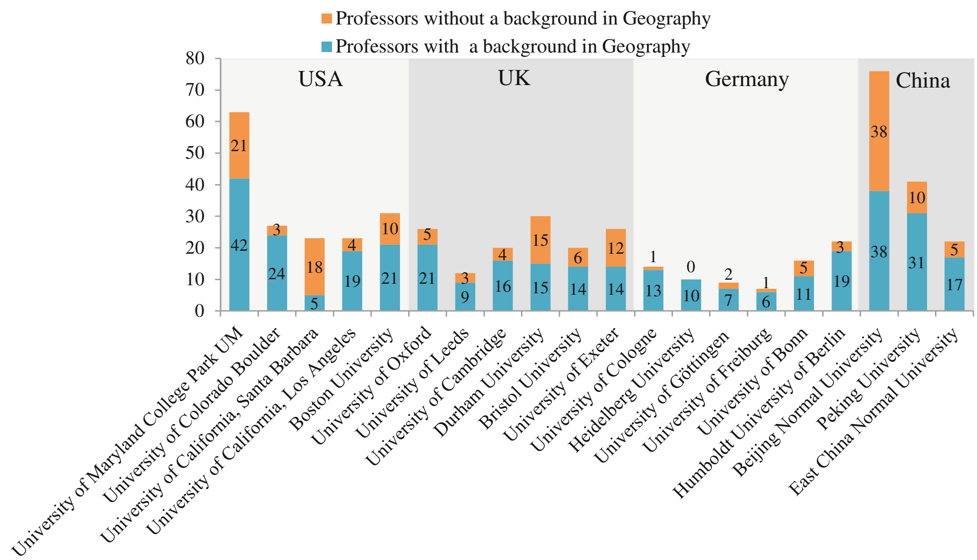


Fig. 1.9 Knowledge background of geographical sciences professors in representative countries and universities. *Note* The statistics also include associate professors in the USA, UK, and Germany

3.8:1, even higher than that of East China Normal University and Peking University. However, the proportion of professors with a geographical background in the College of Resources Science and Technology and School of Environment was only about 37 %, and the ratio was 0.6:1, mainly because of movement away from the traditional core subjects of geography. In summary, there are three major types of background of professors in the four countries. One of the basic professorship requirement in Germany is holding a doctorate degree in Physical and Human Geography, therefore almost all professors in Germany have a geographical background. Lots of professors without a geographical background in the five American universities are from the fields of Biology, Chemistry, Environmental Engineering and Sciences, Environmental Economics and Energy and Resources research, because geographical faculties generally give more attention to the Environmental Science. In the UK, popular backgrounds beyond Geography include Geology, Climatology, Anthropology and Marine Science. It shows that although the ratio was similar, the USA universities have employed more people without a background in the Earth Sciences in geographical teaching and research, while the UK universities are inclined to employ more people in the field of the Earth Sciences. In the four traditional geographical faculties in China, 76 % of full professors have a geographical background, and others hold degrees in Physics, Hydraulics, Atmospheric Science, Biology, Environmental Sciences and Engineering, Agriculture, Architecture and Geochemistry, indicating the importance of interaction between Geography and other disciplines.

1.5.4 Basic Understanding

This examination of the organisational structure, curriculum, subject and major setting and faculty background shows the following findings. (1) Although there was difference in curriculum and subject/major setting, reflecting the characteristics of Geography and the need for interdisciplinary, reflected in relationships between Geography and other branches of the Earth Sciences, Environmental Sciences, Biology, Chemistry and the Liberal Arts. (2) In curriculum setting all countries put emphasis on the integration of Physical and Human Geography in problem solving. However, compared to the other three countries, the subject/major setting in China lacked specialization. (3) The four countries focused on different aspects of discipline: theoretical and practical, and science versus the humanities. Germany and the USA adopted a balanced approach to teaching students improving their knowledge and their ability to apply it, while the UK and China paid more attention to imparting knowledge. Germany and the USA set up a lot of special courses, while curricula in China were more employment-driven and lacked connection with basic knowledge. (4) Professors had different academic backgrounds. Professors in Germany almost all hold a degree in geography; the situation in China was similar and those without a geographical background were trained in Information Science, Environmental Sciences and Planning; more professors in the USA and the UK tended to hold non-geographical degrees, including Environmental Sciences in the USA and Earth Sciences in the UK. Overall, the faculty structure and major setting are affected by university organization, the positioning of the discipline in the field of knowledge, the development of the discipline and resource allocation. These drivers in part reflected educational philosophies and teaching methods.

1.6 Summary

The Geographical Sciences play an increasingly important role in solving global and regional hot issues such as global change, globalisation and sustainability. On the one hand, this is due to the comprehensive nature of geographical thought; on the other, it reflects important developments in field observation and information technology. Research into geographical processes is deepened as well as integrated, with field observation and experimentation contributing greatly to research on physical geographical processes and mechanisms. The Geographical Sciences as a discipline are now improving their ability to simulate and predict the future evolution of the earth surface and environment, assisting with the development of ways of mitigating and adapting to environmental change. Adaptation, vulnerability, uncertainty and resilience have become new frontiers in global change studies. Globalization studies are not only about the world economy, but also about political economy, urban issues and sustainability. Sustainability in a context of global change has become the core concern for the Geographical Sciences and a vital means of contributing to the creation of sustainable societies. To meet the need for the disciplinary development and to serve people, geographical faculties in world-famous institutions are seeking the most appropriate ways of training students. They all pay attention to the nurturing science and humanity-based approaches to geography, practical ability and analytical technologies. They also make every effort to attract faculty from different academic backgrounds to improve students' ability to tackle complex interdisciplinary problems.

International Cooperation in the Geographical Sciences

2

Shuying Leng, Zhonglu Guo, and Siyuan He

Abstract

This chapter analyses the international cooperation network of the articles in the 307 mainstream SCI/SSCI-listed geographical journals, the independent research and international cooperation situation of the top 20 countries as reflected in published research articles, and the research fields where China and its major cooperating countries (regions) are active. International cooperation is a general trend in geographical sciences' research. The pattern of international cooperation is characterized by that the USA, the UK, France, Germany, Canada and Australia lead the cooperation network and that the countries such as China and Brazil are taking the central position in the network as a fast pace. In the past 30 years China has cooperated with 141 countries (regions). In the last five years this number is 6.7 times that for 1986–1990. China cooperates most with the USA, taking 46 % of all cooperatively written articles with foreign researchers. Environmental pollution and global change are two major topics attracting cooperation between China and the USA, the UK, and Germany. Geographical information science, human geography and paleoenvrionment are research fields especially important for cooperation with the USA, the UK and Germany, respectively.

Keywords

International cooperation network • Independent research • Closeness centrality • Sino-USA cooperation

This chapter analyses the international cooperation network of the articles in the 307 mainstream SCI/SSCI-listed geographical journals, the independent research and international cooperation situation of the top 20 countries as reflected in published research articles, and the research fields where China and its major cooperating countries (regions) are active. Statistics are based on the number of articles where the country name can be identified from the mailing address of the first author or the corresponding author. Cooperation between China and its partners is identified by identifying co-published papers.

2.1 Global Cooperation Network

Since 1986, China has built cooperation networks with 141 countries (regions), increasing from 4 in 1986 to 32 in 2000 and 97 in 2014.

From the figure it can be seen that international cooperation networks have evolved from a single centre in 2000 (Fig. 2.1) to a multi-centre and complex network in 2014 (Fig. 2.2). The USA was the centre in 2000, and the whole network was mainly built by the USA, France, Germany, the UK and Canada. China was at the edge of the network and

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its cooperating partners were limited to the USA, and the number of cooperation was even lower than India, Japan, Spain, Australia, Sweden and Switzerland. After 15 years of development, several centres have emerged, including China, the UK, the USA, Canada, Germany, Italy, the Netherlands, Spain and Belgium. China has already built extensive cooperation with the UK, Australia, Germany and Canada besides the USA. There is also an increase in the cooperation network of Asian countries (regions), such as India, Chinese Taiwan, South Korea, Thailand, Pakistan, Malaysia, Vietnam and Singapore.

Closeness centrality represents the extensiveness of cooperating countries (regions) for the countries (regions) occupying critical nodes. The higher the value of this index, the greater the number of countries (regions) cooperating with this country (region) concerned and the more contribution it makes to the forming of this network and the stability of its structure. Comparing these two figures it can be

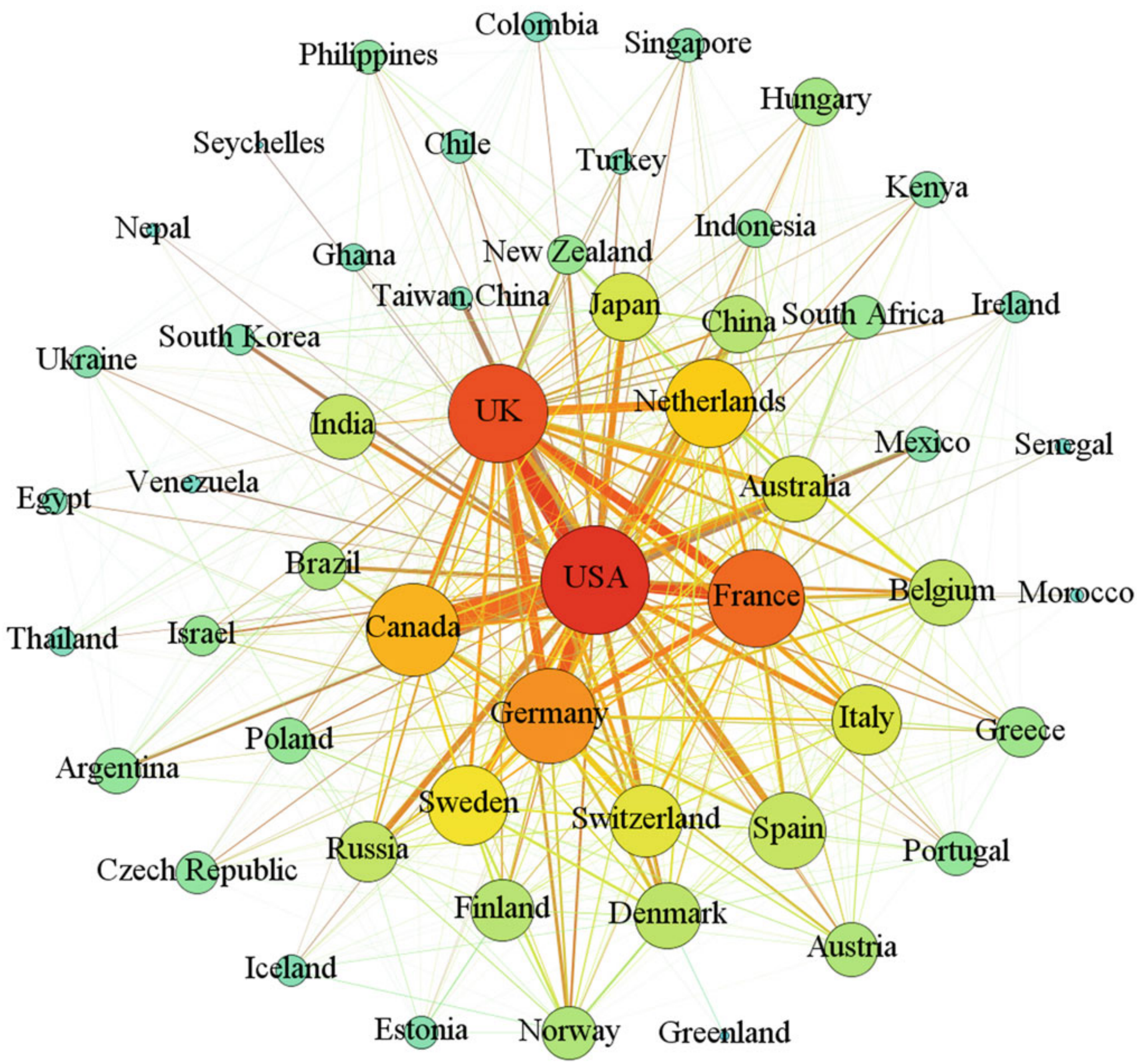

Fig. 2.1 The international cooperation graph in mainstream SCI/SSCI-indexed geographical sciences' journals in 2000. *Note* A threshold frequency for cooperation is 5; each node represents a country or region and the color of nodes represents the number of cooperating regions for a single node; each line connects two cooperating countries (regions) and the thickness of the line represents the cooperation frequency

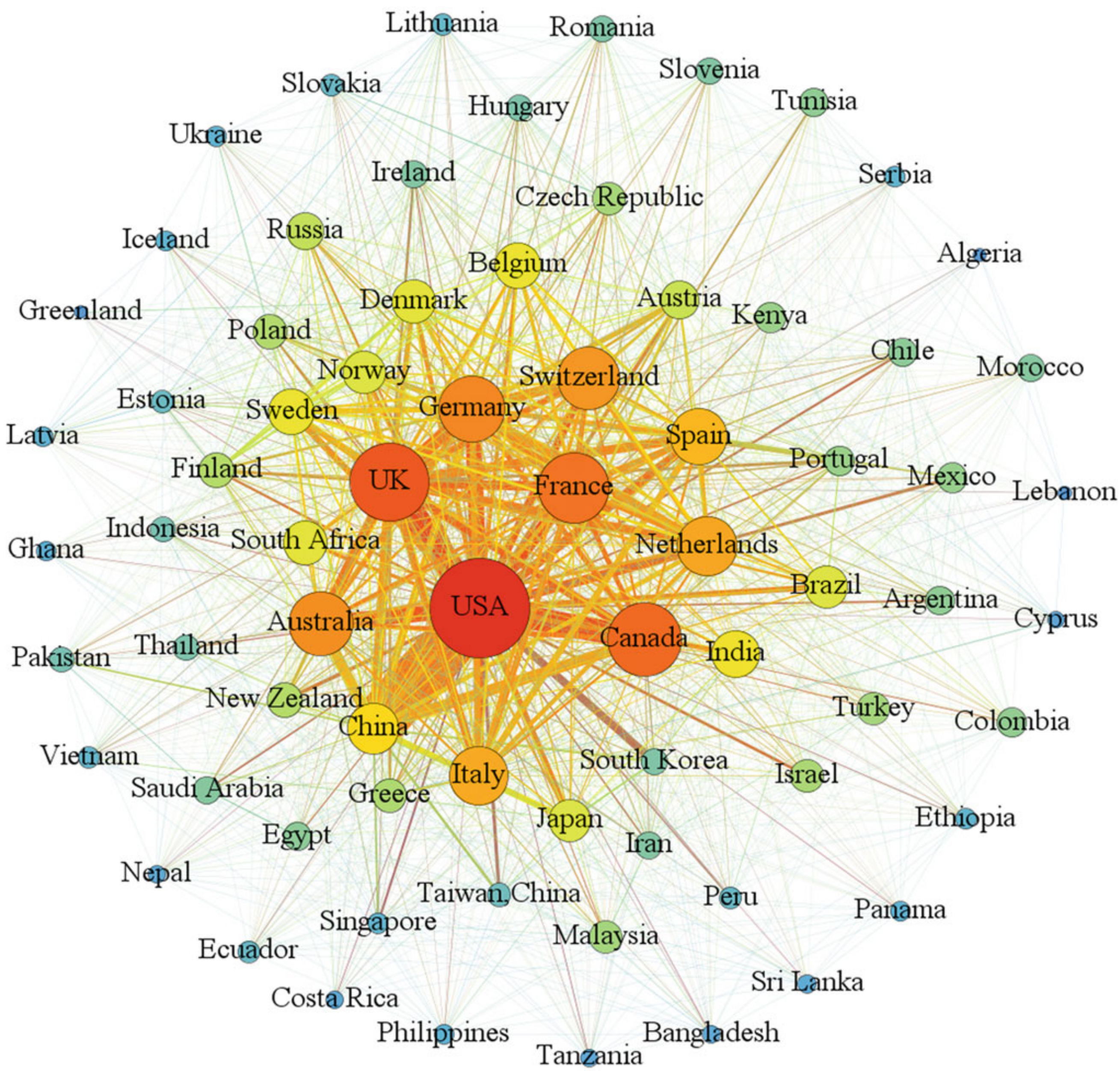

Fig. 2.2 The international cooperation graph in mainstream SCI/SSCI-indexed geographical sciences' journals in 2014. *Note* A threshold frequency for cooperation is 15; each node represents a country or region and the color of nodes represents the number of cooperating regions for a single node; each line connects two cooperating countries (regions) and the thickness of the line represents the cooperation frequency

seen that the USA, the UK, France, Germany and Canada have always dominated the core, leading the development of international cooperation in the Geographical Sciences. Australia, Spain, China, Belgium, Brazil and South Africa rose fast. For China, enhanced centrality mainly came from strengthening cooperation with core countries (regions). By contrast, Japan and Russia were losing centrality (Table 2.1).

2.2 International Cooperation and Independent Research

Independent research/international cooperation is represented by the number of articles written by author(s) from more than one country (region). The country/region was determined by the address of the first author or corresponding author. International cooperation played a growing role in getting

Table 2.1 Top 20 countries (regions) regarding closeness centrality of international cooperation networks in the geographical sciences in 2000 and 2014

Year	Rank	Countries (Regions)	Closeness centrality	Year	Rank	Countries (Regions)	Closeness centrality
2000	1	USA	0.5608	2014	1	USA	0.8174
2000	2	UK	0.4867	2014	2	UK	0.7424
2000	3	France	0.4627	2014	3	Canada	0.7225
2000	4	Germany	0.4410	2014	4	France	0.7129
2000	5	Canada	0.4277	2014	5	Germany	0.6946
2000	6	Netherlands	0.4192	2014	6	Australia	0.6887
2000	7	Sweden	0.4091	2014	7	Switzerland	0.6829
2000	8	Switzerland	0.3994	2014	8	Netherlands	0.6715
2000	9	Australia	0.3957	2014	9	Italy	0.6688
2000	10	Italy	0.3957	2014	10	Spain	0.6606
2000	11	Japan	0.3938	2014	11	China	0.6397
2000	12	Spain	0.3867	2014	12	India	0.6273
2000	13	India	0.3849	2014	13	Sweden	0.6201
2000	14	Belgium	0.3849	2014	14	Belgium	0.6201
2000	15	Russia	0.3849	2014	15	Denmark	0.6130
2000	16	Denmark	0.3832	2014	16	South Africa	0.6130
2000	17	China	0.3797	2014	17	Brazil	0.6084
2000	18	Finland	0.3797	2014	18	Norway	0.6084
2000	19	Norway	0.3763	2014	19	Japan	0.6061
2000	20	Austria	0.3763	2014	20	Austria	0.5928

research results, as indicated by the top 20 countries (regions) regarding the number of articles in mainstream SCI/SSCI-indexed Geographical Sciences' journals in the period 2000–2004 and 2010–2014 (Table 2.2). Articles from cooperation with the UK, Germany, Spain, France, the Netherlands, Switzerland and Belgium all have increased more than 10 % between these two periods; articles from top 10 countries have increased by 8.9 % on average, and all of these countries except India had high centrality. China ranked second in term of number of articles in 2010–2014, with articles involving international cooperation increasing by 4.9 %. However, the share of independent research was still higher for all of these countries, accounting for 68.2 % for the Top 20 countries in 2010–2014. Countries with a generally balanced share in these two modes were Switzerland and Belgium. Countries with a relatively low share of independent research (the difference was less than 20 %) were the Netherlands, France and Germany.

Since 1986, Chinese authors have published 57,912 papers in the Geographical Sciences SCI/SSCI-indexed journals, with those involving cooperation amounting to 21,568 (37.2 %), of which 96.6 % were published after 2000. Compared to 2000, in these cooperatively published papers, the proportion of papers with Chinese scholars as the first or corresponding authors increased to 76.6 % and 73.9 % in 2015 and 2014, increasing by 18.7 % and 16 %, respectively. The most popular partner of China was from the USA (9932, 46 %), followed by Canada (10.2 %), the UK (9.1 %), Australia (9.0 %), Japan (8.5 %) and Germany (7.5 %). Other countries (regions) within the top 10 partners of China were the Netherlands (3.9 %), France (3.7 %), Taiwan, China (2.3 %) and South Korea (2.3 %).

Table 2.3 shows the Top 20 countries (regions) in terms of the number of highly cited articles in mainstream SCI/SSCI-indexed geographical sciences' journals during the period 2000–2004 and 2010–2014. The USA, Germany, Chinese Taiwan and Brazil rank first, fourth, nineteenth and twentieth. The ranks of other countries have changed. The ranking of China, Spain, Switzerland, Italy, India and South Korea has risen with China advancing six places and India and South Korea advancing five. The other countries went backwards with the Netherlands dropping four places and Sweden and Denmark three. Those highly cited articles were mainly from independent research, and the average proportion in 2010–2014 for the Top 20 countries was 57.4 %. In addition, the proportion of the highly cited articles involving

Table 2.2 Top 20 countries (regions) with the number of articles in mainstream SCI/SSCI-indexed geographical sciences' journals during the period 2000–2004 and 2010–2014

Countries (Regions)	Rank	2000 – 2004				2010 – 2014			
		Independent research		International cooperation		Independent research		International cooperation	
		Articles	Proportion	Articles	Proportion	Articles	Proportion	Articles	Proportion
USA	1	26,781	86.8%	4,068	13.2%	36,293	79.2%	9,511	20.8%
China	2	2,611	76.7%	792	23.3%	21,232	71.8%	8,342	28.2%
UK	3	10,677	83.1%	2,164	16.9%	10,986	69.2%	4,898	30.8%
Canada	4	4,777	79.2%	1,258	20.8%	7,415	72.7%	2,788	27.3%
Germany	5	3,302	72.1%	1,275	27.9%	5,601	59.0%	3,894	41.0%
Spain	6	2,076	78.7%	563	21.3%	5,724	65.8%	2,975	34.2%
Australia	7	2,526	78.4%	697	21.6%	6,013	70.6%	2,498	29.4%
France	8	2,054	68.8%	933	31.2%	4,197	58.7%	2,951	41.3%
Italy	9	1,993	78.3%	553	21.7%	4,885	68.4%	2,261	31.6%
India	10	1,369	87.4%	198	12.6%	5,173	84.4%	953	15.6%
Netherlands	11	1,976	73.8%	700	26.2%	2,968	58.7%	2,084	41.3%
Japan	12	2,071	78.7%	560	21.3%	3,117	69.1%	1,393	30.9%
Brazil	13	685	74.5%	234	25.5%	2,480	72.6%	934	27.4%
Sweden	14	1,512	72.1%	584	27.9%	2,164	63.5%	1,245	36.5%
Switzerland	15	886	64.5%	487	35.5%	1,651	49.5%	1,687	50.5%
South Korea	16	647	75.1%	215	24.9%	2,304	69.8%	996	30.2%
Taiwan, China	17	977	87.4%	141	12.6%	2,109	79.9%	531	20.1%
Turkey	18	827	88.2%	111	11.8%	2,190	86.2%	350	13.8%
Belgium	19	724	67.7%	346	32.3%	1,263	51.4%	1,194	48.6%
Portugal	20	274	68.0%	129	32.0%	1,471	62.2%	893	37.8%

Note Rank according to the number of articles in 2010–2014

international cooperation was higher than that for all of the articles considered in Table 2.2, indicating to some extents that international cooperation was particularly important in producing highly cited articles.

2.3 Major Research Fields Involving International Cooperation of China

Since 2000, the USA, the UK, France and Germany have long occupied the central position of international cooperation networks (Figs. 2.1 and 2.2), and they have carried out research with many countries (regions) including China. Considering trends in the development of international cooperation and the characteristics of China's international cooperation networks, this book uses 307 SCI/SSCI mainstream geographical journals as a research object to analyse articles produced by cooperation between China and the USA, the UK and Germany during 1986–2015. The research fields are environmental pollution, global change, biogeography and ecology, hydrology and water resources, human geography, the humanities and the social sciences, geographical information science, paleoenviromental research. CiteSpace was used to analyse the research topics chosen by researchers from China and the other three countries by the clustering of keywords.

Figure 2.3 shows the major fields of cooperation between China and the USA. The total number of articles was 9932, in which there were 6535 (65.8 %) ones with Chinese scholars as the first or corresponding authors. In 2014 this proportion was 77.1 %, which was 21.7 % more than that in 2000. These articles were published in 269 journals with 25,908 keywords used. The ten most frequently chosen journals included 3033 articles accounting for 30.5 % to all the cooperatively published articles. The most frequently chosen journal was *Environmental Science and Technology* (732). Of the top ten chosen journals six focused on environmental pollution, two on geographical information science, one on global change, and one on hydrology and water resources. There were 776 Chinese institutions involved in cooperation with American peers, and the top ten active institutions included Beijing Normal University, Peking University, Institute of Geographic Sciences and Natural Resources Research of CAS, Nanjing University, Tsinghua University, University of

Table 2.3 Top 20 countries (regions) with the number of highly cited articles in mainstream SCI/SSCI-indexed geographical sciences' journals during the period 2000–2004 and 2010–2014

Countries (Regions)	Rank	2000–2004				2010–2014			
		Independent research		International cooperation		Independent research		International cooperation	
		Articles	Proportion	Articles	Proportion	Articles	Proportion	Articles	Proportion
USA	1	3,060	80.5%	739	19.5%	2,165	70.7%	896	29.3%
China	2	170	70.8%	70	29.2%	986	68.2%	459	31.8%
UK	3	734	70.6%	305	29.4%	481	53.4%	420	46.6%
Germany	4	302	63.0%	177	37.0%	294	48.8%	308	51.2%
Canada	5	357	68.9%	161	31.1%	311	61.5%	195	38.5%
Australia	6	212	72.4%	81	27.6%	267	57.5%	197	42.5%
Spain	7	169	71.0%	69	29.0%	261	56.6%	200	43.4%
France	8	169	63.8%	96	36.2%	181	45.0%	221	55.0%
Switzerland	9	134	60.9%	86	39.1%	146	48.2%	157	51.8%
Netherlands	10	179	66.1%	92	33.9%	154	51.0%	148	49.0%
Italy	11	131	73.2%	48	26.8%	168	56.2%	131	43.8%
India	12	74	90.2%	8	9.8%	127	72.6%	48	27.4%
South Korea	13	51	69.9%	22	30.1%	114	66.3%	58	33.7%
Sweden	14	139	63.5%	80	36.5%	78	47.6%	86	52.4%
Japan	15	108	68.4%	50	31.6%	90	58.1%	65	41.9%
Belgium	16	77	67.0%	38	33.0%	60	42.6%	81	57.4%
Denmark	17	89	68.5%	41	31.5%	75	56.0%	59	44.0%
Norway	18	48	53.3%	42	46.7%	60	49.2%	62	50.8%
Taiwan, China	19	63	87.5%	9	12.5%	79	76.0%	25	24.0%
Brazil	20	32	58.2%	23	41.8%	63	62.4%	38	37.6%

Note Rank according to the number of articles in 2010–2014

Chinese Academy of Sciences, Zhejiang University, The University of Hong Kong, the Research Centre for Eco-Environmental Sciences of CAS, and Wuhan University, with 4291 articles published (43.2 % of the total Sino-USA co-authored articles). Major research fields were environmental pollution (35.9 %), geographical information science (15.5 %), global change (15.1 %), biogeography and ecology (9.7 %), human geography, the humanities and the social sciences (8.7 %), paleoenvironment (7.6 %) and hydrology and water resources (7.5 %). Research areas selected more than 15 times included China, the Tibetan Plateau (Qinghai Tibetan Plateau), the United States, South China, the Loess Plateau (Chinese Loess Plateau), Beijing, Hong Kong, Shanghai, the Yangtze River, the Pearl River Delta, Inner Mongolia, South China Sea, North China, East Asia, Northeast China, North America, the North Atlantic, the North Pacific, the East China Sea, the Yellow River, the Gulf of Mexico, Yunnan, the Yangtze River Delta, the Pacific, the Himalayas, California, the Indian Ocean, and Guangzhou.

Environmental Pollution Papers arising from Sino-USA cooperative research on environmental pollution were published mainly in the following five journals: *Environmental Science & Technology*, *Atmospheric Environment*, *Chemosphere*, *Journal of Hazardous Materials*, *Science of the Total Environment*.

Geographical Information Science Papers arising from Sino-USA cooperative research on geographical information sciences were mainly published in the following five journals: *International Journal of Remote Sensing*, *IEEE Transactions on Geoscience and Remote Sensing*, *Remote Sensing of Environment, Remote Sensing*, *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*.

Global Change Papers arising from Sino-USA cooperative research on global change were published mainly in the following five journals: *Journal of Climate*, *Climate Dynamics*, *Global Change Biology*, *Biogeosciences*, *Global and Planetary Change*.

Biogeography and Ecology Papers arising from Sino-USA cooperative research on biogeography and ecology were published mainly in the following five journals: *Ecological Modelling*, *Ecological Engineering*, *Chinese Journal of Oceanology and Limnology*, *Biological Conservation*, *Landscape Ecology*.

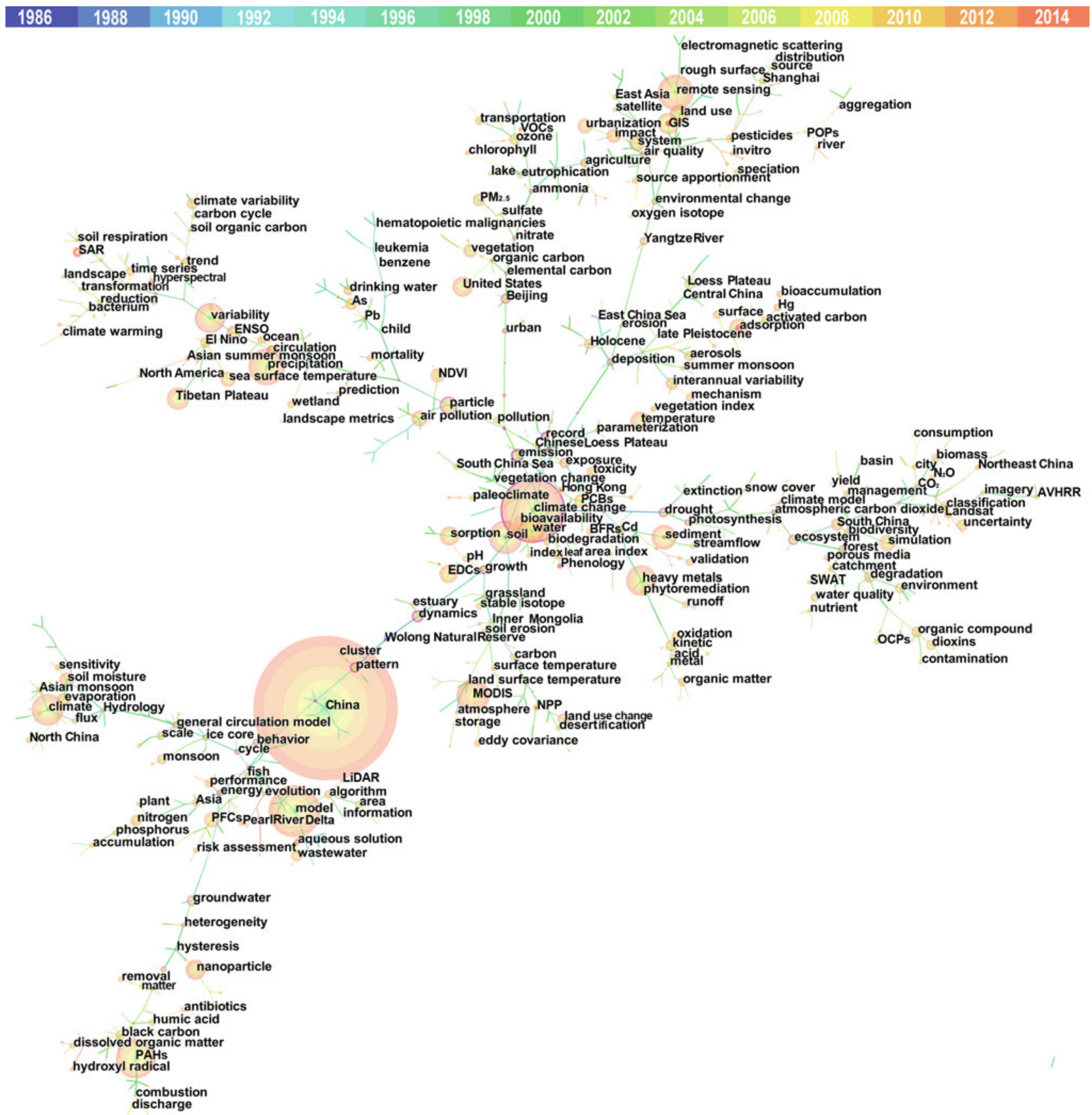

Fig. 2.3 Co-occurrence network of keywords in Sino-USA cooperation articles in mainstream SCI/SSCI-indexed geographical sciences' journals

Human Geography, the Humanities and the Social Sciences Papers arising from Sino-USA cooperative research in human geography, the humanities and the social sciences were published mainly in the following five journals: *Journal of Environmental Management*, *International Journal of Environmental Research and Public Health*, *Environmental Management*, *Landscape and Urban Planning*, *World Development*.

Paleoenvironment The top five journals for publication of Sino-USA cooperatative paleoenvironmental research were *Palaeogeography Palaeoclimatology Palaeoecology*, *Quaternary International*, *Quaternary Science Reviews*, *Quaternary Research*, *Continental Shelf Research*.

Hydrology and Water Resources Sino-USA cooperative research on hydrology and water resource was published mainly in the following five journals: *Journal of Hydrology*, *Water Resources Research*, *Hydrological Processes*, *Journal of Hydrologic Engineering*, and *Journal of Hydrometeorology*.

Figure 2.4 shows the major fields of cooperation between China and the UK. The total number of co-authored articles was 1958, in which there were 1170 (59.8 %) ones with Chinese scholars as the first or corresponding authors. In 2014 this proportion was 59.6 %, which was 1.7 % more than in 2000. These articles were published in 234 journals with 7145 keywords used. The ten most frequently chosen journals accounted for 548 articles (28 % to all the cooperatively published articles). The most frequently chosen journal was *Environmental Science and Technology* (105). Of the top ten journals six focused on environmental pollution, two on the paleoenvironment, one on global change, and one on geographical information science.

There were 355 Chinese institutions involved in cooperation with the UK peers, and the top ten active institutions included Peking University, The University of Hong Kong, University of Chinese Academy of Sciences, Beijing Normal University, Hong Kong Polytechnic University, East China Normal University, Lanzhou University, Institute of Botany of CAS, Nanjing Institute of Geography and Limnology of CAS, Institute of Geographic Sciences and Natural Resources Research of CAS, with 797 articles published (40.7 % of all Sino-UK co-authored articles).

Major research fields were environmental pollution (31.1 %), the paleoenvironment (16.2 %), global change (15.3 %), human geography, the humanities and the social sciences (13.2 %), geographical information science (9.4 %), biogeography and ecology (9 %), and hydrology and water resources (5.9 %). Compared to cooperation with

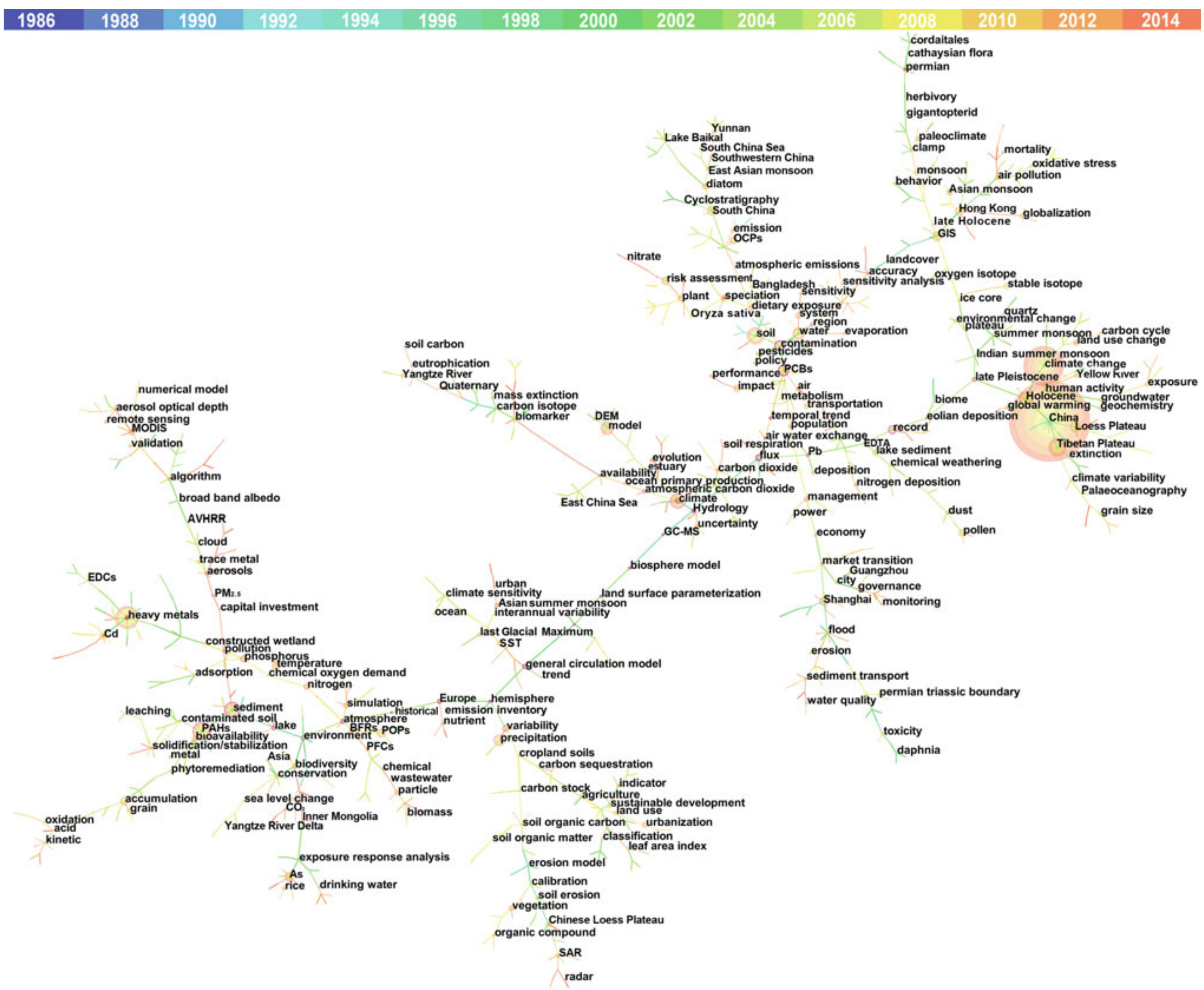

Fig. 2.4 Co-occurrence network of keywords in Sino-UK cooperation articles in mainstream SCI/SSCI-indexed geographical sciences' journals

the USA, cooperation with the UK involved a higher proportion of research in human geography (+4 %) but a lower proportion in environmental pollution (−5 %), indicating an advantage of cooperation in human geography with the UK. Research areas selected more than 15 times were China, Tibetan Plateau (Qinghai Tibetan Plateau), Loess Plateau (Chinese Loess Plateau), South China, Hong Kong and Shanghai.

Environmental Pollution Papers arising from Sino-UK cooperative research on environmental pollution were mainly published in the following five journals: *Environmental Science and Technology, Environmental Pollution*, *Chemosphere*, *Journal of Hazardous Materials*, *Science of the Total Environment*.

Paleoenvironment The top five journals for publication of paleoenvironment research involving Sino-UK cooperation were: *Palaeogeography Palaeoclimatology Palaeoecology*, *Quaternary Science Reviews*, *Review of Palaeobotany and Palynology*, *Quaternary International*, *Holocene*.

Global Change Papers arising from Sino-UK cooperative research on global change were published mainly in the following five journals: *Global and Planetary Change*, *Global Change Biology*, *Biogeosciences*, *Climate Dynamics*, *Natural Hazards*.

Human Geography, the Humanities and the Social Sciences Papers arising from Sino-UK cooperative research in human geography, the humanities and the social sciences were published mainly in the following five journals: *Journal of Environmental Management*, *Annals of Tourism Research*, *Habitat International*, *Urban Studies*, *World Development*.

Geographical Information Science Papers arising from Sino-UK cooperative research in the geographical information science were published mainly in the following five journals: *International Journal of Remote Sensing*, *IEEE Transactions on Geoscience and Remote Sensing*, *IEEE Geoscience and Remote Sensing Letters*, *ISPRS Journal of Photogrammetry and Remote Sensing*, *Journal of Environmental Monitoring*.

Biogeography and Ecology Papers arising from Sino-UK cooperative research in biogeography and ecology were published mainly in the following five journals: *Journal of Biogeography*, *Agriculture Ecosystems and Environment*, *Biological Conservation*, *Ecological Modelling*, *Catena*.

Hydrology and Water Resources Sino-UK cooperative research in hydrology and water resource was published mainly in the following five journals: *Journal of Hydrology*, *Hydrology and Earth System Sciences*, *Hydrological Processes*, *Water Resources Research*, *Water Resources Management*.

Figure 2.5 shows the major fields of cooperation between China and Germany. The total number of co-authored articles was 1623, in which there were 859 (52.9 %) ones with Chinese scholars as the first or corresponding authors. In 2014 this proportion was 50.4 %, which was 22.4 % less than that in 2000. These articles were published in 189 journals with 6064 keywords used. The ten most frequently chosen journals accounted for 562 articles published (34.6 % of all cooperatively written articles). The most frequently chosen journal was *Chemosphere* (99). Of the top ten chosen journals six focused on environmental pollution, three on paleoenvironment, and one on global change.

There were 295 Chinese institutions involved in cooperation with German peers, and the top ten active institutions were Nanjing Institute of Geography and Limnology of CAS, Peking University, Institute of Tibetan Plateau Research of CAS, Nanjing University, Lanzhou University, Institute of Botany of CAS, China Agricultural University, Cold and Arid Regions Environmental and Engineering Research Institute of CAS, University of Chinese Academy of Sciences, Institute of Geographic Sciences and Natural Resources Research of CAS, with 776 articles published (47.8 % of the total Sino-German co-authored articles).

Major research fields were environmental pollution (30.6 %), global change (19.5 %), paleoenvironment (19.4 %), biogeography and ecology (11.3 %), geographical information science (10.5 %), human geography, the humanities and the social sciences (4.3 %), and hydrology and water resources (4.3 %). Environmental pollution accounted for a proportion that was similar to that for the UK. In both cases the share was lower than for the USA. But in paleoenvironmental research there was a great advantage in cooperation with Germany. Research areas selected more than 15 times were China, Tibetan Plateau (Qinghai Tibetan Plateau), Inner Mongolia, Yangtze River and South China Sea.

Environmental Pollution The top five journals for publication of environmental research involving Sino-German cooperation were: *Chemosphere*, *Atmospheric Environment*, *Environmental Science and Technology*, *Science of the Total Environment*, *Environmental Science and Pollution Research*.

Global Change The top five journals for publication of global change research involving Sino-German cooperation were: *Biogeosciences*, *Global and Planetary Change*, *International Journal of Earth Sciences*, *Global Change Biology*, *Climate Dynamics*.

Paleoenviroment "Pollen", "tree ring", "Dendroecology", "Dendrochronology", "Dendroclimatology" and "diatom" are the keywords for biological proxies in the research on paleoenvironment, which is also a prominent research field for Sino-Germany cooperation. The re-occurrence of "pollen" as a cooperative keyword was 27, which was the top number of Sino-USA, Sino-UK and Sino-German cooperation. For Sino-USA cooperation, "glacier", "ice

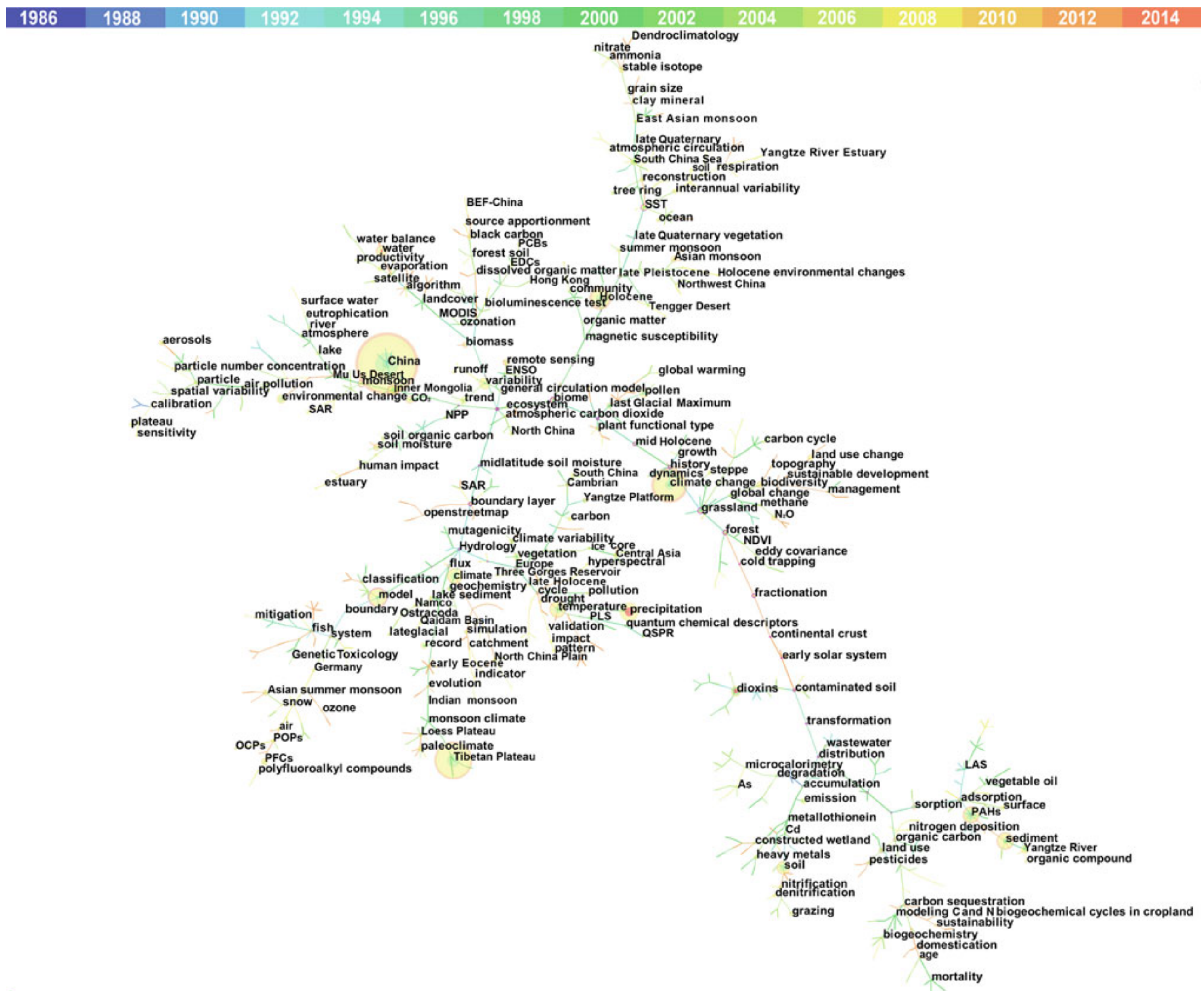

Fig. 2.5 Co-occurrence network of keywords in Sino-German cooperation articles in mainstream SCI/SSCI-indexed geographical sciences' journals

core" and "snow cover" lead all the cooperative research with other countries, and the re-occurrence of these keywords is 67. Sino-UK cooperation on the research using "diatom" also lead all the cooperative research with the re-occurrence of keywords of 16. The top five journals for publication of paleoenvironment by Sino-German cooperation included *Palaeogeography Palaeoclimatology Palaeoecology*, *Quaternary International*, *Quaternary Science Reviews*, *Continental Shelf Research*, *Review of Palaeobotany and Palynology*.

Biogeography and Ecology The top five journals for publication of biogeography and ecology involving Sino-German cooperation were: *Agriculture Ecosystems and Environment*, *Catena*, *Journal of Biogeography*, *Ecological Modelling*, *Ecological Research*.

Geographical Information Sciences The top five journals for publication of geographical information science involving Sino-German cooperation were: *International Journal of Remote Sensing*, *IEEE Transactions on Geoscience and Remote Sensing*, *Journal of Geodesy*, *Remote Sensing*, *IEEE Geoscience and Remote Sensing Letters*.

Human Geography, the Humanities and the Social Sciences The top three journals for publication of human geography, the humanities and the social sciences involving Sino-German cooperation were: *Journal of Environmental Management*, *Land Use Policy*, *International Journal of Environmental Research and Public Health*. The other six journals have all ranked the fourth, including *Environmental Health*, *Environmental Management*, *Environmental Science and Policy*, *Land Degradation and Development*, *Population and Development Review*, *Waste Management and Research*.

Hydrology and Water Resources The top five journals for publication of hydrology and water resource research involving Sino-German cooperation were: *Hydrology and Earth System Sciences*, *Journal of Hydrology*, *Hydrological Processes*, *Water Resources Research*, *Ecohydrology*.

2.4 Summary

International cooperation is a general trend in Geographical Sciences research. The pattern of international cooperation is characterized by that the USA, the UK, France, Germany, Canada and Australia led the cooperation network and that the countries such as China and Brazil were taking the central position in the network at a fast pace. Statistical analysis indicates that although independent research accounted for at least 60 % of all the articles examined, international cooperation made a significant contribution to the publication of the highly cited papers. In the past 30 years China has cooperated with 141 countries (regions). In the last five years this number was 6.7 times that in 1986–1990. Co-authored articles have accounted for 37.2 % of Chinese authored articles, and 65.9 % of these articles had Chinese first or corresponding authors. China cooperated most with the USA, and their cooperation covered 46 % of all cooperatively written articles. At the same time, China also carried out extensive cooperation with Canada, Japan, the UK, Australia and Germany. With regard to research fields, environmental pollution and global change were two major topics attracting cooperation between China and the USA, the UK, and Germany. Geographical information science, human geography and paleoenvrionment were research fields especially important for China's cooperation with the USA, the UK and Germany, respectively.

3 The Background of the Development of the Geographical Sciences in China

Shuying Leng, Guoyou Zhang, Fengkui Qian, Siyuan He, Linwang Yuan, Zhaoyuan Yu, and Wen Luo

Abstract

This chapter sets out the background to the development of geographical sciences from three aspects, namely the funding of investment on the geographical sciences by NSFC, the distribution of faculties in major Chinese universities and their research status, and the development of the Geographical Society of China and its contributions to the construction of an academic platform. Between 1986 and 2015, the number and total value of NSFC geographical sciences funded projects are more than doubled in each 5-year period, and the average funding per project for major types of projects is more than 10 times the earlier figure. Excluding Hong Kong, Macau and Chinese Taiwan, 6893 people from 685 institutions in China's provinces, autonomous regions and municipalities directly under the Central Government have been supported in the past 30 years. Researchers from Beijing, Jiangsu, Gansu, Hubei and Guangdong account for 58.7 % of the total funded people and 68.8 % of the total funding. The funding of these 33 universities, which involved in the Ministry of Education's 2012 curriculum assessment for Geography, shows that research which are reality-oriented and which explores scientific questions drives the development of geographical sciences; however, funding for education receives only 6 % of the total. The Geographical Society of China is building an advanced platform for communication in geography at both home and abroad, contributing to the training of talented people and the development of the geographical sciences in China.

Keywords

Investment for basic research of chinese geographical sciences • NSFC funding • Geographical education and research in chinese universities • The geographical society of china

The development of Geographical Sciences in China has benefited from the investment in basic research and higher education from central and local government. The Geographical Sciences as a discipline has branches in both the natural and social sciences, giving it great development potential in Chinese universities. This section sets out the background to the development of Geographical Sciences from three aspects, namely the funding of investment and training of people in the Geographical Sciences by the NSFC, the distribution of faculties in major Chinese universities and their research status, and the development of the Geographical Society of China and the construction of an academic platform.

The information on investment in the Geographical Sciences by NSFC and the application institutions for NSFC funding were obtained by searching for "D01" in the NSFC

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project funding database (excluding the projects with code "D0105" on soil science). The distribution of geography faculties was inferred from the internet and questionnaires.

3.1 Funds for the Geographical Sciences from the NSFC

The number of NSFC-funded projects, the annual total funding and average funding per project for the Geographical Sciences in 1986–2015 have all increased annually, making a great contribution to promoting an overall, balanced and harmonious development of the geographical sciences and to improving basic research.

There were several turning points in the trend in total NSFC funding in the last 30 years. In 2011, 2012 and 2014 there were huge increases in total funds, leading to a significant increase in funding for single projects and grants for the General Programme (GP). Another reason was the securing of funds for Major Programmes (MP), Major Research Plans (MRP) or Science Fund for Creative Research Groups (CRG Fund) which were generous and led to huge difference compared with previous years. In addition, funds allocated to the National Science Fund for Distinguished Young Scholar (DYS Fund) and Excellent Young Scientists Fund (EYS Fund) also impacted on the increase in annual total funds.

With the increase in the total funds, there was however a difference in funds allocated to different types of fund. Five-year averages show that the fund for the General Programme (GP) accounted for the largest share in 1986–1990 (90.7 %) and dropped to 58.7 % in 1991–1995; the lowest share for this fund was 42.2 % in 2001–2005; in the last 10 years it increased a little to 48 %. Among the total fund, the Young Scientists Fund (YSF) had increased from 5.6 % in the first five years to around 10 % in 1991–2000 and then to 16 % in 2001–2005, peaking at 22.2 % and then dropping to stabilize at 19.7 % in the last 10 years. The Fund for Less Developed Regions (LDR Fund) peaked twice at 4.7 % in 1991–1995 and 6.5 % in 2011–2015, and stood at 2–3 % at other times. Allocation to the Young Scientists Fund (YSF) and the Fund for Less Developed Regions (LDR Fund) basically depends on the proportion of applications, so that the increasing proportion reflected an increase in applications. These increases played a positive role in the development of the discipline and the training of young scientists (see Fig. 3.1).

The total funds for the General Programme (GP), Young Scientists Fund (YSF) and Fund for Less Developed Regions (LDR Fund) accounted for 98.8 % of the total in 1986–1990. The share was at its lowest (61 %) in 1996–2005. It then increased to 75 % in 2011–2015, higher than an average level for the NSFC. The proportion of the funds allocated to Key Programme (KP) reached three peaks

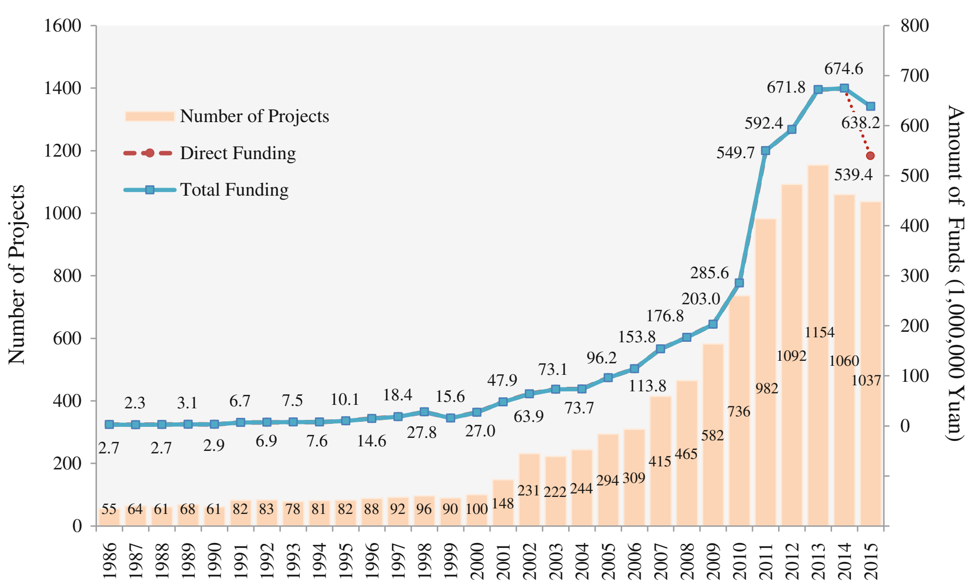


Fig. 3.1 Number and funding of NSFC-funded projects for the geographical sciences during the period 1986–2015. *Note* 1. The funding of the Science Fund for Creative Research Groups (CRG Fund) included only newly approved in the current year; 2. The funding of the National Science Fund for Distinguished Young Scholar (DYS Fund) included both the newly approved in the current year and extended funding; 3. The number and funding of the projects under Major Programme (MP) included only those with application code in D01; 4. Total funding of 2015 included direct and indirect funding; 5. The start year for the DYS Fund, the CRG Fund and the Excellent Young Scientist Fund (EYS Fund) was 1994, 2000, and 2012, respectively

in 1991–1995 (17.1 %), 1996–2000 (15.8 %) and 2006–2010 (14.9 %), and stood at 11 % at all the other times. This is because on the one hand, the macro policy of the NSFC is to ensure that the share of the General Programme (GP), Young Scientists Fund (YSF) and Fund for Less Developed Regions (LDR Fund) is no less than 60 % so that scientists have sufficient research flexibility and a guaranteed research development fund; on the other hand, after 2002, Department of Earth Science in the NSFC changed its Key Programme (KP) funding allocation mode from depending on annual individual disciplinary planning to depending on department scientific five-year planning. As a result each individual discipline has lost the ability to determine the funding for Key Programme (KP).

The proportion of funding allocated to the Key Programme for the Geographical Sciences by the Department of Earth Science varied during different periods. The lowest proportion was in 2001–2005 (16.9 %). In the last 10 years it stood at about 28 %, as in 1991–1995. Since 2007, the Department of Earth Science has increased the research fields for the Key Programme (KP) from six in 2002–2006 to 10 in 2007–2011. The new fields including “progress and mechanisms of changes in terrestrial surface system”, “water cycle and water resources” and “the effect of human activities on environmental change and its central principles”, expanded the research scope of the previous “regional sustainable development” programme and led to an increase in the number of Key Programme (KP) for the Geographical Sciences from 10 (14,350 thousand yuan) in 2006 to 16 (27,200 thousand yuan) in 2007. In addition, since 2012 the number of research fields has increased to 11 with the new field of “earth observation and its information processing” increasing the application opportunities for the Geographical Information Science. As a result in 2012–2015, the Geographical Sciences have secured 83 Key Programmes (KP) in this four years with a total funding of 269,607 thousand yuan. This number approached the total number (91) of the five years from 2007 to 2011 and surpassed the total funding of 190,390 thousand yuan of the 91 programmes (see Table 3.1).

With more state financial investment, average funding per project in the Geographical Sciences by the NSFC has also increased, especially since 2011 (Table 3.2). The average funding per project for General Programme (GP), Key Programme (KP) and Fund for Less Developed Regions (LDR Fund) in 2011–2015, reached 756 thousand yuan, 3193 thousand yuan and 498 thousand yuan, respectively, being 9.3, 8.4 and 7.8 times those in 1991–1995. The average funding per project for the Young Scientists Fund (YSF) was less but increased from 30 thousand yuan in 1986–1990 to a peak of 253 thousand yuan in 2001–2005 after which it stabilised for 10 years. In the last 30 years, NSFC not only paid attention to the average funding per project for research promotion projects, but also raised the average funding for talent training projects. The average funding per project for the National Science Fund for Distinguished Young Scholar (DYS Fund) increased from the original 600 thousand yuan in 1994 to 4000 thousand yuan in 2014, that for the Science Fund for Creative Research Groups (CGR Fund) increased from 3600 thousand yuan in 2000 to 12,000 thousand yuan in 2014 (the research period changed from three years to six years), and that for the Excellent Young Scientists Fund (EYS Fund) increased from 1 million yuan in 2012 to 1500 thousand yuan in 2015.

The success rate is defined as the ratio of number of projects funded to the number of applications, so that it is constrained by both the funding principles and the application situation. There was mild fluctuation in the success rates for applications for different types of NSFC fund for the Geographical Sciences (Table 3.3). The most competitive fund type was the National Science Fund for Distinguished Young Scholars (DYS Fund), where the success rate had decreased since the period 1996–2000 and was only 8.4 % in 2011–2015. The second highly competitive programme was the newly established Excellent Young Scientists Fund (EYS Fund) set up in 2012. The average success rate in the current year was 9.8 %. The success rate for the Key Programme (KP) had decreased from 78.9 % in 1996–2000 to around 15 % in the last 15 years, indicating very intense competition. Growing competition for the above three types of fund reflect on the one hand increases in the number of talented applicants, and, on the other hand, the fact that current research evaluation mechanisms have forced a much larger number of people to apply because the former two funds play a critical role in the evaluation of young scientists, while successful application for the latter fund is essential for promotion to a professorship or a research fellowship. In the case of Major Research Plan (MRP) there is distinct increase in success rates over an average plan period of 8–10 years. When a plan was initiated, qualified researchers are keen to apply, leading to intense competition and a decreased success rate. After 3–5 years’ funding support, further funding is directed to those programmes oriented to integrated research. As a result, qualifying institutions and people decrease, resulting in an increasing success rate under a stable funding programme number.

Differences in success rates among various disciplines coming under the Department of Earth Science are obvious, due primarily to the fund allocation principles and scale of research teams. The Department of Earth Science includes Geography, Geology, Geochemistry, Geophysics, the Atmospheric Sciences and Marine Sciences. The Young Scientists Fund (YSF) and the Fund for Less Developed Regions (LDR Fund) are allocated according to the proportion of applications from each discipline in the total

Table 3.1 Total funding of NSFC's funding instrument for the geographical sciences during the period 1986–2015 (10,000 yuan)

Funding instrument	1986-1990	1991-1995	1996-2000	2001-2005	2006-2010	2011-2015
Programmes for Research Promotion						
General Programme (GP)	1,238.6	2,272.5	5,130.5	14,970	41,700	152,704.5
Key Programme (KP)	0	664	1,630	4,125	13,904	33,530.7
Major Programme (MP)	0	0	951.5	0	360	9,640
Major Research Plan (MRP)	0	0	0	4,937	4,035	14,247
International (Regional) Joint Research Programme	0	0	0	202	1,395	3,694
Programmes for Talent Training						
Young Scientists Fund (YSF)	76.7	402.2	1,028.5	5,672	20,723	61,518.5
Excellent Young Scientists Fund (EYS Fund)	0	0	0	0	0	3,750
National Science Fund for Distinguished Young Scholar (scholars with foreign citizenship included) (DYS Fund)	0	260	670	1,700	3,000	5,200
Science Fund for Creative Research Groups (CRG Fund)	0	0	360	1,830	3,130	3,650
Fund for Less Developed Regions (LDR Fund)	34	180	310	828	3,049	20,205.9
Joint Research Fund for Overseas Chinese Scholars and Scholars in Hong Kong and Macao	0	0	0	320	80	576
Research Fund for International Young Scientists (IYS Fund)	0	0	0	0	60	103.5
Programmes for Infrastructure Construction						
Joint Funds	0	0	0	0	180	1,754.7
International (Regional) Cooperation and Exchange	0	0	0.4	411.2	532.7	575.2
Fund for Chinese Scholars Abroad Returning for Short-period of Work or Lecture	0	0	0	0	5.5	0
High Technology Explore	5	53	97.5	0	0	0
NSFC's President Fund and Science Department Director Fund	11.5	29	84	339	466	882
Excellent State Key Lab Research Fund	0	13	80	120	600	300
Special Grant for Pubic Understanding of Science	0	0	0	10	80	77
Project of Science Publication	0	0	0	16.5	0	0
Special Grant for Key Academic Journals	0	0	0	0	0	44

Note 1. The funding of the CRG Fund included only newly approved in the current year
2. The funding of the DYS Fund included both the newly approved in the current year and extended funding
3. The number and funding of the projects under MP included only those with application code in D01; 4. Total funding of 2015 included direct and indirect funding; 5. The start year for the DYS Fund, the CRG Fund and the EYS Fund was 1994, 2000, and 2012, respectively

applications, so the success rate is mainly influenced by the number of research teams. As for the General Programmes (GP), the previously mentioned individual application ratio has only taken a weight of 10 %, and the rest 90 % is the historical number of funded projects. Therefore, the enormous increase in applications does not lead to a parallel increase in the number of successful applications, and the success rate increased slowly and sometimes even decreased. The situation has improved very slightly in the last five years, but the success rate for funding application in Geography remains 8–10 %, lower than in those of other disciplines under the Department of Earth Science in NSFC.

The age distribution of Principal Investigators (PIs) for the General Programme (GP) and the Key Programme (KP) (Figs. 3.2 and 3.3) shows that the average age was between 51 and 61 in 1986–1995; however, it declined fast

Table 3.2 Average grant of NSFC's funding instrument for the geographical sciences during the period 1986–2015 (10,000 yuan/project)

Funding instrument	1986-1990	1991-1995	1996-2000	2001-2005	2006-2010	2011-2015
Programmes for Research Promotion						
General Programme (GP)	4.6	8.1	16.1	28.8	39.5	75.6
Key Programme (KP)	-	44.3	108.7	133.1	176	319.3
Major Programme (MP)	-	-	500	-	-	2,000
Major Research Plan (MRP)	-	-	-	82.3	130.2	274.0
International (Regional) Joint Research Programme	-	-	-	67.3	77.5	255.5
Programmes for Talent Training						
Young Scientists Fund (YSF)	3.0	6.4	14.1	25.3	20.4	24.9
Excellent Young Scientists Fund (EYS Fund)	-	-	-	-	-	110.3
National Science Fund for Distinguished Young Scholar (scholars with foreign citizenship included) (DYS Fund)	-	86.7	74.4	121.4	200	273.7
Science Fund for Creative Research Groups (CRG Fund)	-	-	360	366	521.7	730
Fund for Less Developed Regions (LDR Fund)	3.4	5.6	11.5	20.2	23.6	49.8
Joint Research Fund for Overseas Chinese Scholars and Scholars in Hong Kong and Macao	-	-	-	40	26.7	48
Research Fund for International Young Scientists (IYS Fund)	-	-	-	-	20	17.3
Programmes for Infrastructure Construction						
Joint Funds	-	-	-	-	90	87.7
International (Regional) Cooperation and Exchange	-	-	0.4	2.0	4.9	5.5
Fund for Chinese Scholars Abroad Returning for Short-period of Work or Lecture	-	-	-	-	1.4	-
High Technology Explore	5	6.6	24.4	-	-	-
NSFC's President Fund and Science Department Director Fund	3.8	5.8	6.5	13.6	17.9	20
Excellent State Key Lab Research Fund	-	13	80	120	200	300
Special Grant for Pubic Understanding of Science	-	-	-	5.0	26.7	25.7
Project of Science Publication	-	-	-	5.5	-	-
Special Grant for Key Academic Journals	-	-	-	-	-	22

Note See Table 3.1

to between 36 and 45 in 1996–2005. In the last 10 years these age groups still dominated, but there were significant numbers in the age bands, 46–50, 31–35 and 51–60. Generally, PIs aged under 30 and over 60 were rare. This wide distribution range of the age of PIs in charge of General Programme (GP) indicates on the one hand that young people developed rapidly and were able to continue with General Programme (GP) funding after securing support from the Young Scientists Fund (YSF); on the other hand, the General Programme (GP) is very attractive to researchers seeking to stabilise the development of a research team, because 30 % of PIs of General Programme (GP) obtained funds from more than two programmes. PIs of Key Programme (KP) tended to be younger. Researchers aged over 51 accounted for 80 % of funded projects in 1986–1995, 50 % in 1996–2005 and only 32.6 % in the last 10 years. At the same time, PIs of Key Programme (KP) aged between 46 and 50 have established themselves as lynchpins of these programmes accounting for 39.7 % of the total, a figure which was 8.1 times that in 1996–2005. PIs aged under 45 accounted for 27.7 % of all PIs. This is of course related to the increase in the number of funded projects, and also to the

Table 3.3 Success rate of NSFC's funding instrument for the geographical sciences during the period 1986–2015 (%)

Funding instrument	1986-1990	1991-1995	1996-2000	2001-2005	2006-2010	2011-2015
Programmes for Research Promotion						
General Programme (GP)	100	100	26.1	18.3	19.6	22.9
Key Programme (KP)	-	100	78.9	16.5	16.5	14.4
Major Programme (MP)	-	-	-	-	-	-
Major Research Plan (MRP)	-	-	-	18.6	31.0	48.1
International (Regional) Joint Research Programme	-	-	-	33.3	32.1	13.5
Programmes for Talent Training						
Young Scientists Fund (YSF)	100	100	32.7	27.2	28.1	29.9
Excellent Young Scientists Fund(EYS Fund)	-	-	-	-	-	9.8
National Science Fund for Distinguished Young Scholar (scholars with foreign citizenship included) (DYS Fund)	-	100	28.1	14.3	7.5	8.4
Science Fund for Creative Research Groups (CRG Fund)	-	-	100	45.5	50.0	33.3
Fund for Less Developed Regions (LDR Fund)	100	100	22.9	15.2	24.1	22.4
Joint Research Fund for Overseas Chinese Scholars and Scholars in Hong Kong and Macao	-	-	-	100	15.0	22.6
Research Fund for International Young Scientists (IYS Fund)	-	-	-	-	60.0	60.0
Programmes for Infrastructure Construction						
Joint Funds	-	-	-	-	8.3	10.8
International (Regional) Cooperation and Exchange	-	-	100	92.3	67.7	59.8
Fund for Chinese Scholars Abroad Returning for Short-period of Work or Lecture	-	-	-	-	100	-
High Technology Explore	100	100	40.0	-	-	-
NSFC's President Fund and Science Department Director Fund	100	100	100	96.2	89.7	95.7
Excellent State Key Lab Research Fund	-	100	100	100	100	100
Special Grant for Pubic Understanding of Science	-	-	-	5.6	60.0	100
Project of Science Publication	-	-	-	50.0	-	-
Special Grant for Key Academic Journals	-	-	-	-	-	100

Note 1. "–" represents no applications, so there is no need to calculate the success rate
2. The success rate of MP was not calculated because MP was rare
3. The number of projects funded equaled to the number of applications because there was no project application information in the database for the period of 1986–1997. Therefore the success rate was recorded as 100 %

fact that young researchers now are in a stronger competitive position and develop faster.

Because of focusing on regional studies, NSFC funded geographical research was scattered around the country in the past 30 years. Except home institutions from Hong Kong, Macau and Chinese Taiwan, all provinces (autonomous regions, municipalities) have been allocated fund through application (Figs. 3.4 and 3.5). There were in total 6893 people from 685 institutions who have carried out research projects funded by NSFC. In Beijing, there were 1968 people from 143 host institutions. People who have been supported by NSFC increased from 55 in 1986 to 99 in 2000 and 1042 in 2015, and the host institutions have increased from 28 in 1986 to 46 in 2000 and 306 in 2015. Between 2000 and 2015, people who have been supported have increased by 9.5 times and host institutions have increased by 5.7 times. The top

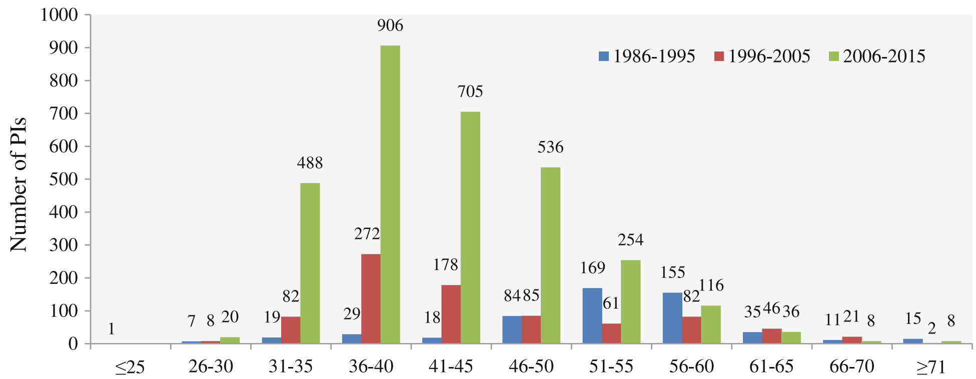


Fig. 3.2 Age distribution of PIs in the NSFC-funded General Programme (GP) for the geographical sciences during the period 1986–2015

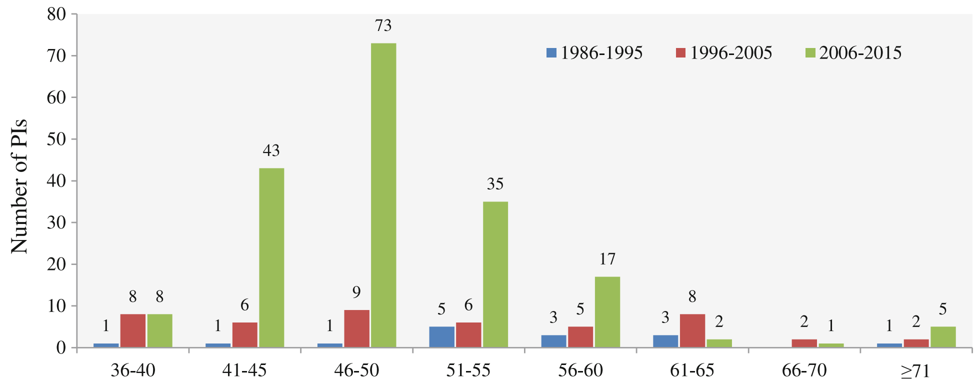


Fig. 3.3 Age distribution of PIs in the NSFC-funded Key Programme (KP) for the geographical sciences during the period 1986–2015

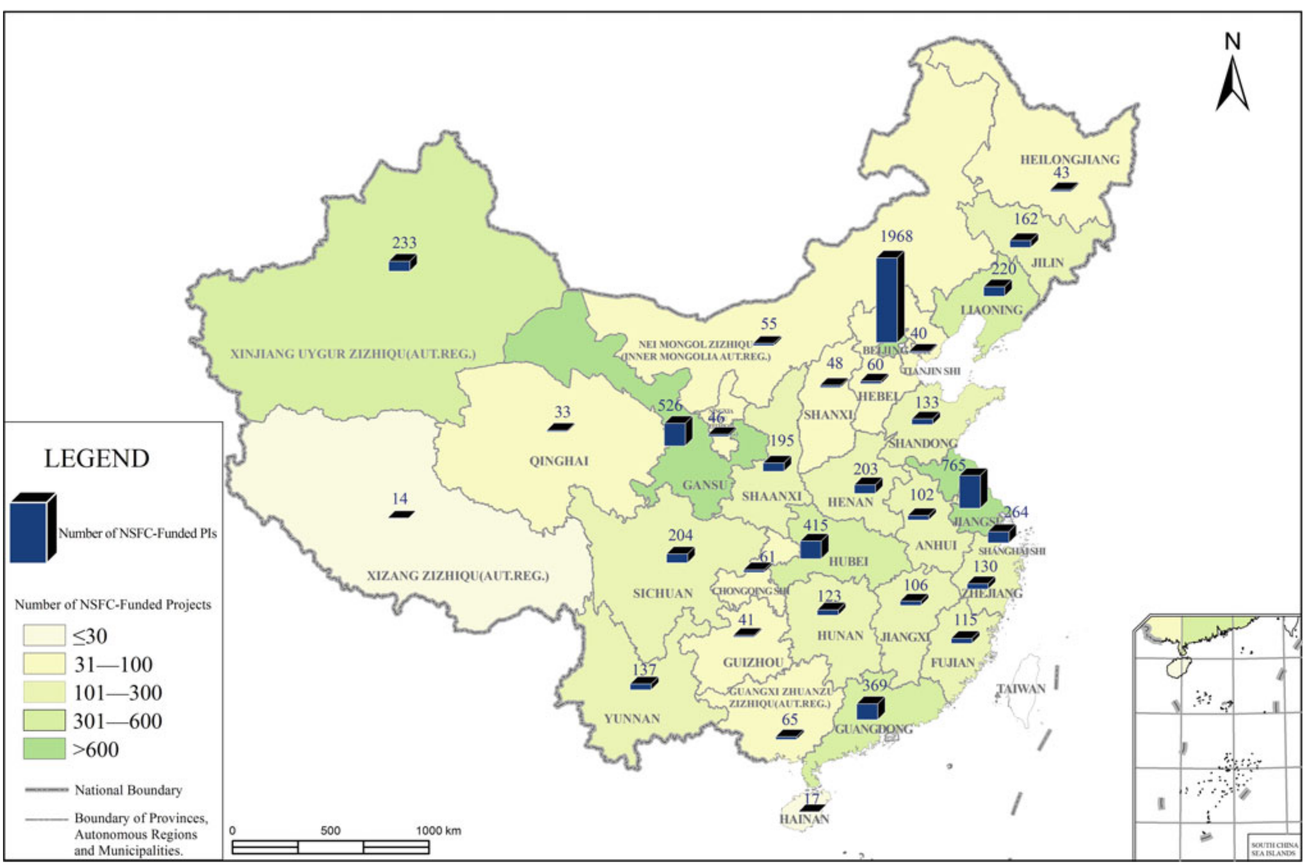


Fig. 3.4 Number of PIs and their provincial distribution of the NSFC-funded projects for the geographical sciences during the period 1986–2015

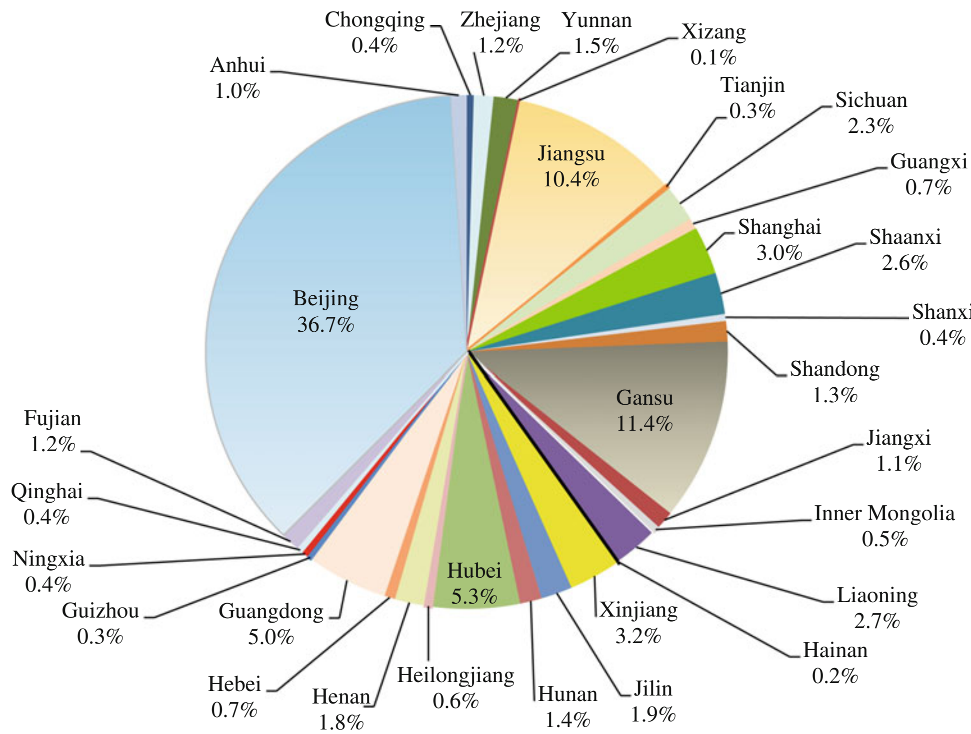


Fig. 3.5 Proportion of the total funding of the NSFC-funded projects for the geographical sciences in each province during the period 1986–2015

supported areas were Beijing, Jiangsu, Gansu, Hubei and Guangdong, all with more than 300 people, with a proportion of 58.7 % of all geographical PIs, and 68.8 % of all the funding. These regions were the major locations for geographical research institutions of CAS, including Institute of Geographic Sciences and Natural Resources Research, Institute of Tibetan Plateau Research, Cold and Arid Regions Environmental and Engineering Research Institute, Nanjing Institute of Geography and Limnology, and also home to many universities with complete geographical subjects, such as Peking University, Beijing Normal University, Nanjing University, Nanjing Normal University, Lanzhou University, Wuhan University and Sun Yat-sen University. These areas had a core distribution of the major institutions of CAS and universities with complete branches of Geographical Sciences in disciplinary design, which bears a great advantage in research. By contrast, areas with the fewest geographical researchers are Xizang (Tibet) and Hainan. It was worth mentioning that geographical research in Xinjiang is carried out extensively, with 223 people from 17 home institutions running 144,757 thousand yuan for 324 projects. The total funding received ranks sixth and the average funding per person ranks eighth. Of all the institutions in Xinjiang, Xinjiang Institute of Ecology and Geography of CAS has obtained 167 projects and 84,080 thousand yuan, which is 51.5 and 58.1 % of all the projects and fund, respectively. Xinjiang University and Xinjiang Normal University and Shihezi University have all obtained much support.

3.2 Geographical Sciences Education

Searching with all the subject names approved by the Ministry of Education, we found that there are in total 816 faculties in 505 higher education institutions in which geography related courses were taught. 165 faculties in 149 institutions had majors in the Geographical Sciences, and 49 faculties had "geography" in their name. According to the public information about curriculum assessment carried out by the Ministry of Education, there were 33 institutions involved in the curriculum assessment for Geography in 2012 (the authority number). We have carried out questionnaire investigation to the above-mentioned institutions and focused on the 38 Geographical Sciences related faculties in 33 institutions who were ranked in the curriculum assessment (Table 3.4 and Fig. 3.6), to reflect the Geographical Sciences education in China.

Of the 33 institutions, there are 7 belonging to the "985 Project" institutions and 9 belonging to "211 Project". In total there are 33 stations qualified to award doctorate, 242 qualified for master of the primary disciplines of Geographical Sciences and related ones. For teaching, there are

Table 3.4 Chinese faculties of geographical sciences in 2014 in the universities involved in the Ministry of Education's 2012 curriculum assessment for geography

University	Types	College (School, department)	First-level doctoral discipline	Master degree discipline	Number of professor	Number of doctorate	Doctorate enrolment numbers	Master enrolment numbers	Number of undergraduate majors
Peking University	985 Project	College of Urban and Environmental Sciences	2	7	41	69	40	60	5
Beijing Normal University	985 Project	School of Geography	1	9	24	64	32	130	4
Beijing Normal University	985 Project	College of Resources Science and Technology	1	3	24	42	34	54	1
Beijing Normal University	985 Project	School of Environment	1	3	28	76	43	74	3
East China Normal University	985 Project	School of Geographic Sciences	1	8	15	42	14	75	2
East China Normal University	985 Project	School of Urban and Regional Science	2	2	7	23	18	40	1
Lanzhou University	985 Project	College of Earth Environmental Sciences	1	9	40	111	35	88	3
Nanjing University	985 Project	School of Geographic and Oceanographic Sciences	3	9	31	96	57	109	5
Wuhan University	985 Project	School of Remote Sensing and Information Engineering	2	4	26	67	32	130	2
Wuhan University	985 Project	School of Resource and Environment Sciences	2	5	32	90	51	214	4
Sun Yat-sen University	985 Project	School of Geography and Planning	1	7	33	72	72	105	5
Northeast Normal University	211 Project	School of Geographic Sciences	1	8	22	51	17	57	4
Fuzhou University	211 Project	College of Environment and Resources (Spatial Information Research Centre of Fujian)	0	3	7	34	5	44	1
South China Normal University	211 Project	School of Geographic Sciences	1	3	17	32	4	72	3
Nanjing Normal University	211 Project	School of Geographic Sciences	1	13	54	137	34	167	8
Shaanxi Normal University	211 Project	Tourism and Environment College	2	13	21	66	13	125	2
Northwest University	211 Project	College of Urban and Environmental Sciences	1	7	17	41	11	102	7
Southwest University	211 Project	School of Geographic Sciences	1	4	10	49	3	77	3
Xinjiang University	211 Project	School of Resource and Environment Sciences	2	7	12	40	12	106	7
China University of Geosciences(Wuhan)	211 Project	Faculty of Earth Sciences (Geography Department)	0	1	7	18	7	30	1
Fujian Normal University	Others	School of Geographic Sciences	2	10	34	74	11	157	7

(continued)

Table 3.4 (continued)

University	Types	College (School, department)	First-level doctoral discipline	Master degree discipline	Number of professor	Number of doctorate	Doctorate enrolment numbers	Master enrolment numbers	Number of undergraduate majors
Guangzhou University	Others	School of Geographic Sciences	0	3	12	32	0	37	3
Harbin Normal University	Others	School of Geographic Sciences	0	4	12	28	7	62	5
Henan University	Others	College of Environment and Planning	1	16	31	88	15	97	4
Jiangsu Normal University	Others	School of Geodesy and Geometics	0	3	7	17	0	10	3
Jiangsu Normal University	Others	College of Urban and Environmental Sciences	0	6	15	26	0	44	7
Liaoning Normal University	Others	College of Urban and Environmental Sciences	1	7	19	38	10	104	4
Ludong University	Others	Institute of Geography and planning	0	2	11	20	0	30	4
Inner Mongolia Normal University	Others	School of Geographic Sciences	0	10	20	26	1	114	7
Shanghai Normal University	Others	College of Tourism	0	7	10	62	9	64	3
Capital Normal University	Others	College of Resource Environment and Tourism	1	11	22	62	17	145	4
Sichuan Normal University	Others	College of Geography and Resources Science	0	5	9	24	0	53	4
Tianjin Normal University	Others	College of Urban and Environmental Science	0	4	10	46	0	36	3
Xi'an International Studies University	Others	School of Tourism & Research Institute of Human Geography	0	1	8	8	0	36	5
Northwest Normal University	Others	College of Geography and Environment Science	1	8	21	46	8	85	6
Yunnan Normal University	Others	College of Tourism and Geographical Sciences	1	11	14	31	15	113	7
Zhejiang Normal University	Others	College of Geography and Environment Science	0	4	10	23	21	48	3
Chongqing Normal University	Others	College of Geography and Tourism	0	5	11	31	0	85	3

744 professors, 920 associate professors, and 942 lecturers and others. Of the 38 faculties 25 have research staff. In average numbers of stations qualified to award doctorate, master and bachelor are 2.4, 9.4 and 5 in "985 Project" institutions, 1, 6.6 and 4 for "211 Project" institutions and 0.4, 6.9 and 4.8 for other institutions. It is therefore shown that those "985 Project" institutions play an important role in expanding the development direction of Geographical Sciences, promoting interdisciplinary research with other primary discipline including Economy, Environmental Sciences, Cartographical Science and Technology and Geology, elevating a comprehensive recognition of the earth surface system, and training all-round students. The 9 "211 Project" institutions are only qualified for awarding doctorate in the Geographical Sciences as the primary discipline, but they all take advantage in master training by using their specialism and expensing interaction with other primary and secondary disciplines such as Regional Economy, Tourism

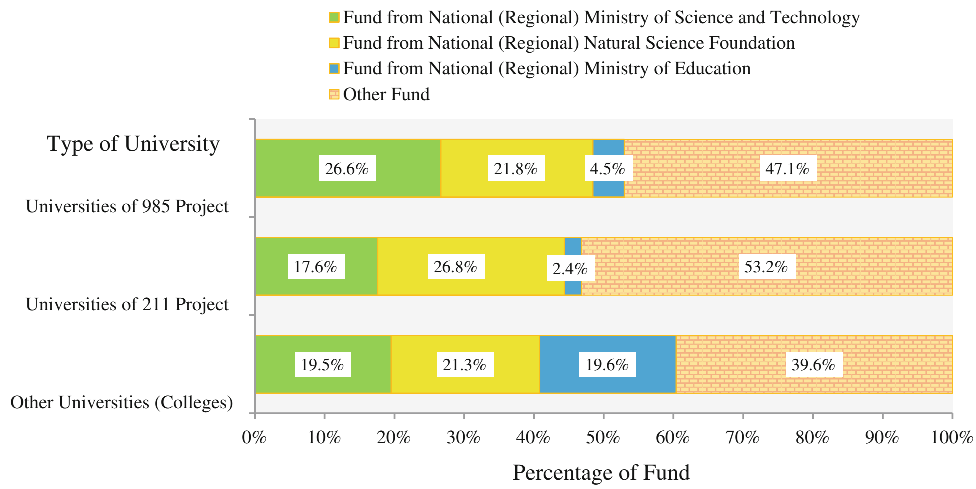


Fig. 3.6 Funding sources of geographical sciences faculties in universities of China in 2013

Management, Land Management, Hydrology and Water Resources, so as to make contribution to training students with a perspective of Geographical Sciences and ability to do interdisciplinary research. The other 17 universities are mainly local and normal universities, and two out of three of them have "Geography" in name. These universities focus fully on regional research of Geographical Sciences, to provide large amounts of data for resource exploration and exploitation, environment management and planning and social sustainable development. They have grown to be important advisers to local policy makers. Through serving local development, these geographical faculties also have trained a lot of graduates who have mastered geographical knowledge, known local conditions and participated in regional research, by combining teaching with practices. These graduates therefore become pool of human resources to improve the ability of Geographical Sciences to serve our society.

As to the numbers of professors, there are in average 43 in "985 Project" universities, 18.6 in "211 Project" universities and "16.2" in other universities. As for staff holding a doctorate degree, there are in average 107.4, 52 and 40.1 in the three types of universities. As for the enrolment as a postgraduate student pursuing a doctorate and master degree, there are 61.1 and 154.1 for "985 Project" universities, 11.8 and 86.7 for "211 Project" universities and 6.7 and 77.6 for other universities. The average Ph.D candidate for each professor is 1.4, 0.6 and 0.4 for the three types of universities. These data indicate on the one hand that both "985 Project" and "211 Project" universities are strong in academic staff reserve and are essential base for geographical teaching; on the other hand, "985 Project" universities do get the greatest development space in talent training, with an average number of professors 2.3 times "211 Project" universities and 2.7 times other universities, and the number of Ph.D candidates 5.2 times and 9.1 times "211 Project" universities and other universities, respectively. By contrast, there is no distinct difference in the number of professors and the enrolments of postgraduate students between "211 Project" universities and non "211 Project" ones.

3.3 Universities Involved in Research on Geographical Sciences

The number of NSFC Geographical Sciences funded universities increased from 14 in 1986 to 22 in 2000 and then 204 in 2014. The according proportion to the total funded institutions changed from 50 % in 1986 down to 47.8 % in 2000 and up to 66.7 % in 2014. Not only the exact number but also the proportion in all funded institutions were increasing, indicating that universities engaged in geographical research have made great contribution to the development of Geographical Sciences.

In 2013, 33 universities obtained a total fund of 948,430 thousand yuan, of which "985 Project" universities took 53.4 %, "211 Project" 24.4 % and the other 22.2 %. The total fund came from different sources, including the Ministry of Education or provincial Bureau of Education (7.4 %), NSFC or provincial natural science fund (22.9 %), the Ministry of Science and Technology or its provincial departments (22.8 %) and others (46.9 %). As for the competitive ability, "985 Project" universities have obtained 62.2 % of all the fund from the Ministry (Bureau) of Science and Technology, 50.8 % of NSFC or provincial natural science fund, 53.6 % of others, showing an absolute competitive advantage. As for education funds investment, non-"985 Project" and non-"211 Project" universities obtained 59.1 %, compared to 32.8 % for

"985 Project" universities, and 8.1 % for "211 Project" universities. This suggests that geography has gained attention in local universities and remained a certain status in famous comprehensive universities, but has not gained more attention in "211 Project" universities.

Funding sources of the three types of university (Fig. 3.6) show that, if fund from the Ministry (Bureau) of Science and Technology and National (Regional) scientific research fund were integrated as national research input fund, and the ratio of national research input and "other fund" for "985 Project" universities were almost 1:1. In the same way, this ratio for "211 Project" universities was 0.8:1 and it was also 1:1 for other universities. Data also shows that the development of Geographical Sciences has been driven by both the investment from national research fund and social need (funds from other sources). Regardless of types of universities, all kinds of universities promoting geographical teaching and research could find certain sources of funding. It is reasonable to say that funding was critical for the development of Geography, so we believe that NSFC and provincial natural science funds were especially important for the development of "211 Project" universities. When there was few funds allocated from the Ministry (Bureau) of Sciences and Technology and education investment, NSFC and provincial natural science fund was a major supporting way to keep the basic research, otherwise the research ability would be directed away from basic research to more practical research. If proportion of education investment is taken as an important index for the potential development of Geography, it is straightforward to say that non-"985 Project" and non-"211 Project" universities are facing a great opportunity for their development in Geography. Obtaining more local education investment, Geography in these universities could become better and better.

As the NSFC is an essential source of funds for basic research, success in securing support may reflect the standing of universities in the field of geographical research. The Top 20 universities in terms of allocated NSFC funds in 1986–2015 are listed in Table 3.5. Fifteen out of the 20 universities listed in 2006–2015 were assessed in 2012 for Geographical Sciences by the Ministry of Education, and granted the status of leading universities for geographical research. Universities not included in the assessment included Hohai University, China Agricultural University, Tsinghua University, The PLA Information Engineering University, Nanjing University of Information Science & Technology and Anhui Normal University. Except Anhui Normal University, the others are not considered to be universities famous for geography. There were ten "985 Project" universities, six "211 Project" universities and 4 other universities in the Top 20, indicating their high standing for basic research and higher education as a whole. However, some "211 Project" universities including Southwest University, China University of Geosciences (Wuhan) and Fuzhou University were not ranked in the Top 20 for NSFC Geographical Sciences funding in the last 30 years, so there seemed to be a lot of room for improvement in basic research. Comparing the three decades there is basically no change in the rankings of the top seven universities, although the rank order fluctuated. The top seven were mainly "985 Project" universities in the Geographical Sciences. Peking University and Beijing Normal University were always the top two, indicating their absolute advantage in geographical research. The rankings for Lanzhou University, Wuhan University, Nanjing University and Sun Yat-Sen University fluctuated all the time but they never dropped out of top seven, while the rank of East China University has steadily decreased to eighth in the last period. The university with the fastest increase in ranking is Nanjing Normal University, the only "211 Project" university among the top seven growing from the 16th in 1986–1995 to 6th in the last ten years. The ability of senior researchers to secure NSFC funds could be calculated by subtracting the Young Scientists Fund (YSF) from the total allocated NSFC funds in 2014, and then dividing by the total number of professors and associate professors. Of the top eight universities Peking University and Nanjing Normal University performed best, both with per capita averages of 190,000 yuan, followed by Sun Yat-Sen University with an average of 150,000 yuan. The third tier included Wuhan University, Lanzhou University, Beijing Normal University and East China University, with averages of 100,000 yuan, followed by Nanjing University with an average of 60,000 yuan. The other Top 20 universities (excluding the above-mentioned Top eight universities and 5 universities that do not offer geography, such as Hohai University) usually have between 35 to 50 professors and associate professors in geography faculties. This figure was just 50 % of the figure for the top eight universities. Benefitting from a preferential NSFC policy, Xinjiang University has obtained many grants from the NSFC-Xinjiang Joint Funds as well as from normal funds, enabling it to rank in the Top 20 in the last 10 years.

The rankings of the Top 20 universities were closely linked to the number of researchers and success in obtaining large grants for a single project during a particular period of time. Since the NSFC adopted the international approach of peer review in fund allocation, the rankings nonetheless reflected the academic influence and competitiveness of different universities. The top seven universities obtained 81 Key Programme (KP) grants (33.1 % of the total for the Geographical Sciences). There were nine projects supported by the Science Fund for Creative Research Groups (CRG Fund). Another eight were a continuation of previous projects. Four of them were granted to Peking University, Lanzhou University, Wuhan University and Beijing Normal University (with another four continuing ones). There were

Table 3.5 Top 20 universities with NSFC funding for the geographical sciences during the period 1986-2015

1986-1995		1996-2005		2006-2015	
Universities	**Funding (10,000 yuan)**	**Universities**	**Funding (10,000 yuan)**	**Universities**	**Funding (10,000 yuan)**
Peking University	487.2	Peking University	4,743.5	Beijing Normal University	18,852.4
Beijing Normal University	245.0	Beijing Normal University	2,366.4	Peking University	18,376.4
Nanjing University	217.6	Lanzhou University	2,025.0	Wuhan University	13,807.6
Wuhan University	211.8	Nanjing University	1,676.1	Lanzhou University	11,156.8
East China Normal University	139.9	Sun Yat-sen University	1,378.4	Nanjing University	8,056.2
Sun Yat-sen University	118.5	Wuhan University	1,268.2	Nanjing Normal University	7,772.6
Lanzhou University	102.8	East China Normal University	1,066.5	Sun Yat-sen University	6,932.8
Yunnan University	75.7	Nanjing Normal University	661.0	East China Normal University	5,553.0
Northeast Normal University	71.0	Zhejiang University	445.5	Hohai University	4,755.6
Sichuan University	58.5	Northeast Normal University	380.1	China Agricultural University	3,931.5
Henan University	52.2	Shaanxi Normal University	347.0	Tsinghua University	3,427.7
Central China Normal University	31.5	Yunnan University	318.5	Northeast Normal University	3,004.1
Northwest University	28.5	Fudan University	303.0	Shaanxi Normal University	2,801.0
Tsinghua University	28.0	Tsinghua University	293.2	Henan University	2,412.2
Shaanxi Normal University	27.0	Tongji University	252.0	Capital Normal University	2,376.2
Nanjing Normal University	26.2	Henan University	243.5	Anhui Normal University	2,312.4
South China Normal University	26.2	China Agricultural University	240.0	Information Engineering University, People's Liberation Army of China	2,256.9
Fudan University	22.9	Nanjing Agricultural University	195.0	Xinjiang University	2,241.1
China University of Mining and Technology	21.5	Xi'an Jiaotong University	173.0	South China Normal University	2,087.0
Qinghai Normal University	19.6	Liaoning Normal University	168.0	Nanjing University of Information Science & Technology	2,055.9

Note University listed in descending order of funding

60 persons supported by the National Science Fund for Distinguished Young Scholar (including scholars with foreign citizenship) (DYS Fund), of which Peking University received nine, Lanzhou University five, Beijing Normal University and Sun Yat-Sen University two each, and Wuhan University and Nanjing University one each.

The number of areas of specialisation and academic characteristics of a university also affect its access to funds. For example, there are six geography related faculties in Beijing Normal University. Three of them mainly recruit undergraduate students, namely the School of Geography, College of Resources Science & Technology and the School of Environment. Another three teach postgraduate students, namely the Academy of Disaster Reduction and Emergency Management, the College of Global Change and Earth System Science and the College of Water Sciences. These three research institutions cover almost all branches of the Geographical Sciences and inter-disciplinary oriented research fields. By contrast, Nanjing Normal University has only School of Geographic Sciences, but has a series of subjects covering Physical Geography, Resources and Environment, Tourism Management, Human Geography and Regional Planning, Geographical Information Science and Cartographical Engineering, Environmental Science and Engineering, and the Development of Marine Resources.

The development of a geography faculty should depend not only on the expansion of research teams, but also a sound disciplinary system and a clear research orientation, otherwise it will affect long-term development of geographical research. Therefore, when analysing their advantages, we must also pay attention to some problems in their development. Here are some examples. Geographical research in Wuhan University mainly focuses on Geographical Information Science and Lanzhou University on Geomorphology and the Quaternary. There is no clear orientation but a vague inter-disciplinary research of Geographical Sciences, Marine Sciences and Environmental Sciences in the East China Normal University. Similarly, Nanjing University's advantage in Geographical Sciences research is increasingly blurred. There is a lack of Remote Sensing and Geographical Information System research in the College of Urban and Environmental Sciences in Peking University, while the Physical Geography research team in the School of Geography and Planning at Sun Yat-Sen University is too small.

3.4 The Geographical Society of China

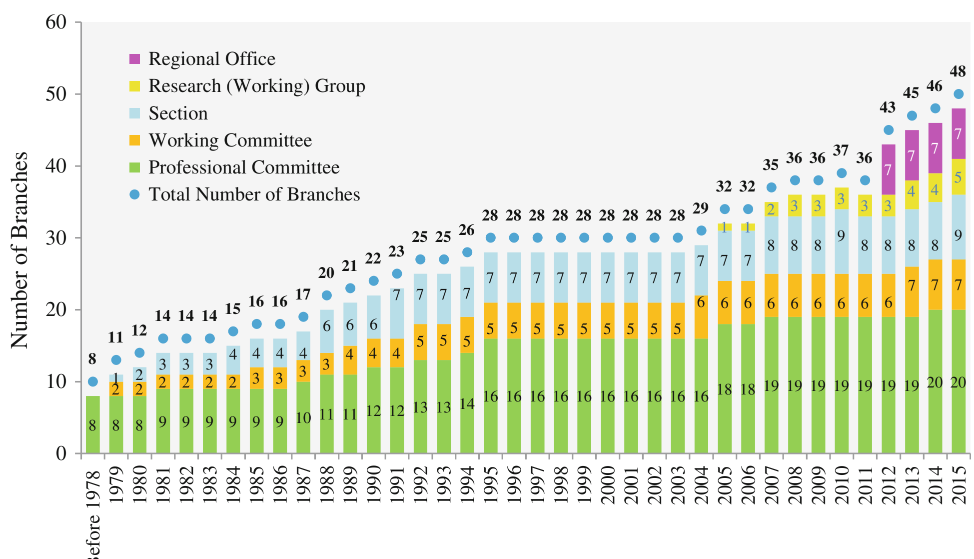
3.4.1 The Development of Society Membership

Changes in the number of members demonstrate the solidarity of the Society, as well as research team and disciplinary development. Before 1999, the management system did not permit individual application for membership. The members of local societies were automatically entitled to national membership. At the peak there were 20,000 members but no membership database. After 1999, the Society changed its management system to allow the direct enrolment of members by the national Society, and adopted a hierarchical membership system so that local members did not automatically become national members. The implementation of this policy for a 17 year period from 1999 to 2015 saw a fast increase in the number of registered member from zero to more than 10,000, indicating the growing influence of the Society and a healthy development of China's Geographical Sciences, with more and more members focusing on and engaging in teaching and geographical research.

3.4.2 Establishment of Secondary Organisations

The establishment of secondary organisations is one of the key activities of the Geographical Society of China. Before 1978, the Society only had eight branches. With the implementation of China's reform and opening-up policies, and China's rapid socio-economic development, there was a social need to broaden the academic scope of the Society and strengthen its branches. The development of the Society's branches is shown in Fig. 3.7. There was a rapid increase around 1990 and then again in the last 10 years. With growing professionalism, there was a constant division of the subject into more specialised areas. At the same time, with economic development and social progress, the importance of some subjects closely linked to everyday life, such as social and cultural geography and behavioural and spatial geography, increased.

Fig. 3.7 Number of branches of the Geographical Society of China



There are current 48 branches including professional committees, sections, working committees, research (working) groups and regional offices. Among them there are professional committees for Human Geography, Urban Geography and Tourism Geography, the establishment of which were driven by rapidly growing social needs. Some sections were a response to research calls such as the traditional Desert Section, Glacier and Permafrost Section, Mountain Section, and the Lake and Wetland Section newly established in 2015. Under the working committee there are also a Science Popularisation working committee, Editing and Publishing working committee and academic working committee. These sub-divisions improve functioning of the Society, the management of academic communication and quality control. In 2015 a new working group on Industrial Policy and Development Geography was established. Regional offices including South China, Central China, North China and so on promote progress of regional geography and upgrade overall regional geography research.

Through the setting up of an academic communication platform by the secondary organisation, the Society can carry out extensive academic communications to further facilitate the development of the Geographical Sciences, strengthen the links among members/geographers, and mobilise teachers and students to participate in the activities of the Geographical Society of China, so that geographical knowledge can be disseminated more broadly. At the same time, by conducting diverse scientific popularisation activities, the Society can enhance understanding of the Geographical Sciences.

3.4.3 Academic Activities

Academic Communication

With the development of China's science and technology, the Geographical Sciences must also take the road of internationalisation. In 1985, the Geographical Society of China regained its legitimate seat in the International Geographical Union (IGU). The Society has participated in the International Geographical Congress and IGU Regional Conferences. In addition, the Society organised teams to participate in the International Geographical Olympiad to cultivate young people's interest in Geography and to demonstrate Chinese young people's understanding and mastery of Geography. The Society also has successfully recommended a number of domestic geographers to take positions in the IGU. Academicians including Wu Chuanjun, Liu Changming, Qin Dahe and Zhou Chenghu have all been successfully elected Vice-Chairman of the IGU Executive Committee. The Society also hosted almost 20 annual academic conferences of IGU committees, and successfully bid to host the 33rd International Geographical Congress in 2016. Besides working with the IGU, the Society has helped to create the International Permafrost Association (IPA) and the International Association of Geomorphologists (IAG) and hosted congresses, regional conferences and thematic meetings of these two organisations. In addition, the Society has participated in important conferences hosted by international organisations. Academicians including Cheng Guodong, Wang Ying, Zhu Yuanlin, Ma Wei and Yang Xiaoping have all held positions consecutively in the IPA and IAG Executive Committee. Furthermore, Cheng Guodong was once the Vice-Chairman and then Chairman of the IPA, and Yang Xiaoping is now the Vice-Chairman of IAG.

As to the bilateral communication, Japan and South Korea are the two major cooperating partners. Communication started with visits and then escalated to holding the China-Japan-Korea Joint Conference on Geography in 2006. In 2015, this series of Joint Conferences developed into the first Asian Conference on Geography held in Shanghai.

As for multilateral communication, there are other international platforms besides the IGU, IPA and IAG related academic activities, some of which are associated with the organisation of a series of international conferences. For example, the Society created Sino-European Symposium on Environment and Health (SESEH) in 2012 (now Symposium on Environment and Health).

For communication in the Greater China area, the Society sent delegation to the "Symposium on Geography and Development" in Hong Kong in 1990, starting an era of active communication. The professional committees for Geomorphology and the Quaternary, Economic Geography, and Rural Landscape and Leisure Industry Development Research Group have all held a series of joint meetings with scholars of Chinese Taiwan. Some have met more than 10 times.

While establishing extensive contacts with international and regional research teams, the Society also makes efforts to build domestic academic platforms to show new trends in China's Geographical Research. Since the initiation of the Annual Meeting of the Geographical Society of China (GSC) in Shanghai in 2001, the number of participants has increased from 400 to 2000. This annual meeting has changed to a biannual meeting since 2012. The themes of these meetings have reflected the latest progress in Geography (Table 3.6). There were also regional meetings as required. So far 13 have taken place.

Extensive communication both home and abroad has not only enlarged researchers' horizons but has also set young scientists and students on a fast development track, promoting innovation and progress in Geography.

Academic Achievements and Publications

Academic journals are an important platform for communication for Chinese geographers. The number of journals

Table 3.6 Themes of academic conference of the Geographical Society of China during the period 2000–2014

Year	Theme	Year	Theme
2000	Development strategies of Chinese geography in 21st century	2007	Geography and construction of earth system science
2001	Chinese geography for one century: basic research and education development	2008	Geography and ecological civilization
2002	Geography education and discipline development	2009	Centennial celebration of the Geographical Society of China
2003	Understand geographic process, show solicitude for man's homeland	2010	Geography and urban construction
2004	Geography and the scientific viewpoint of development	2011	Key issues and themes in geography
2005	Geography and China development	2012	Development of geography: science and society
2006	Building of a harmonious society and innovation of geographical sciences	2014	Chinese geographical sciences: facing the future, moving towards the world

sponsored by the Society increased from 7 in 1996 to 16 in 2015. The Journal of Geographical Sciences (English version) has been included in SCIE (SCI-expanded) since 2007. *Chinese National Geography* has become a well-known domestic science popularisation journal and has had an impact at home and abroad. The Society has also carried out a lot of work in compiling academic achievements, and refining academic standards setting, resulting in dozens of academic conference proceedings. From 2003 to 2005, the Society edited an annual academic development Blue Book. From 2006 onwards, it published *Report on Advances in Geography* (2007), *Recent Progress of Geography in China: A perspective in the 21st Century* (English Version, 2008), *Report on Advances in Geography: Physical Geography* (2009), *Report on Advances in Geography: Human-Economic Geography* (2012) and *Report on Advances in Geography: Cartography and GIS* (2014). From 2002 onward, there were *Chinese Terms in Geography* (2006) and *Cross-strait Terms in Geography* (2011). These journals and monographs have played an important role in publicising geographical research progress, improving geographical research outputs and promoting discipline construction (see Fig. 3.8).

3.4.4 Science and Technology Award

The science and technology award is an important engine to promote the growth of talent and technological progress. Since 1991, the Society has established three individual awards for members and geographers, namely the National Young Geographic Technology Award, the National Outstanding High School Geography Educators Award and the Chinese Geographical Sciences Achievement Award. In total 128 people have received the first award, and the early winners have already gone on to become leaders in geographical research and in some cases are now academicians in Chinese Academy of Sciences. Almost 900 people have received the second award since 2001. These geographers are the lynchpin of basic geographical education and play an important role in strengthening it. The third is the highest award. It has been awarded to 47 people in 6 sessions since 2004. These winners are all geographers who have made great contribution to the development of the Geographical Sciences in China. These awards are not only a recognition of their outstanding achievements, but also inspire future generations to work harder to promote the development of the Geographical Sciences.

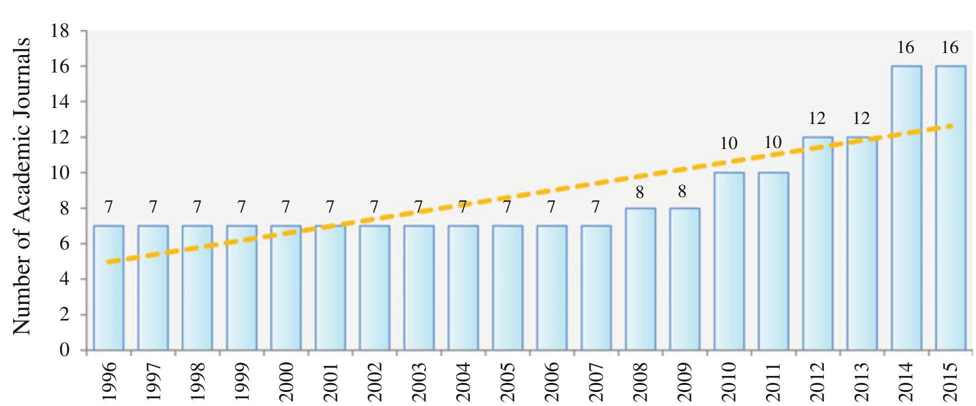


Fig. 3.8 Number of academic journals sponsored by the Geographical Society of China during the period 1996–2015

3.5 Summary

Thanks to constant investment in research and higher education by central and provincial government, the Geographical Sciences in China have made great progress. Between 1986 and 2015, the number and total value of NSFC Geographical Sciences funded projects were more than doubled in each 5-year period, and the average funding per project for major types of projects was more than 10 times the earlier figure. Excluding Hong Kong, Macau and Chinese Taiwan, 6893 people from 685 institutions in China's provinces, autonomous regions and municipalities directly under the Central Government have been supported in the past 30 years. Researchers from Beijing, Jiangsu, Gansu, Hubei and Guangdong accounted for 58.7 % of the total funded people and 68.8 % of the total funding. The number of funded institutions in 2015 was 6.7 times that in 2000 and 10.9 times that in 1986. Up to 2014, 816 faculties in 505 higher education institutions offered geographical related courses, and 165 faculties in 149 institutions had majors in the Geographical Sciences. Thirty three universities were involved in the Ministry of Education's 2012 curriculum assessment for Geography, of them one-half were "985 Project" and "211 Project" universities. They have obtained a large amount of research funding by virtue of the existence of large teams, comprehensive research orientations, strong research capabilities, and an absolute competitive advantage in research. The funding of these 33 universities shows that research which were reality-oriented and which explored scientific questions drove the development of Geographical Sciences; however, funding for education received only 6 % of the total. The establishment of the Geographical Society of China is closely related to the development of the Geographical Sciences. The Society now has more than 10,000 members and 48 branches. The Society also hosts 16 academic geography journals and grants three science and technology awards, building an advanced platform for communication in geography both at home and abroad, contributing to the training of talented people and the development of the Geographical Sciences in China.

Part II

Trends in the Development of the Four Branches of the Geographical Sciences

Abstract

Part II consists of four Chapters focusing on the achievements and development of the four branches of the geographical sciences, namely physical geography, human geography, geographical information science and environmental geography. The analyses examine the number of articles, high frequency keywords, research topics, Chinese research teams and NSFC funding and its effects. Based on statistics relating to publications and article citations in 307 SCI/SSCI mainstream journals, we have found that the international rankings of all four branches of the Chinese geographical sciences are rising. By analyzing the co-occurrence network of keywords in 118 SCI/SSCI mainstream journals and 29 Chinese (CSCD) core journals (Appendix C), this chapter identifies the distribution and evolution of research topics in each sub-disciplinary area in a series of 5- or 10-year periods in 1986–2015. The development of research topics is characterized by an emphasis on global/climate change and its regional response, social and economic changes and accompanying revolutions in social thought, advancement of earth observation technology driven by demand from the earth sciences, and the improvement of instrumental accuracy driven by environmental problems. Research in the geographical sciences in China has made many practical advances that have contributed to solving regional problems and serving national strategies, as well as closely connecting with international hot issues. There has been an increase in the share of applications and NSFC-funded projects for environmental geography and geographical information science and a decline in the share for physical geography. The per capita number of papers and the proportion of highly cited SCI/SSCI-indexed articles funded by NSFC grants for research in the geographical sciences have increased significantly in the last 10 years. The top 10 funded institutions and major research teams supported by NSFC geographical sciences grants are playing a more prominent international role in leading the development of the Chinese geographical sciences.

Keywords

Physical geography • Human geography • Geographical information science • Geographical sciences in China • NSFC geographical sciences

4 Physical Geography

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and Xianyan Wang

Abstract

Studies in physical geography aim to reveal characteristics of the natural environment, its evolution, and the geographical diversity of the earth surface. Research objects include the troposphere, hydrosphere, biosphere, and upper layer of the lithosphere. Physical geography under NSFC has several branches, including geomorphology, hydrology, applied climatology, biogeography, cryospheric geography, and integrated physical geography. Research on landscape, environmental change and prediction are also included in physical geography Analysis in this section is based on 134 SCI/SSCI mainstream journals of physical geography, of which 39 are comprehensive journals and 95 are specialised. In the past 30 years, with the promotion of many international major scientific programmes, research into physical geography in China has gradually developed a main line of research guided by global change and the comprehensive pattern of the earth surface. Frontier research in China has followed trending global topics in the water cycle and water resources, terrestrial ecosystems, LUCC, and cryosphere evolution. However, faced by regional environmental problems, Chinese scholars have done substantial research in permafrost engineering and the permafrost environment, natural hazards and risk, lake ecosystems and eutrophication, and ecohydrological processes and water resource utilisation in arid regions. In 1986–2015, the number of papers in physical geography has rapidly increased. The proportion of papers published by Chinese authors in the SCI/SSCI mainstream journals, has reached 12.9 % in the last 5 years. The per capita publication figure is 5.3, 2.1 times that of 10 years ago. Average citations of the top 100 highly cited papers of each country in the SCI/SSCI mainstream journals show that the rank of China has risen to 8. As to the role of NSFC funding, 76.4 % of the SCI/SSCI-indexed articles and 73 % of the CSCD-indexed articles published by Chinese authors in the past 10 years are supported by NSFC projects. Of the top 50 highly cited papers in SCI/SSCI journals published by Chinese authors in 2010–2014, 85.6 % are supported by NSFC projects.

Keywords

Physical geography • Research topics in physical geography • NSFC-funded projects for physical geography • Chinese scholars and institutions of physical geography

Studies in physical geography aim to reveal characteristics of the natural environment, its evolution, and the geographic diversity of the earth surface. Research objects include the troposphere, hydrosphere, biosphere, and upper layer of the lithosphere. In practice, the objects could be a certain environmental element, such as geomorphology, hydrology, climate, biology and soil, a natural complex such as landscape or a land unit, or they could be typical objects such as the cryosphere. Physical geography under NSFC has several branches, including geomorphology, hydrology, applied climatology, biogeography, cryospheric geography, and integrated physical geography. Research on landscape, environmental change and prediction are also included in physical geography. Regional environmental quality, safety

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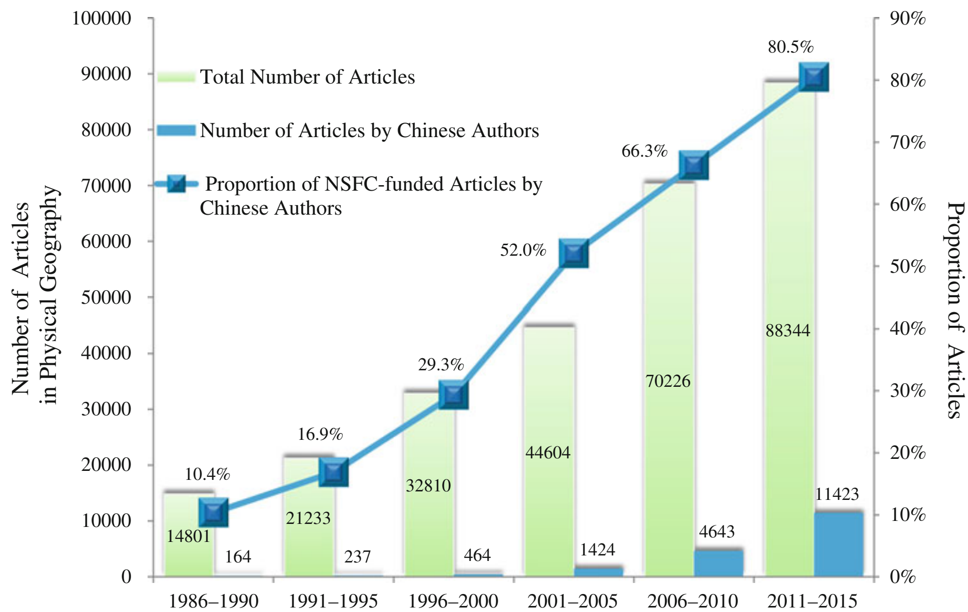


Fig. 4.1 Number of SCI/SSCI-indexed articles and proportion of NSFC-funded articles by Chinese authors in physical geography during the period 1986–2015

and natural resource management are part of environmental geography, but they are also closely related to physical geography. Analysis in this section is based on 134 SCI/SSCI mainstream journals of physical geography, of which 39 are comprehensive journals and 95 are specialised.

Figure 4.1 shows the number of articles published in 134 SCI/SSCI mainstream journals and the contribution of Chinese authors during the past 30 years. Overall, 272,018 articles were searched (some journals before 1990 are not indexed in Web of Science database), of which 58.3 % were published in the last 10 years (2006–2015). Chinese authors contributed 18,355 articles (6.8 %), and 87.5 % were published in the last 10 years. They contributed 10.1 % of total articles in the last decade, and 12.9 % in the last 5 years. The number of NSFC-funded papers was 13,206, and 92.9 % were published in the last decade. The proportion of research funded by NSFC in the past 30 years is 72 %. This is smaller than the 29.3 % before 1996–2000, but rapidly increased to 52 % in 2001–2005 and 80.5 % in the last 5 years. Data from Fig. 4.1 suggest that NSFC has had an increasingly important role in supporting exploration of the frontiers of physical geography.

Figure 4.2 shows the total number and NSFC-funded articles in the 19 core Chinese journals over the past 30 years. The 19 journals are *Journal of Glaciology and Geocryology*, *Resources and Environment in the Yangtze Basin*, *Scientia Geographica Sinica*, *Acta Geographica Sinica*, *Geographical Research*, *Areal Research and Development*, *Quaternary Sciences*, *Journal of Lake Sciences*, *Chinese Science Bulletin*, *Acta Ecologica Sinica*, *Advances in Water Science*, *Chinese Journal of Applied Ecology*, *Scientia Sinica Terrae*, *China Population, Resources and Environment*, *Journal of Desert Research*, *China Land Sciences*, *Resources Science*, *Journal of Natural Disasters*, and *Journal of Natural Resources*. There were a total of 26,369 Chinese articles, 54 % of which were published in the last decade. NSFC-funded papers were 16,288 in number, and 63.8 % of those were from the last decade. The proportion of NSFC-funded papers in the past 30 years is 61.8 %, less than the 45.8 % before 1996–2000; this increased rapidly to 68 % in 2001–2005 and reached 73.5 % in the last 5 years. These data indicate that research output from physical geography published in the Chinese language had been rapidly increasing and that NSFC had a major research role. In addition, the citation of papers in the core Chinese journals indicates that NSFC-funded papers had always had more citations than non-NSFC-supported papers in each 5-year period over the past 30 years, with an average citation number of 23.4, compared with 9.4 for non-NSFC-funded papers. This suggests that NSFC-funded research had greater quality and had attracted more attention.

Table 4.1 shows average citations of the top 100 highly cited papers in the SCI/SSCI mainstream journals of physical geography, which representing the top research results of each country/region listed. China was among the top 20 countries in the past 30 years, with an increasing ranking

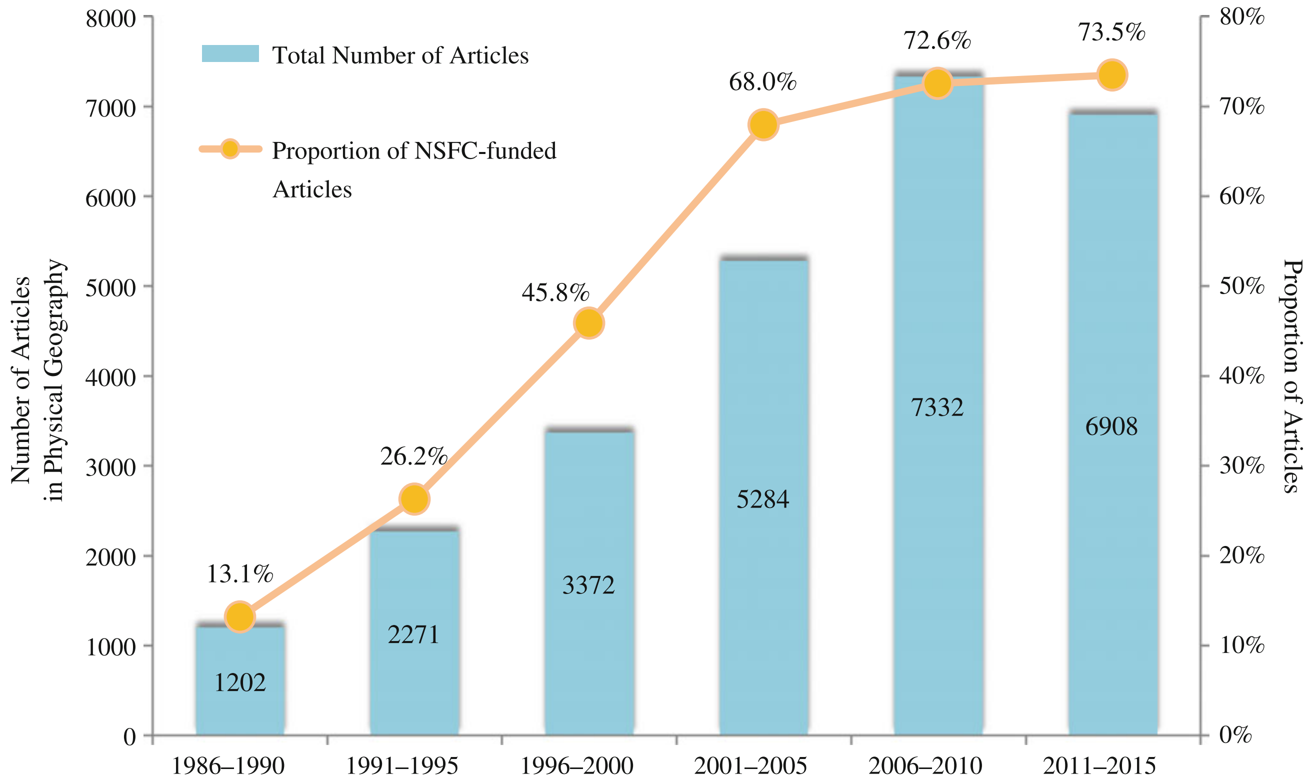


Fig. 4.2 Number of CSCD-indexed articles and proportion of NSFC-funded articles in physical geography during the period 1986–2015

from 17th in 1986–1990 to 10th in 2006–2010 to 8th in the last 5 years. The gap in average citations narrowed compared with Germany, Britain, Australia, Netherlands, Canada and France, but remained wide compared with the leader, the United States, which had an average citation number equalling the sum of Germany and Britain. If the average citation number of all published papers was considered, for China this equalled 17.2, 26.4 and 12.4 in 1986–1990, 1996–2000, and 2006–2010, respectively, which was much smaller than corresponding average numbers for the top 20 countries (29.3, 34.3, and 17.5). The ranking of China was only higher than that of Japan, Brazil, and Chinese Taiwan. This situation clearly shows that research done by Chinese geographers did not attract substantial attention from international colleagues.

4.1 General Characteristics of the Research Topics Over the Past 30 Years

This section focuses on the major topics indicated by keywords from papers in the SCI/SSCI mainstream journals and CSCD core Chinese journals over 1986–2015. The co-occurrence of major topics (keywords) was analysed to show a general pattern of research in physical geography.

Figure 4.3 shows the general pattern of co-occurrence of major research topics. These topics in the past 30 years were in the fields of earth surface patterns, biological processes, carbon cycle, physical processes, vegetation–water interaction, and the Quaternary environment. China had received much attention as a research region. (1) For research on **earth surface patterns**, major topics included not only landscape patterns driven by climate change, but also environmental change or degradation indicated by land-use and landscape types. (2) For **biological processes** research, popular topics were the distribution and diversity of organisms at scales of community, population, and species, which revealed the response and adaptation of biodiversity to climate change. Another topic was the interaction of plants and temperature, revealing the response and adaptation of vegetation to climate change. In addition, researches into ecosystem or diversity conservation (indicated by keywords *conservation*, *conservation biogeography*, *soil conservation*, *nature conservation*, and *conservation planning*) have linked biology to geography, soil, and human activities. (3) Research on the **carbon cycle** had focused on the impact of atmospheric carbon dioxide (CO_2) concentration on air temperature (CO_2 enrichment), plant growth, and grain yield. In addition, *carbon* as a keyword also had high co-occurrence frequency with several other keywords such as *soil, forest, ecosystem, vegetation*, and *land-use change*,

Table 4.1 Top 20 countries (regions) of average cites per paper for highly cited SCI/SSCI-indexed articles in physical geography during the period 1986–2015

Rank	Countries (Regions)	1986–1990	1991–1995	1996–2000	2001–2005	2006–2010	2011–2015
1	USA	410	538.9	570.7	459	331.7	72.4
2	Germany	77.5	119.1	169.2	192.5	143.1	40.2
3	UK	187	225.1	312.3	277.3	173.2	39.4
4	Australia	141.3	162.9	183.5	178	140.5	34.5
5	Netherlands	88.3	133.1	149.5	146.3	93.3	29.4
6	Canada	139.7	175.3	209.5	177.4	116.5	28.6
7	France	105.8	147.7	151.2	148.5	127.6	28.2
8	China	27.5	55	79.6	91.7	87	27
9	Switzerland	43.1	81.2	153.4	135.7	101.7	26.1
10	Spain	27.1	65.7	103.5	116.9	98.4	26.1
11	Italy	29.2	64.7	93.3	92.1	76.1	22.1
12	Sweden	89.9	107.5	127.5	125.4	76.8	19.9
13	Belgium	28.1	55.3	100.7	92.8	59.6	16.7
14	Norway	52.2	75.8	101.2	82.8	46.8	16.2
15	Japan	30.1	53.9	67.8	73.7	56.1	15.2
16	Austria	20.9	19.3	39	57.2	50.9	14.8
17	Denmark	49.6	84.6	94.6	88.8	65.3	14.8
18	India	22.6	41.5	47.3	55.1	41.8	13.4
19	Brazil	37.7	43.8	68.5	71.7	53.7	12.7
20	Taiwan, China	41	20.1	27.1	36.4	30.3	12.1

Note Top 20 countries (regions) were selected based on average cites of the top 100 highly cited articles in each county (region) out of 25 countries (regions) with the largest number of articles from the 134 SCI/SSCI mainstream journals in physical geography; that is, total cites of the 100 articles were divided by 100, with listing by descending order for the period 2011–2015 in the last column

strongly indicating that research on *carbon* in physical geography has involved various ecosystems. (4) For research on **physical processes, earth surface processes driven by precipitation** had received the most attention. These processes included erosion, hedgerows, bedload transport, and suspended sediment. There had been interdisciplinary research between fluvial geomorphology and hydraulic geometry. There had also been research into salt weathering, which is a physico-chemical process driven by evaporation (mainly in arid areas), and photosynthesis, which was a biochemical process driven by radiation. (5) In research on **vegetation–water interaction**, there was a lack of keywords associated with "vegetation" and "water," because these two keywords were extremely frequent (Fig. 4.3). In combination with the frequency of clustered keywords, we found that *runoff* and *infiltration* were the major keywords in vegetation–water research. Runoff production and infiltration under various types of vegetation and soil directly influence the accuracy of hydrologic simulation models for hydrologic processes. (6) In **Quaternary paleoenvironmental** research, the Holocene was an important period. For this period, *vegetation*, *lake basin*, *sediment*, (Chinese) *loess* or *Loess Plateau*, *cave stalagmite*, and *glacier* (or *ice core*) were the major research subjects. *Pollen* and *tree ring* were two common indicators in environmental change research, and *stable isotope* was also an important proxy for paleoclimate. In addition, chronology technologies such as *thermoluminescence* and *optically stimulated luminescence* had been focuses for many years. (7) In all **targeted geographic regions**, *China* had the highest word frequency, closely associated with climate change, natural disasters (including *debris flow*, *earthquake*, and *hazard assessment*), and the Qinghai-Tibetan Plateau (*Tibetan Plateau*, *Qinghai*). Antarctica (including *Antarctica*, *the Antarctic Peninsula*, and *Antarctic ice sheet*), the Arctic (*Arctic Ocean* and *Arctic tundra*), and the North Atlantic (*North Atlantic*, *North Atlantic Oscillation*, *North Atlantic Ocean*, and *North Atlantic climate*) had also attracted widespread attention.

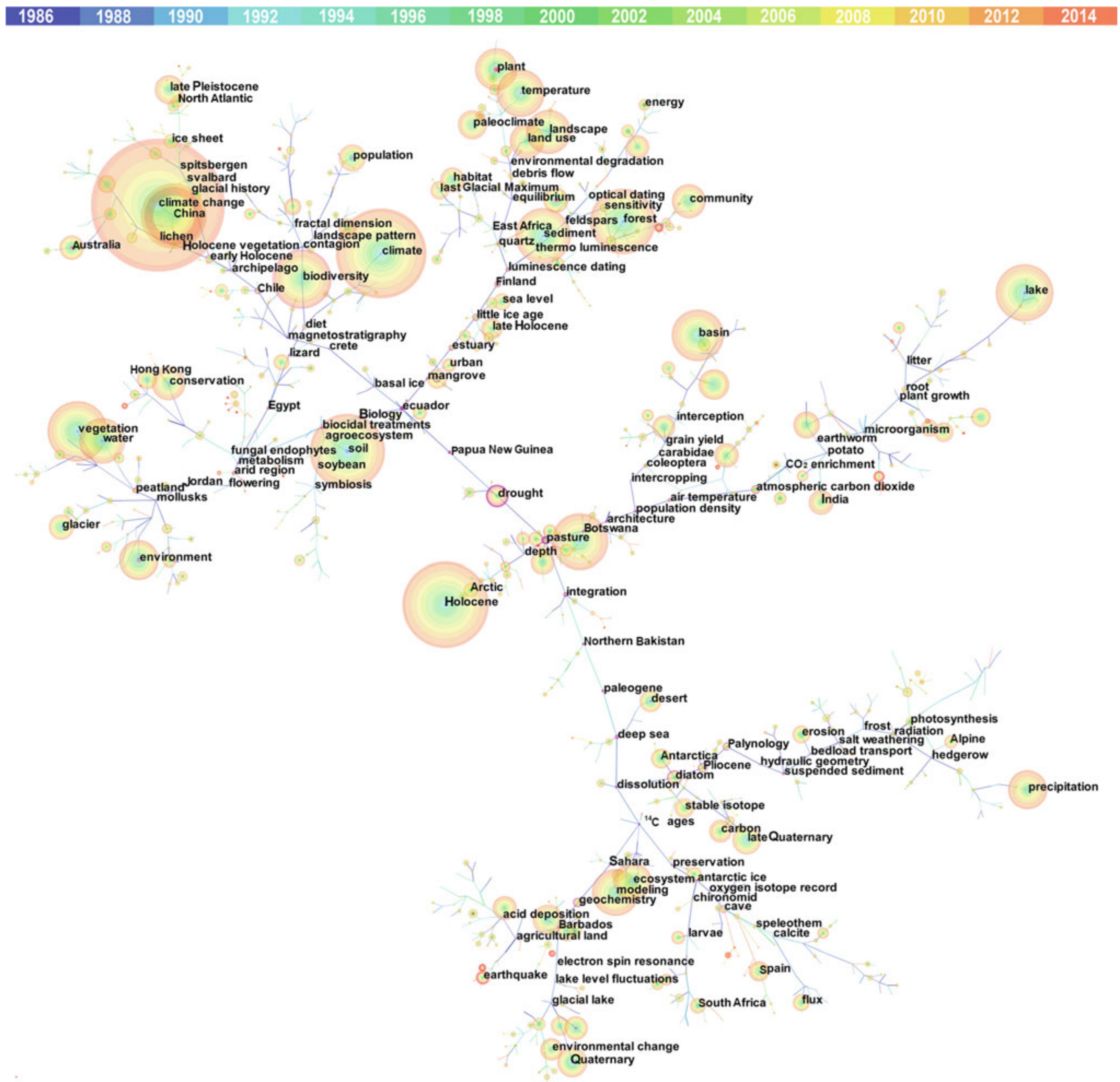


Fig. 4.3 Co-occurrence network of keywords in SCI/SSCI mainstream journals of physical geography during the period 1986–2015

Figure 4.4 shows research keywords in the core Chinese journals over the past 30 years, including not only problem-driven topics, such as *climate change*, *land use*, *water resources*, and *natural hazards*, but also regional physicogeographical units such as *China*, *Tibetan Plateau*, *Taihu Lake*, and *Loess Plateau*. There were also frequent topics regarding methods and approaches such as *remote sensing*, *GIS*, and *model simulation*. These research topics or research-targeted regions were situated as central nodes of the co-occurrence network, indicating a certain degree of balanced research between problem-driven and region-based research in China. Colour patterns in Fig. 4.4 show that in the last three decades, the most popular research topics began to emerge in the last 10–15 years. Some of the early major issues such as *sustainable development*, *paleoclimate*, and *environmental evolution* have begun to decline in interest. Several features can be summarised from the cluster pattern. (1) Research into **global change** mainly focused on changes of evapotranspiration and runoff driven by temperature and precipitation change, and on simulations of hydrologic processes, particularly in arid and cold regions. For example, the *SWAT model* appeared in 2004. Natural

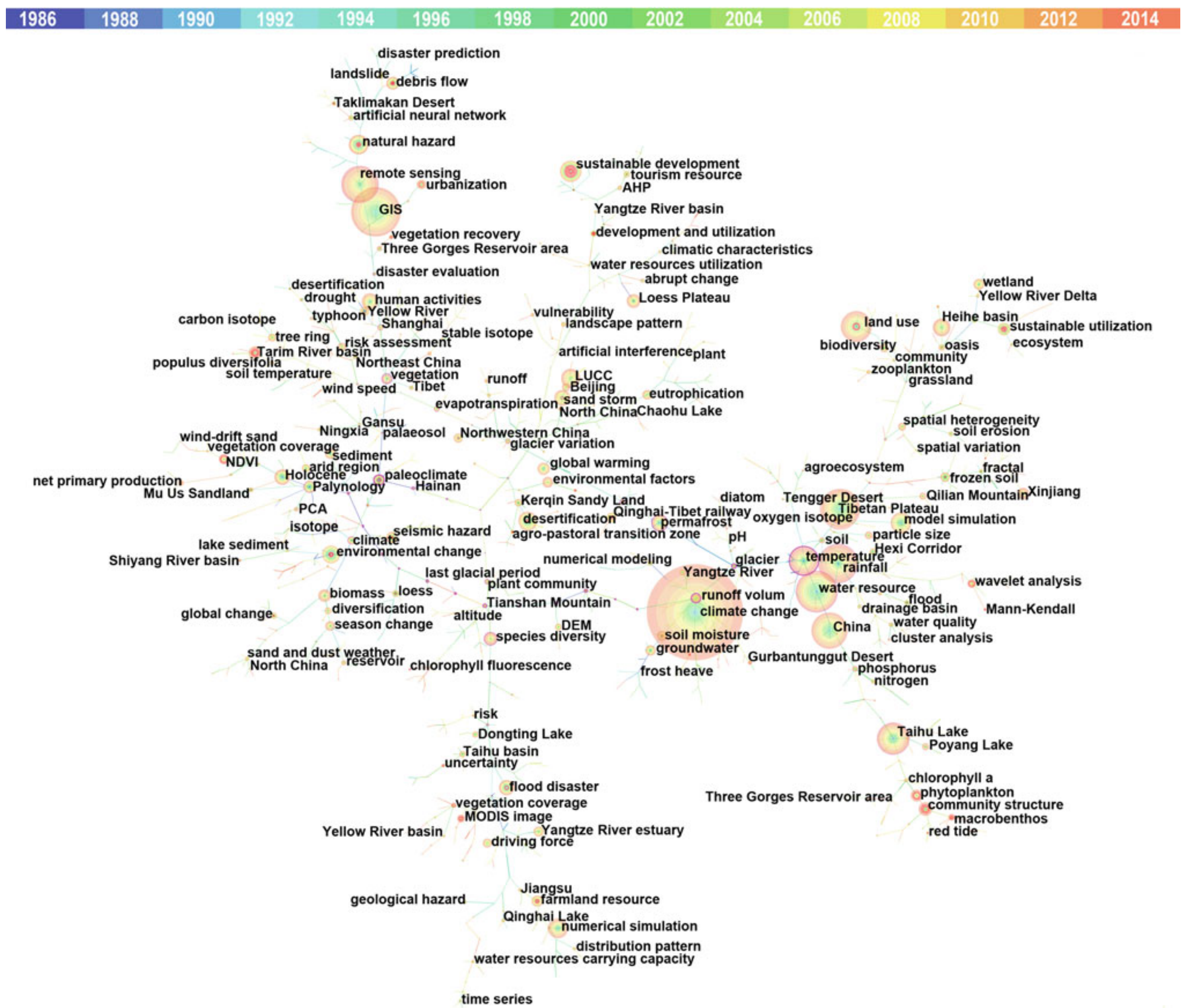


Fig. 4.4 Co-occurrence network of keywords in CSCD journals of physical geography during the period 1986–2015

hazards related to global warming, including glacier variation, geologic hazards, climate change, and related droughts and floods, were also a focus. (2) Research on **water resources** focused around keywords of *water resources*, *China*, and *sustainable utilisation*, highlighting tremendous concern for these subjects. Major impacts on water resources in China include *vulnerability* under *climate change*, *land management*, *south-to-north water diversion*, and *the return* of *farmland* to *forest* or *pasture*. Negative effects of water utilisation mainly included land degradation and desertification. In terms of water utilisation, the *North China Plain* and *north western arid area* were frequently researched regions. The research content mainly involved water resource *carrying capacity*, *virtual* water, *water footprint*, *ecological water demand*, and *water use efficiency*, indicating interactions among water resources, ecology, and economy. (3) Research on **land** within physical geography in China comprised *land use* as well as *land-use* and *land-cover change* (*LUCC*). Remote sensing is commonly used to study the spatial distribution and dynamic change of land use, and has also been used to analyse the relationship between land use and desertification or soil loss. *The agriculture-pasture ecotone* had been the focus of much concern. Land-use/land-cover change (LUCC) had mainly centred on *spatial heterogeneity*, *driving factors*, impacts on *soil moisture* and *nutrients*, *landscape patterns*, *plant diversity*, *water* and *soil conservation*, and *ecosystem services*. Major research methods are experiments in small watersheds, geostatistics, and scenario simulation. *The loess hilly-gully region* had also seen substantial research. (4) Research into **natural hazards** differed from that in international studies. This topic included research on *floods*, *typhoons*, *rainfall*, *hail*, *ice floods*, *thunderstorms*, *droughts*, *fires*, *sand dust*, *freeze injury* (*cold spells from low temperature*), *earthquakes*, *debris flow*, *landslides*, *abrupt change of climate*, and *extreme weather*. Accordingly, the research focus has gradually changed from single geological or climatic hazards to complex hazards, climate change, and extreme weather caused by global change. Remote sensing and GIS are the two major approaches to studying natural hazards. The research topics of *hazard processes*, *risk assessment*, *risk zonation*, *loss evaluation*, *hazard reduction mitigation*, and *hazard prediction* indicated the research directions of reduction–prediction–risk as well as a focus change from a hazard itself to human–economy–society. This change fitted the scientific development rules of our perception of hazards and long-term precautions against them and their amelioration. (5) **Environmental change** research had focused on timescales of the *Quaternary*, *late Pleistocene*, *Holocene*, last glacial, and historical periods. The major objects had been *vegetation*, *geomorphology*, *paleosol*, *lacustrine sediments*, and *Quaternary glaciations*. Important environmental indicators included *pollen* (*spores*), *tree rings*, *ice cores*, *stalagmites*, *magnetic susceptibility*, and *particle size*, which were used in paleovegetation, paleoclimate and paleofloods. *Isotopes* (*oxygen* and *carbon*) and *chronology* (mainly *radiocarbon* ^{14}C and *optical luminescence dating, OSL*) were also important methods. The *Tibetan Plateau*, *Loess Plateau*, *Xinjiang*, *Inner Mongolia*, *Qinghai*, *middle and lower reaches* of *the Yangtze River*, and *Yunnan-Guizhou Plateau* were regions where samples had been collected. The Tibetan Plateau was not only a priority region in the study of paleoclimate and environmental change but also a focus of global change research, because it was important for large-scale climate models and climate change simulations. Therefore, the cluster shows that the *Tibetan Plateau* had a close relationship with *temperature*, *precipitation*, *climate reconstruction*, *glacier change*, *global warming*, and *ENSO*. (6) There were **other prominent issues** discussed in Chinese articles, such as ecosystems of *Taihu Lake* and its impact on the *Yangtze River basin*, the water environment, *biodiversity*, *nature conservation*, change of *permafrost* under climate change, and the construction of railways and highways.

4.2 Change of Research Topics in Various Periods

In the following sections, change of major research topics internationally and in China as indicated by papers in SCI/SSCI journals was analysed and compared at a 5-year (or 10-year) interval over the past 30 years.

4.2.1 Period of 1986–1995

Figure 4.5 shows research topics in SCI/SSCI mainstream journals over 1986–1995. This period was the beginning of research into single physical geography elements and global change. During the period, research on individual elements, such as *soil*, *climate*, *geomorphology*, *water and vegetation*, as well as *environmental change* based on *sediments*, had a large proportion that increased. Branches of physical geography such as *geomorphology*, *biogeography*, *paleogeography*, *paleoecology*, *landscape ecology*, *ecology*, and *phenology* are thematic words but lack organic links. The cluster graph in Fig. 4.5 illustrates several points. (1) Climate and vegetation had gained more attention than other elements since 1991. In the same period, carbon and carbon dioxide had emerged as research topics. (2) *Soil* had the highest frequency in this period and was associated with *land use*, *soil loss*, *deforestation*, and *forestry*, indicating a close relationship. (3) The study of plant geography had focused on the relationship between vegetation and soil, in addition to traditional aspects of succession, vegetation–environment relationships, and growth. Spatiotemporal patterns of forest and desert ecosystems had also seen development. At the same time, landscapes were an emergent topic in vegetation research. Europe was a major area for vegetation research, and landscapes and ecology had seen an explosion in the first half of the period. (4) Climate change and its impact plus the carbon cycle had materialised as new research directions but still lack interaction with the traditional climatology within physical geography. (5) Early attention was given to high-resolution research into environmental change. New technologies in dating such as the accelerator mass spectrometer began to be used in research. During the subject period, research into environmental change concentrated on high latitudes of both northern and southern hemispheres, such as northern Europe, Antarctica, New Zealand, and South America. There was no particularly dominant theme in research on global change, but it clustered around *sea ice*, *Antarctica*, *Younger Dryas*, and *biostratigraphy*, indicating a focus on paleoclimatic history or events. *Climate* was clustered around *tropical forest*, *coastal dunes*, *coral*, *fishery*, and *sediments*, signifying that climate had a close relationship with these subjects. (6) Regional studies were mainly in Europe, North America, Australia, and Antarctica and its islands. Research in China began to increase but lacked a clustered topic.

Research topics retrieved from the core Chinese journals of the same period (1986–1995) shows an overall pattern of research in China over the past 30 years (Fig. 4.6). (1) Keywords of *climate change* and *carbon dioxide*

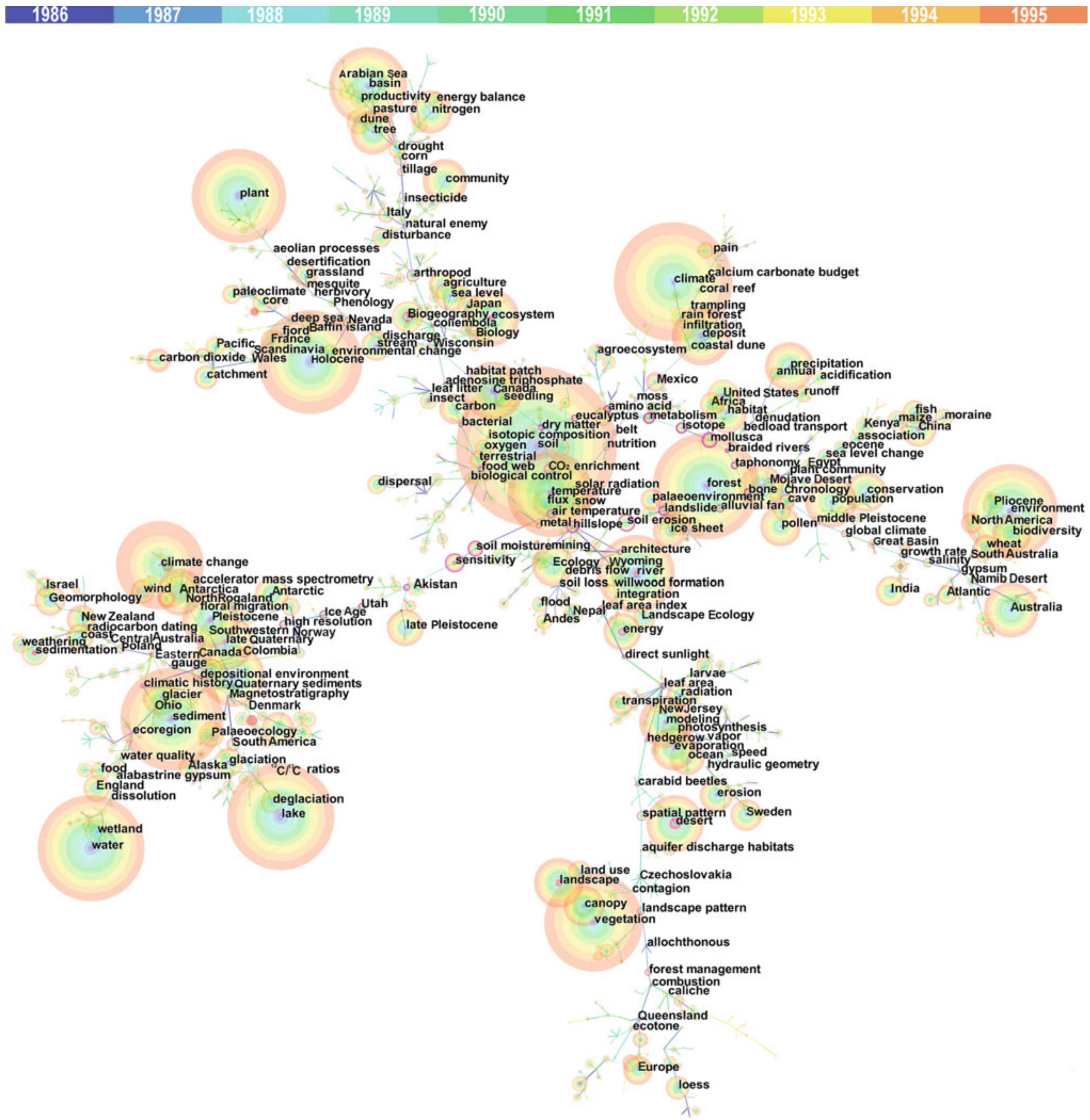


Fig. 4.5 Co-occurrence network of keywords in SCI/SSCI mainstream journals of physical geography during the period 1986–1995

appeared in 1987, but substantial research progress was not made until 1990. This gradually evolved to a node with strong clustering in the subsequent 10 years. Research topics included **climate change** relative to *desertification, glacier mass balance, seasonal frozen soil/permafrost*, and *sea level rise*. *China Antarctic Great Wall Station* appeared in 1993 as a keyword, and *Antarctica* in 1995. (2) Research on **natural hazards** became a popular topic after the keyword *natural hazard* appeared in 1991 as a strong focus. Major research objects included *floods*, *thunderstorms*, *typhoons*, *fire*, *earthquakes*, *debris flow*, and *landslides*. *Disaster evaluation* plus *disaster prevention* and *reduction engineering* were also major topics. (3) There was a burst of ***paleoclimate*** and *late Pleistocene* in 1987, and these continued to be keywords with high centrality in the subsequent 10 years. Timescales included the *Holocene*, *late Pleistocene*, and *last glacial*. *The Loess Plateau*, *Mu Us Sandland*, *Aibi Lake, Hulun Lake*, *Yellow River Delta*, *Jianghan Plain*, and *Liaodong*

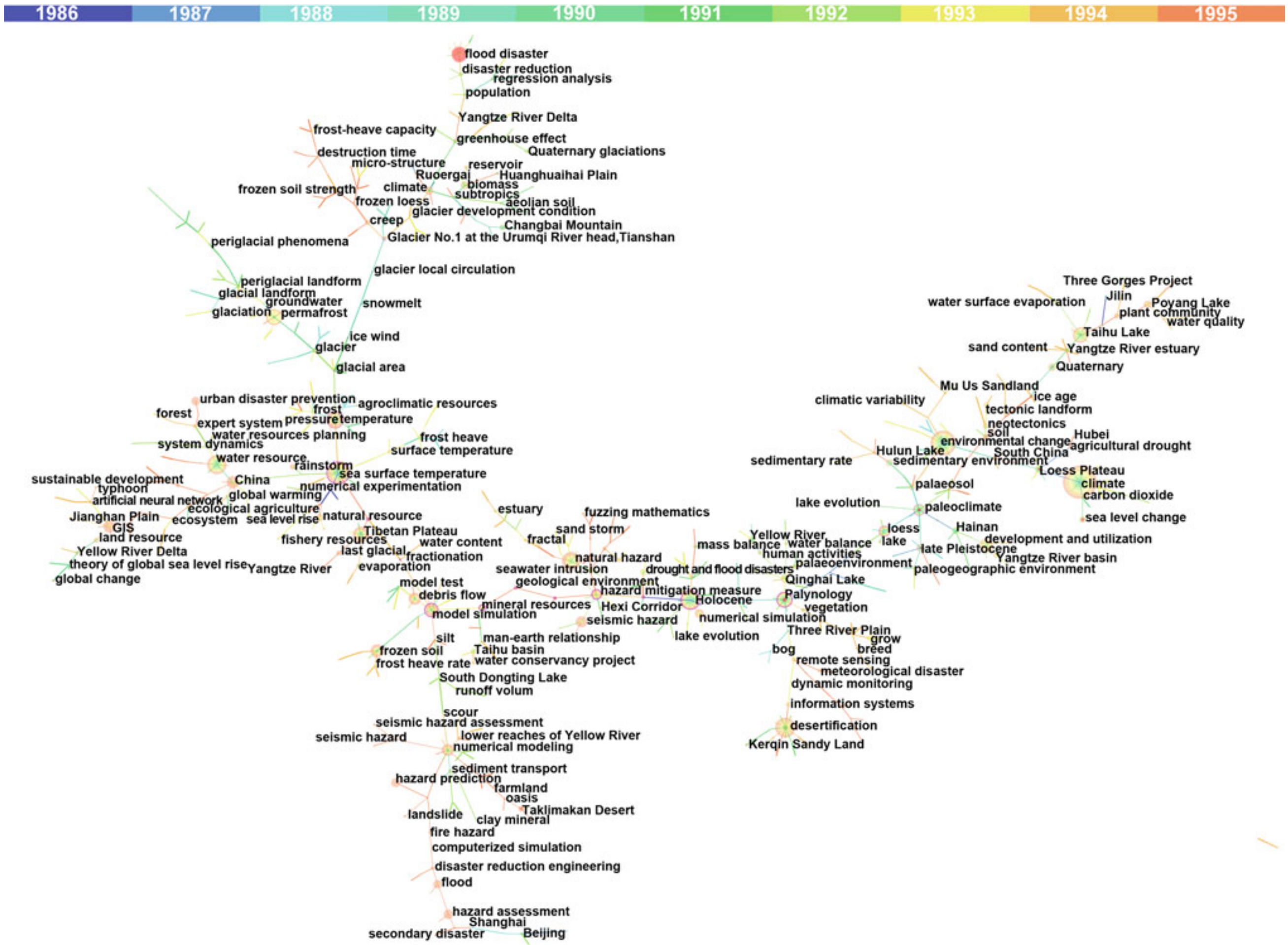


Fig. 4.6 Co-occurrence network of keywords in CSCD journals of physical geography during the period 1986–1995

Peninsula were regions where samples were concentrated. Paleoclimate reconstruction was based on proxies from loess and lake sediments and ice cores. The keyword *loess* appeared in 1987, *pollen* in 1990, and *ice core* in 1992. Research on the Tibetan Plateau focused on permafrost and Quaternary glaciers. (4) *Taihu Lake* appeared in 1987 with high frequency and *Poyang Lake* in 1992, mainly in research on **wetland plant communities** and **water surface evaporation**. *Three Gorges Project* appeared in 1991, but then only four times in total in the 5-year period. (5) **Water resource** appeared in 1989 in research related to droughts, floods, and agriculture. Attention was paid to the influences of climate change on permafrost and seasonal frozen soil of the Tibetan Plateau.

Figure 4.7 shows a comparison of prominent keywords in SCI/SSCI journals used by Chinese authors and others. In the decade shown (1986 to 1995), the 15 keywords with highest frequency use by foreign authors covered the research area of global change and climate (*climate change, carbon dioxide,* and *climate*), ecology (*landscape ecology*, *biogeography*, *biodiversity*, *disturbance*, and *conservation*), geomorphology, and paleoenvironment (*the Holocene*). Additionally, attention was paid to methods and technologies for data analysis (*modelling*, *remote sensing*, and *geographic information system* or *GIS*). Regional studies focused on Antarctica and Australia. There was a rapid increase in the frequency of keywords including *carbon dioxide*, *climate change*, *modelling*, and *the Holocene*. Of the most frequently used 15 keywords by Chinese authors, only *geomorphology* had a similar frequency to that used by foreign authors. In general, the top 15 keywords used by Chinese authors reflected the prevalent topics, including China (*China* and *Inner Mongolia*), sustainable development of resource and environment (*sustainable development, environment*, *sustainability*, *resource*, and *development*), sedimentology and geomorphology (*sand dune*, *sedimentology*, and *geomorphology*), storm surges, biology-soil processes and ecosystems (*grassland*, *primary productivity*, and *soil water*), and numerical simulation. Only *geomorphology*, *sustainable development*, and *grassland* had a frequency in excess of 10, indicating that other research topics of interest to Chinese authors were not very common during this period.

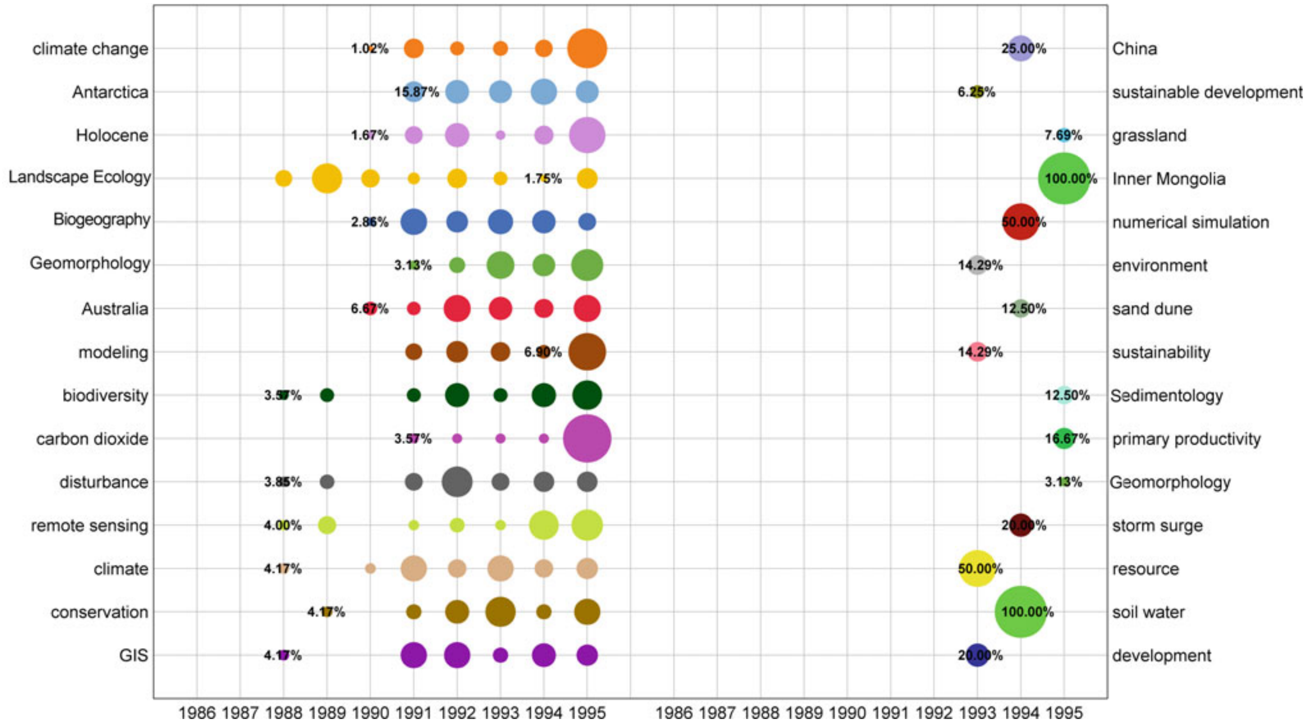


Fig. 4.7 Comparative diagram of prominent keywords by Chinese authors and others in SCI/SSCI mainstream journals of physical geography during the period 1986–1995. *Note* Right panel shows keywords used by Chinese authors and left panel shows those used by the authors from other countries (regions). Size of circles represents the proportion of keyword frequency in a single year to its total frequency in 1986–1995. Each keyword has the same colour. Keywords are listed in descending order according to their total frequencies in the above period

4.2.2 Period of 1996–2000

Figure 4.8 shows research topics in the SCI/SSCI mainstream journals over 1996–2000. This was a period of research into physicogeographical processes centred on global change. **First**, there were close relationships among climate change, vegetation dynamics, and the carbon cycle within ecosystems. Since 1996, *climate change* had become the most frequent keyword, followed by *the Holocene*, *climate*, *soil*, *forest*, *vegetation*, *sediment*, *biodiversity*, and *lake*. Research on global change during this period were centred on paleoclimate and past environmental change, with timescales concentrating on the late Quaternary, the last glacial maximum, and the Holocene. Paleoclimate and paleoenvironment were reconstructed through sediments from lakes, glaciers, and the ocean, with proxies such as pollen (spores). The keyword *temperature* was very popular and was used in ~ 1 % of all published papers. Isotopes received attention in research on the paleoenvironment and modern ecological carbon cycle. Research into vegetation dynamics was associated with that on plant growth and productivity, and was also related that on carbon and nitrogen in ecosystems. Accordingly, research on forests (especially tropical forest, where carbon flux is strong) increased rapidly. There was modelling work centred on the carbon–moisture balance in individual trees, reflecting the contribution of vegetation to climate change. **Second**, ecology and biogeography increasingly merged, with a concentration of research in the field of landscape patterns, community diversity, and ecological conservation, which were all major research issues of earth-surface ecological processes. Research on landscape ecology and biodiversity conservation developed vigorously during this period. **Third**, as research into soil is closely linked to that into water, soil-water loss related to land-use change was a principal research field during the period. **Finally**, research in regional geography still focused on North America, Europe, and Oceania, but that on Africa, South America, and Asia increased substantially, indicating a multi-regional trend.

Figure 4.9 shows dominant research topics in the core Chinese journals for 1996–2000, which reflected development of the previous period (1986–1995). (1) Research on **global change**, **paleoenvironment**, **and the Tibetan Plateau and Loess Plateau** began to be combined. The keyword *Loess Plateau* was frequent in 1998, and *paleoclimate*, *environmental change*, *climate warming*, *global warming*, *temperature*, and *precipitation* became keyword nodes with high centrality. *Temperature*, *precipitation*, and *runoff* were closely related. Climate change related to desertification and glacier mass balance remained important research themes.

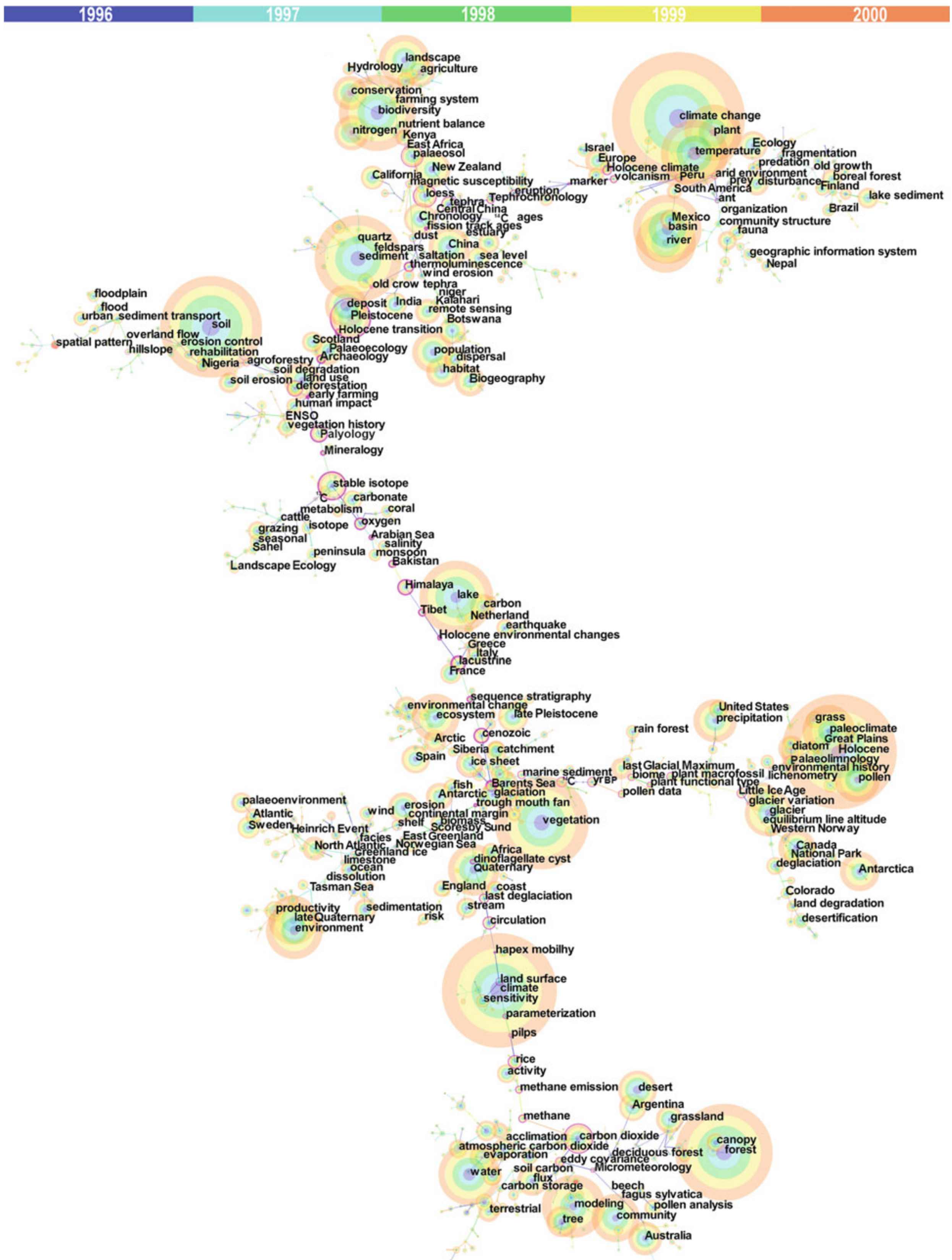


Fig. 4.8 Co-occurrence network of keywords in SCI/SSCI mainstream journals of physical geography during the period 1996–2000

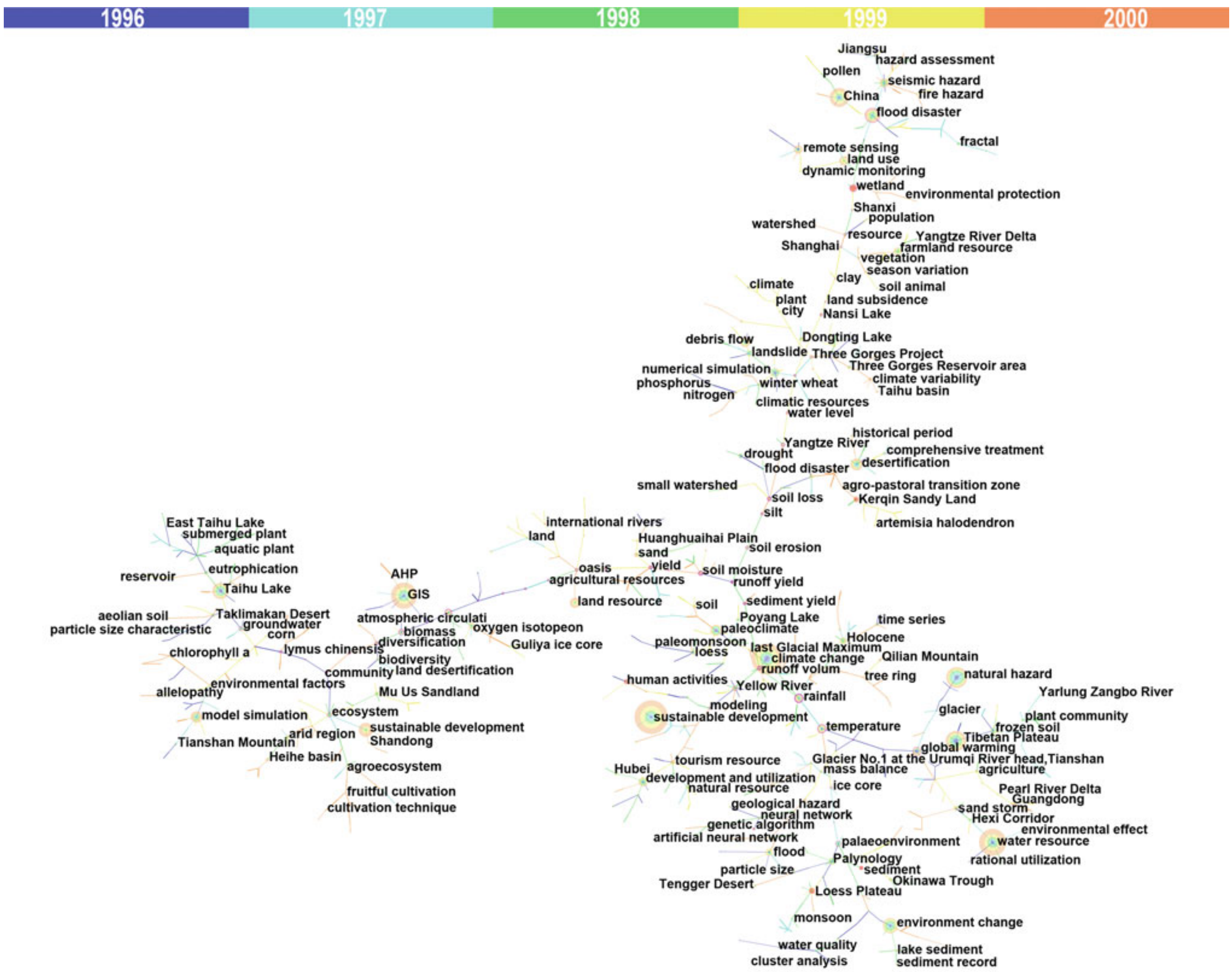


Fig. 4.9 Co-occurrence network of keywords in CSCD journals of physical geography during the period 1996–2000

Pollen and *grain size*, as two important paleoenvironmental proxies, occurred simultaneously with *oxygen isotope* in 1996. As critical progress in paleoenvironmental research of the Tibetan Plateau, *Guliya ice core* and *Dunde ice core* appeared in the co-occurrence network of keywords in 1999. Periods of this research concentrated on the *Quaternary* and *historical period,* which appeared in 1998, and the *late Pleistocene* remained frequent. (2) Research on **water resources** began to be linked to evapotranspiration and other hydrologic processes, and reasonable utilisation of water resources also became an important research topic. (3) **Land use** appeared in 1997, and attention was devoted to dynamic monitoring of land use by remote sensing, land use, and sustainability, and land use in natural reserves. (4) Research into **natural hazards** continued to receive attention, with many studies on *floods* in the *Huaihe River basin*. There was research into the relationship between floods, climate variation and the East Asian monsoon. Methods related to hazards research, such as fractal, neural network and genetic algorithms also began to be used. (5) Research on Taihu Lake began to centre on **species diversity and population dynamics**. S*hallow lake* appeared in 2000 as a keyword and lake hydraulics began to be emphasised. Although *Three Gorges Project* had some centrality, its total frequency was only four times in 5 years. (6) *Wetland* appeared in 1998 and was very frequent. Research in this field was mainly in the Yellow River and Liaohe River deltas and middle and lower reaches of the Yangtze River, focusing on **biodiversity and wetland resources**.

Figure 4.10 shows a comparison of major issue keywords in SCI/SSCI journals used by Chinese authors and others during 1996–2000 (the diagram description see the note of Fig. 4.7). There was a significant increase in both the number of published papers and total keyword frequency, and a slight increase in the frequency of the top 15 keywords used by Chinese authors. In this 5-year period, frequencies of the top 15 keywords used by foreign authors were all greater than 75. Compared with 1986–1995, high-frequency

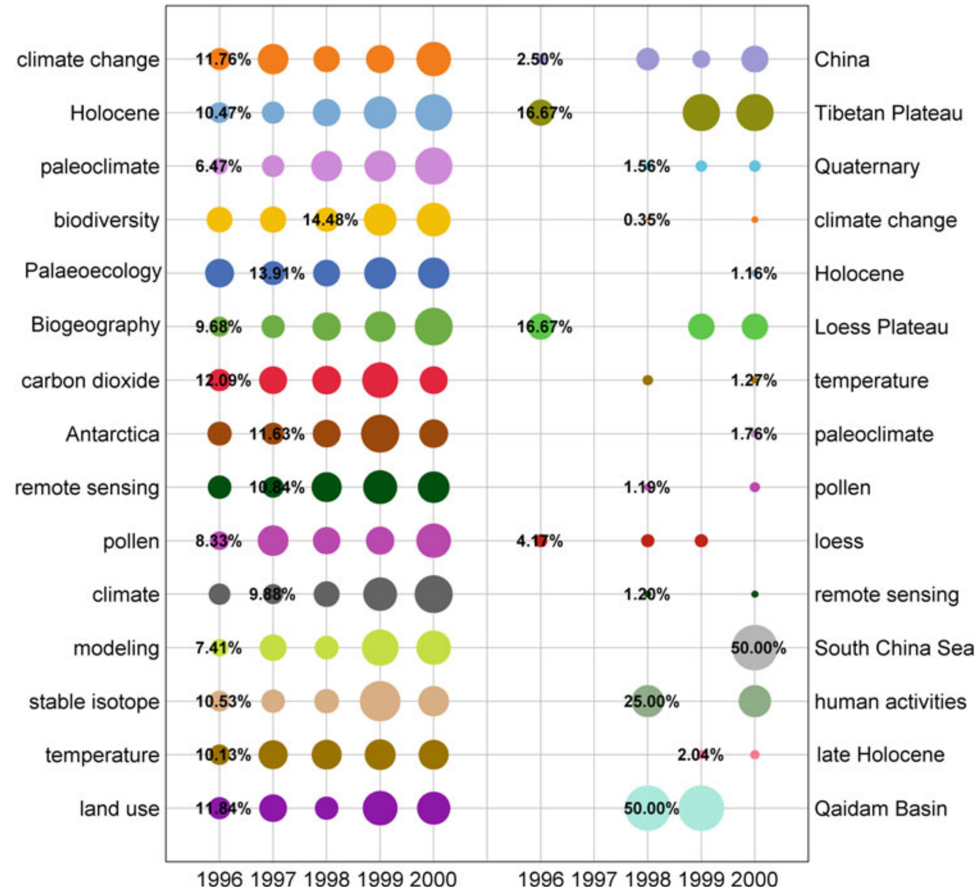


Fig. 4.10 Comparative diagram of prominent keywords by Chinese authors and others in SCI/SSCI mainstream journals of physical geography during the period 1996–2000

keywords reflected that prominent research topics included the following characteristics. Global change, especially the Holocene paleoclimate and paleoecology (indicated by keywords *climate change*, *Holocene*, *paleoclimate*, *Paleoecology*, *carbon dioxide*, *pollen*, *climate*, and *temperature*) were of further concern. Isotopes continued to be an important proxy (*stable isotope*), and research on biodiversity and its geographical distribution became more important (*biodiversity*, *biogeography*). Research on land use became a popular topic (*land use*). Remote sensing and simulations (*remote sensing*, *modelling*) and Antarctica were still frequent research topics. Judged by growth rates of the top 15 keywords used by Chinese authors, all 15 increased, among which *paleoclimate*, *biogeography*, and *stable isotope* increased slightly faster. An obvious change during this period was that six of the top 15 keywords used by Chinese authors overlapped those used by foreign colleagues, indicating that the Chinese researchers were paying more attention to popular international topics. Overall, the top 15 keywords used in papers published by Chinese authors had the following aspects: regional issues within China (*China*, *Tibetan Plateau*, *Loess Plateau*, *South China Sea*, and *Qaidam Basin*), Quaternary paleoclimate and paleoecology (*Quaternary*, *climate change*, *Holocene*, *temperature*, *paleoclimate*, *pollen*, *loess*, and *late Holocene*). These keywords were not only the same as the major international topics but also had Chinese characteristics, such as *loess*, *Tibetan Plateau*, and *human activities*. Attention began to be directed toward remote sensing. However, the frequency of these keywords with Chinese characteristics remained low (10 times; *Tibetan Plateau*, *Loess Plateau*, *South China Sea*, *human activities*, and *Qaidam Basin*). This indicates that foreign researchers rarely touched upon regional research inside China. However, there was also the problem of different English terminology for the same region. For example, Chinese authors preferred to use the keywords “Tibetan Plateau” or “Qinghai-Xizang (Tibetan) Plateau”, which emphasise the part within China, while foreign authors preferred to use the “Hindu Kush-Himalayan region”, which emphasized regions within Nepal, India, and Pakistan. Statistics suggest the number of papers using “Himalaya” as a keyword for research by foreign authors was 1–1.5 times that using “Tibetan Plateau,” indicating that this region attracted similar attention both locally and abroad.

4.2.3 Period of 2001–2005

Figure 4.11 shows research topics in the SCI/SSCI mainstream journals during the period 2001–2005. This was

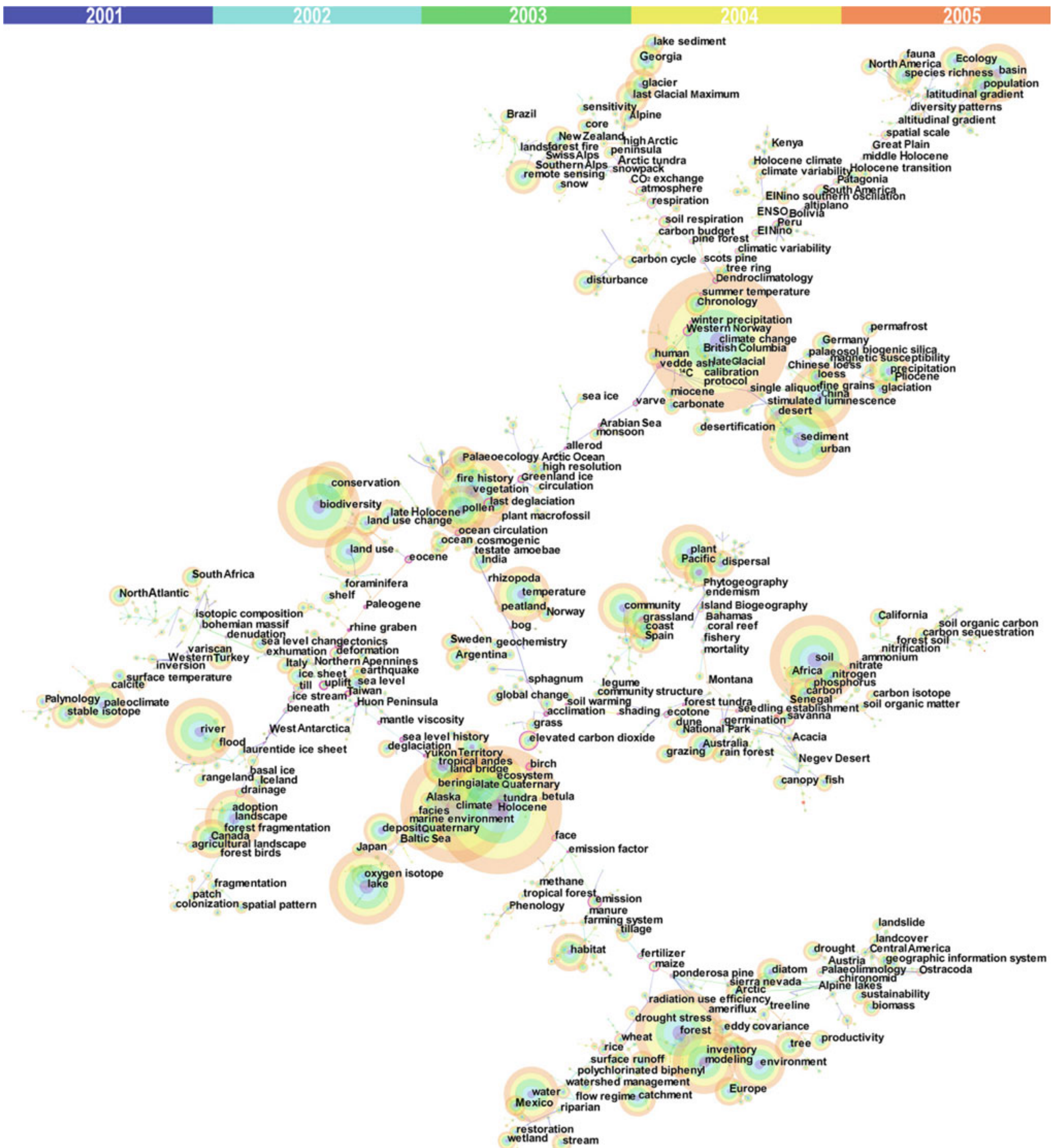


Fig. 4.11 Co-occurrence network of keywords in SCI/SSCI mainstream journals of physical geography during the period 2001–2005

another period of popular research focused on global change. Compared with the previous 5 years, the top five keywords were identical, and there were only slight changes in keyword order from fifth through ninth. "China" as a keyword increased its frequency ranking from No. 161 in 1996–2000 to No. 11 in this period. Keywords clustered with *climate change* included *late glacial*, *monsoon*, *sea ice*, and *Tibetan Plateau*, revealing that research on climate change in China began to occupy an important position in global change research. The keyword *climate* was clustered with *Holocen*e, *late glacial*, *the Quaternary*, and *sediment*, with no significant changes over the previous period. *Model* was clustered with *forest*, *environment*, *vortex*, *carbon dioxide*, *energy*, and *Europe*, suggesting that modelling during the period was focused on simulations of vegetation carbon sequestration processes. Such research was widespread in Europe.

Figure 4.12 shows popular research topics in core Chinese journals over 2001–2005. Major topics developed further on the basis of the previous period (1996–2000), entering a period of physicogeographical-process research centred on global change. (1) A mutual combination pattern formed among research on **global change, paleoenvironmental reconstruction, the Tibetan Plateau and Loess Plateau, and modern global change** research increased. The keyword *climate change* appeared in 2001 in the co-occurrence network of keywords. First, the keywords *atmospheric circulation* and *interdecadal variation* in climate change research were closely linked to the Normalized Difference Vegetation Index (NDVI), representing vegetation growth, and became keyword nodes with high centrality. Second, the keyword *permafrost* had an emergence in 2001 together with *roadbed* and *surface temperature*, indicating that climate change and its impact on the permafrost zone and engineering construction on the Tibetan Plateau became major research topics. Third, there was increasing co-occurrence of research topics temperature and precipitation, focusing on their impacts on biodiversity, soil temperature, seed germination, crop growth, and soil microbiotic crusts. Finally, paleoenvironmental research centred more on short timescales. The appearance of *last glacial maximum* (LGM) occurred in 2001, and keywords *last interglacial* and *the Holocene megathermal* had high centrality. Research objects concentrated on *loess-paleosol*, *paleosol*, and *stalagmite*, and research results involving *Dasuopu ice core* emerged. (2) **Water resource**

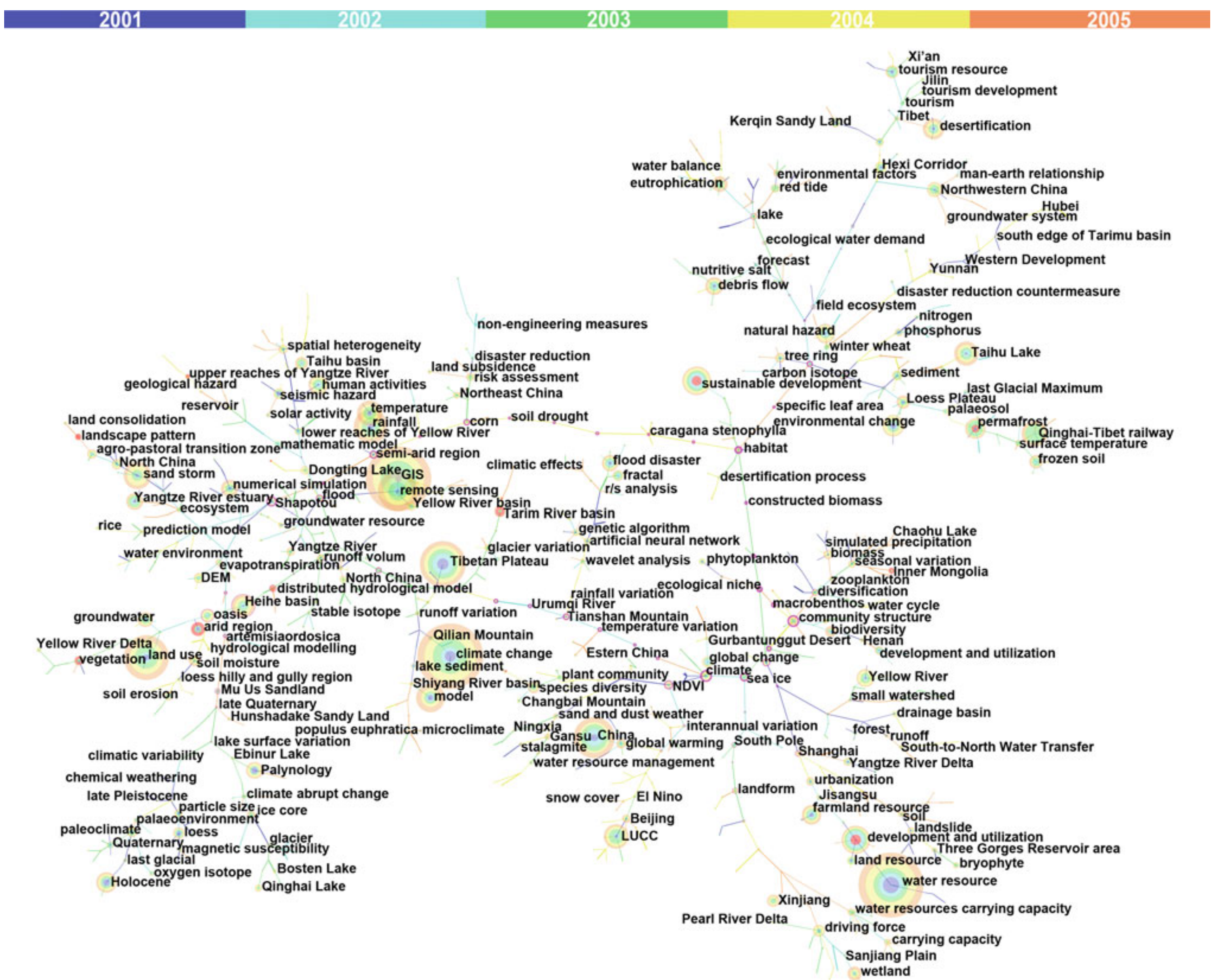


Fig. 4.12 Co-occurrence network of keywords in CSCD journals of physical geography during the period 2001–2005

research began to be combined with that on landscape patterns. The keyword *landscape pattern* appeared in 2003. Other keywords like *ecosystem*, *water saving*, *cyclic economy*, and *ecological footprint* co-occurred with *water resource*, indicating that water resource research began to be associated with ecology and the economy. With the occurrence of *water pollution* in 2003, the concept of water resources expanded from water quantity to water quality. (3) Research on **land use** merged with LUCC. In addition to the influences of desertification, research focused on the effects of hydrology and water resources resulting from LUCC, such as topics of soil erosion, soil water, groundwater, irrigation drainage, and solute transport. In addition, the keyword *Heihe River Basin* appeared in 2001, and related research focused on the impact of oasis land use on groundwater, aboveground biomass and agricultural ecosystems. This research was strongly promoted by the Major Research Plan (MRP) of Environmental and Ecological Research in Western China, launched by NSFC in 2000. (4) Research into **ecological processes** significantly strengthened. Keywords such as *community structure*, *distribution pattern*, *vegetation cover*, *diversity*, and *ecological niche* became nodes with high centrality. There were appearances of the keywords *red tide* and *nutrients* in 2001 and 2003 in the co-occurrence networks of keywords. (5) Research works on **natural hazards** decreased and mainly focused on sandstorms and debris flow during the period. There was also the appearance of *agricultural drought* in 2002. Research on Taihu Lake continued the topics of water environment, hydraulics, and aquatic ecosystems.

Figure 4.13 compares popular keywords in SCI/SSCI journals between Chinese authors and others during the period 2001–2005 (the diagram description see the note of Fig. 4.7). There was a significant increase in both journals and articles. Total keyword frequency and the top 15 keywords selected by Chinese authors also increased. The top 15 keywords all had word frequencies greater than 123, and the top two *Holocene* and *climate change* reached 467 and 458 times. Compared with the previous period, major research topics had some new features. Research on climate change, especially paleoclimate and paleoecology, increased further to become the most popular topics (indicated by keywords like *Holocene*, *climate change*, *paleoclimate*, *pollen*, *paleoecology*, *climate*, *diatom*, and *carbon dioxide*). Of the environmental change proxies, *diatom* appeared for the first time, as did *pollen* in the previous period. *Holocene* became the most popular keyword.

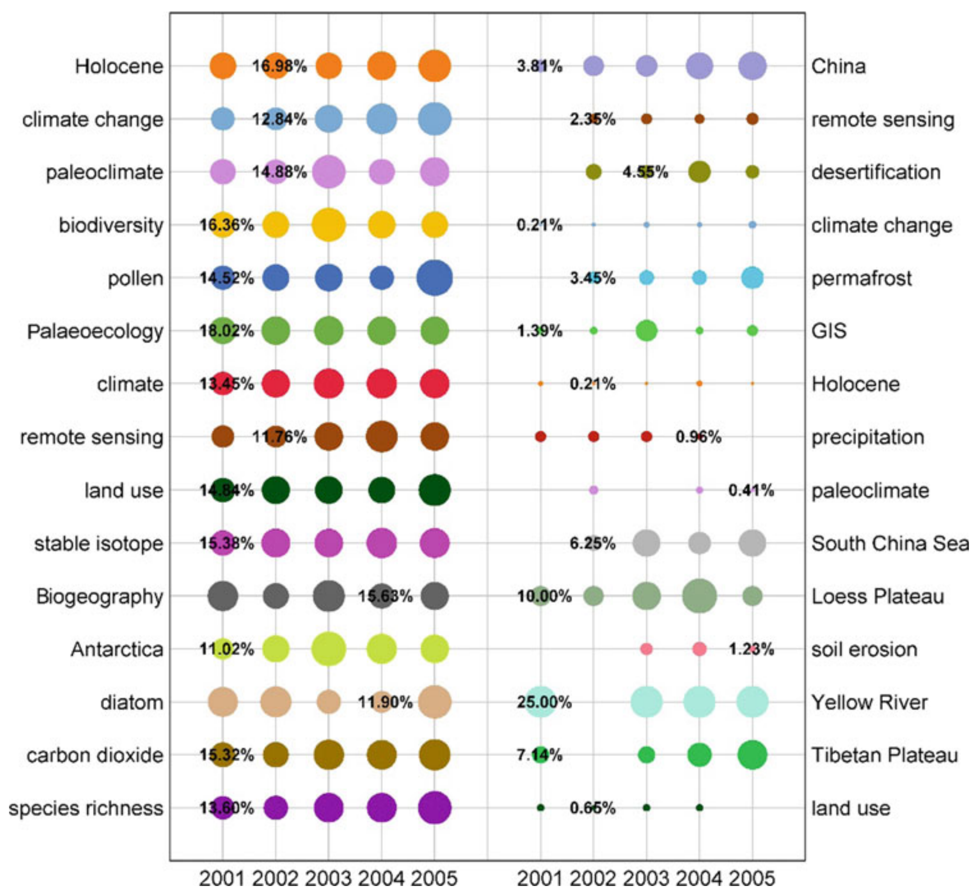


Fig. 4.13 Comparative diagram of prominent keywords by Chinese authors and others in SCI/SSCI mainstream journals of physical geography during the period 2001–2005

Research in biodiversity, especially those at species level, became a prominent topic (indicated by keywords such as *biodiversity*, *biogeography*, and *species richness*). Research into land use by remote sensing received additional attention (*remote sensing*, and *land use*). Five keywords in articles published by Chinese authors were the same as those by foreign authors, four of which focused on paleoclimate and paleoenvironment and the other on land use. This indicates a rapid catch-up of Chinese researchers with international research on land use. Overall, research on scientific issues within China was still a priority, as the frequency of *China* was 67 as used by Chinese authors, accounting for 63.8 % of the total frequency of keywords used by all authors. China's regional issues were also a priority, such as research on permafrost (25.9 % of the total frequency). The Yellow River was added to regional research (*South China Sea*, *Loess Plateau*, *Yellow River*, and *Tibetan Plateau*). Research into paleoclimate and paleoenvironment continued to track the major international issues (*climate change*, *Holocene*, and *paleoclimate*), prominently represented by precipitation research. Attention was also given to the impacts of human activity and climate change on the earth surface. Remote sensing and GIS remained powerful tools in regional research. In short, keywords used by Chinese authors indicated growing attention to the country's cold and arid regions and a global perspective on regional issues.

4.2.4 Period of 2006–2010

Figure 4.14 shows research topics in the SCI/SSCI mainstream journals during 2006–2010. During this period, physical geography research was dominated by global change, focusing on physicographical processes and dynamic comprehensive research. (1) **Climate change** remained the most frequent keyword. Compared with the previous period, *Holocene* gave way to *climate*, which became the second most frequent. *China* rose to fifth place. *Climate change*, *climate*, and *Holocene* were clustered in one group. Other keywords within this group included *pollen*, *high mountains*, and *oceans*, indicating that the role of oceans in the mechanism of climate change received attention. (2) Research themes in **physicogeographical processes** focused on three aspects. The first was climate change processes and their ecological responses, including paleoclimate reconstruction and climate change trends, as well as responses of water, soil, and vegetation to climate change. The second was ecosystem dynamics, especially for forest and grassland ecosystems. The third was geobotany and landscape ecology, with emphasis on vegetation productivity and land-use change. (3) Major features of research during the period were the emergence of keywords **model and simulation**, and a focus on interactions between global change and earth surface systems, covered by keywords like

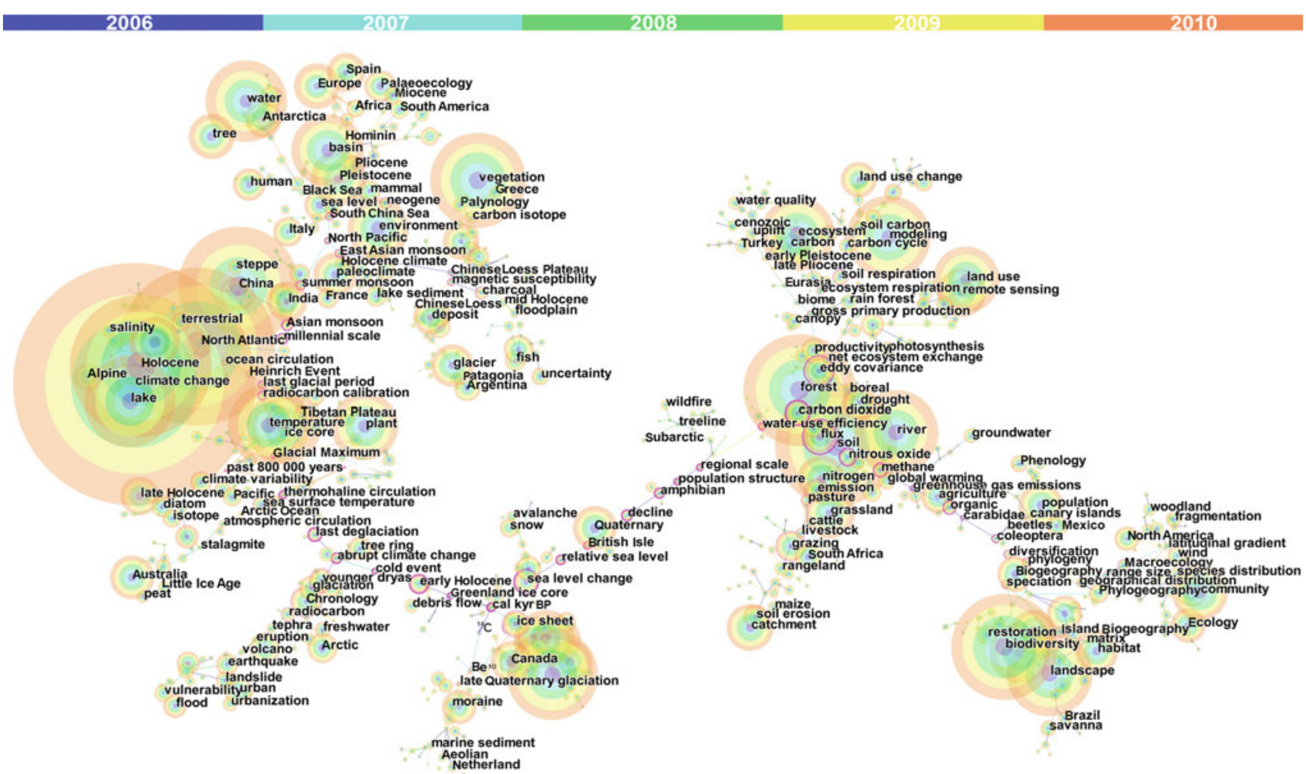


Fig. 4.14 Co-occurrence network of keywords in SCI/SSCI mainstream journals of physical geography during the period 2006–2010

climate change impact, *adaptation*, *vulnerability*, and *resilience*. Such features show that attention was directed at the impacts of global change on human society and societal adaptation to climate change. Simulating the characteristics of global change with models and predicting possible future climate trends became essential content for research into that change. (4) **Regional research** centred on China rapidly increased with more than three focus regions, excepting North America, Europe, and Oceania.

Figure 4.15 shows the dominant research topics in the core Chinese journals over 2006–2010. It can be seen that research on global change had greatly facilitated the development of physical geography based on the previous period (2001–2005). A greater number of studies focused on the impacts of global change. (1) Research on **climate change and paleoenvironment** continued the previous mutual combination and there was a significant enhancement of interest in impacts of climate change on the ecosystem and human activities. **First**, the Holocene remained the dominant period of research into paleoclimate and environmental change. *Antarctica* became a central node of keywords, indicating that it was an important research area for environmental change. Pollen became a key proxy for investigation into paleoenvironmental change, and the ecology of modern surface pollen enabled more quantitative research, with improved accuracy in the reconstruction of paleoclimate using paleovegetation. Simultaneously, reconstructions of paleotemperature and paleoprecipitaiton using lake sediments were strengthened. The keyword *ice core* appeared in 2006 in the co-occurrence network of keywords and research results centred on *East Rongbuk ice core* materialised in 2009. **Second**, keywords reflecting the impact of climate change on glacial and water resources became nodes, with high centrality in research on the impacts of climate change on glaciation, such as *glacier*, *glaciation*, *glacial variation*, *glacial retreat*, *glacial landform*, *glacial runoff*, and *glacial meltwater*. The most studied glaciers were mountainous ones, including the No. 1 glacier at the Urumqi River head, Tianshan, Miaoergou flat-topped glacier, Qiyi glacier, and Zhadang glacier. **Third**, western China became a popular

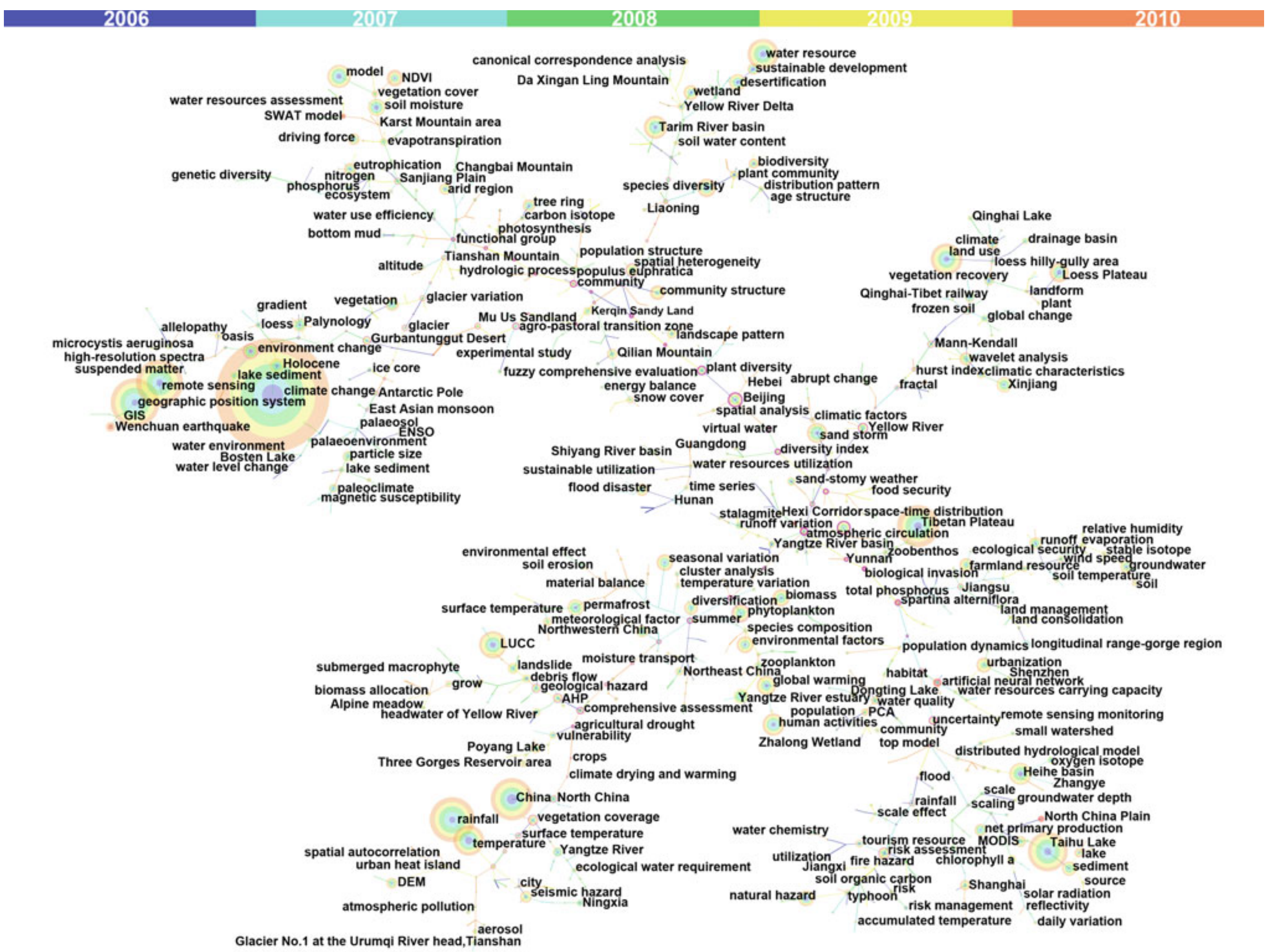


Fig. 4.15 Co-occurrence network of keywords in CSCD journals of physical geography during the period 2006–2010

research target for global change. In addition to climatic characteristics of temperature and precipitation variation, researchers paid more attention to ecosystem variation driven by climate change and human activity. As an important embodiment of human activity, *land use* gained much attention. Keywords such as *Qinghai-Tibet railway* and *vegetation recovery* had an emergence in 2006, and *cold region*, *arid region*, *agro-pastoral transition zone*, *permafrost degradation*, *community characteristics*, *desert plant*, *hydrologic process*, *carbon cycle*, *soil respiration*, *grassland ecosystem*, and a*gricultural ecosystem* all became critical nodes. (2) Research into **ecological processes** continuously strengthened and combined with hydrologic processes. **First**, keywords in this field such as *biodiversity*, *spatial variation*, and *plant community* all became keyword nodes with high centrality, with one appearance of the keyword *plant functional group* in 2008. **Second**, ecosystems in arid and semiarid regions became a focus. Nodes of keywords with high centrality included *Tengger Desert*, *biological soil crusts*, *Artemisia ordosica*, and *typical grassland*. **Third,** research on ecosystems addressed not only natural but also artificial ones, and the interference of human activity on ecosystems. For example, keywords *artificial vegetation*, *enclosure*, and *ecological water delivery* had high frequencies. **Finally**, research into soil moisture in ecohydrology greatly increased, driven by the Major Research Plan (MRP) of Environmental and Ecological Research in Western China launched by NSFC in 2000. Because soil is an important link between ecological and hydrologic processes, research on soil moisture revealed greater involvement in ecohydrology, especially for arid and semiarid regions. During 2006–2010, *soil water*, *green water*, and *evapotranspiration* were all keyword nodes with high centrality, and *SWAT model* appeared in 2008. At the same time, *Heihe River Basin*, *Tarim River Basin*, *isotope*, *water cycle*, and *distributed hydrological model* became important keyword nodes, demonstrating significant progress in the study of ecohydrology in inland river drainages of arid regions. (3) The themes of **LUCC** combined with ecological processes, ecological conservation, and water resource allocation. *Spatial heterogeneity*, *ecological water demand*, *groundwater*, and *habitat* became nodes with high centrality. Various topics were involved in research on land use. As one of the three major aspects of global change, land use together with climate change were subjects of studies on the water cycle, water resources, and ecosystems. (4) Research on **water resources** increased regarding the utilisation, management, evaluation, and capacity of water resources, and regarding water quality and international water disputes under the impacts of urbanisation and land use. Important study regions included Shenzhen, the Yangtze River Delta, Dongting Lake, Northern China, Shiyang River drainage, karst regions, and international rivers. (5) **Natural hazards** again received substantial attention in 2006–2010. *Natural hazards*, *agricultural hazards*, and *risk management* were popular keywords in 2006. *Wenchuan Earthquake* and *Sichuan Basin* were frequent keywords. (6) Research into **lake** water environments, hydrodynamics and aquatic ecology expanded. *Cyanobacteria* emerged in 2008 with high centrality. Research on *eutrophication* was not limited to Taihu Lake but extended to Dianchi, Fuxian, and Wuli lakes. *Nutrients*, *vertical distribution*, *biomass*, *phytoplankton*, *species composition*, and *temporal-spatial characteristics* were all important keywords. *Phosphorus* appeared in the co-occurrence network of keywords in 2006.

Figure 4.16 shows a comparison of prominent keywords in SCI/SSCI journals used by Chinese authors and others during the period 2006–2010 (the diagram description see the note of Fig. 4.7). Compared with 2001–2005, this period had some new traits of keywords with high frequency. Global change became the most popular research topic and climate change research continued to focus on paleoclimate and paleoecology (indicated by keywords such as *Holocene*, *paleoclimate*, *climate*, *paleoecology*, and *pollen*), and began to address changes to its elements and its impact on ecosystems (*precipitation*, *temperature*, and *eddy covariance*). Biodiversity and biogeography received consistent attention, and the frequency of *biodiversity* jumped to third place. There was also enduring consideration of geographical data collection, analysis and simulation (*remote sensing*, *stable isotope*, and *modelling*). Investigation of land use maintained the same level as in 2001–2005. Of the top 15 keywords used by Chinese authors, seven were the same as those used by foreign authors (*climate change*, *remote sensing*, *Holocene*, *precipitation*, *temperature*, *land use*, and *eddy covariance*). Most of these were related to global change, indicating that geographical research in China had caught up with the international research pace. *Eddy covariance*, *precipitation*, *temperature*, *evaporation*, and *soil organic carbon* all appeared simultaneously in the top 15 popular keywords of Chinese authors, indicating extensive observations and research of the carbon cycle in Chinese ecosystems. In addition, there was emergence of a focus on the water cycle under global change and ecological processes in soil. Keywords related to this topic made up 13.7 % of all keywords used by both Chinese and foreign authors. Research into local issues was still a centre of attention, with *China* the most frequent keyword, accounting for 69.2 % of total keyword frequency. Research using the

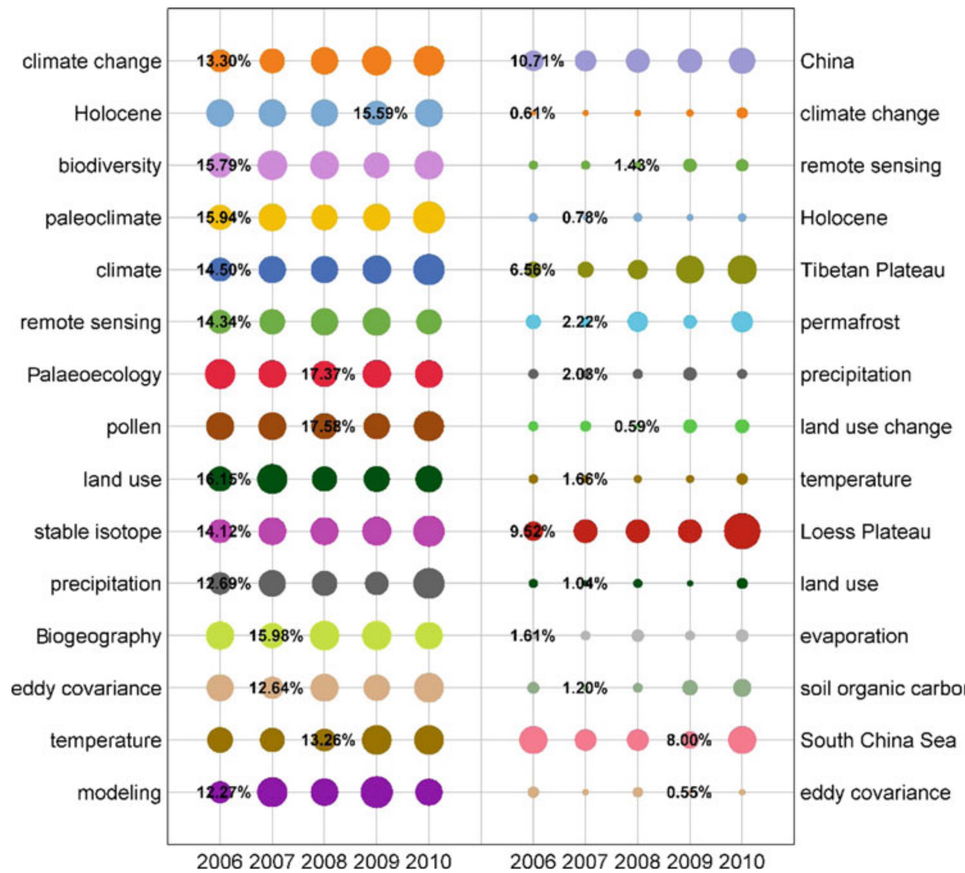


Fig. 4.16 Comparative diagram of prominent keywords by Chinese authors and others in SCI/SSCI mainstream journals of physical geography during the period 2006–2010

keyword *permafrost* by Chinese researchers made up 1/3 of all the research, a small increase over the 25.9 % during the previous period. This suggests a continuing focus on permafrost by Chinese researchers. *Tibetan Plateau*, *Loess Plateau*, and *South China Sea* were popular research target regions, with a proportion of 70 % of keywords used. This indicates that attention to Chinese regions by foreign researchers and the extent of foreign cooperation had not improved. However, *Tibetan Plateau* was cited a total of 61 times by Chinese and foreign authors, 10 times that during 1996–2000, and foreign authors mentioned it 22 times, a factor of 22 increase over that during 1996–2000.

4.2.5 Period of 2011–2015

Figure 4.17 shows research topics in the SCI/SSCI mainstream journals during the period 2011–2015. This remained a period when research topics centred on geographical processes and comprehensive dynamics under global change. As the most popular keyword, from 2011 *global change* led research in physical geography. The top 10 most frequent keywords were similar to those in 2006–2010, but *China* rose to second place, before *climate*. *Global change* was clustered with *climate*, *vegetation*, *trees*, *carbon flux*, *uncertainty*, and *sensitivity*, indicating that global change research focused on the accuracy of measurement of carbon flux in the global carbon cycle. Research on *China* was clustered with ice core, lithological records of climatic events, and radiocarbon dating, showing that paleoenvironmental research in the country was still an important aspect of global change. The ranking of *temperature* rose to eighth place, from 15th in 2006–2010. Being clustered with *precipitation*, *continent, carbon cycle*, and *fir*, *temperature* had high co-occurrence with *desert*, *NDVI*, and *productivity*. This pattern reveals a strong increase in research into the responses of precipitation, vegetation productivity, and carbon cycle to temperature change.

Figure 4.18 shows dominant research topics in the core Chinese journals over 2011–2015. During this period, global change led studies in physical geography in China, concentrating on physicogeographical processes and comprehensive dynamics. (1) Research into **impacts of global change** took a prominent position. **First**, greater attention was given to paleofloods, slack water deposits, solar activity, atmospheric circulation, cold climate events in paleoclimate, and environmental change research. *Qing Dynasty* became a frequent keyword. **Second**, the impact of global change on

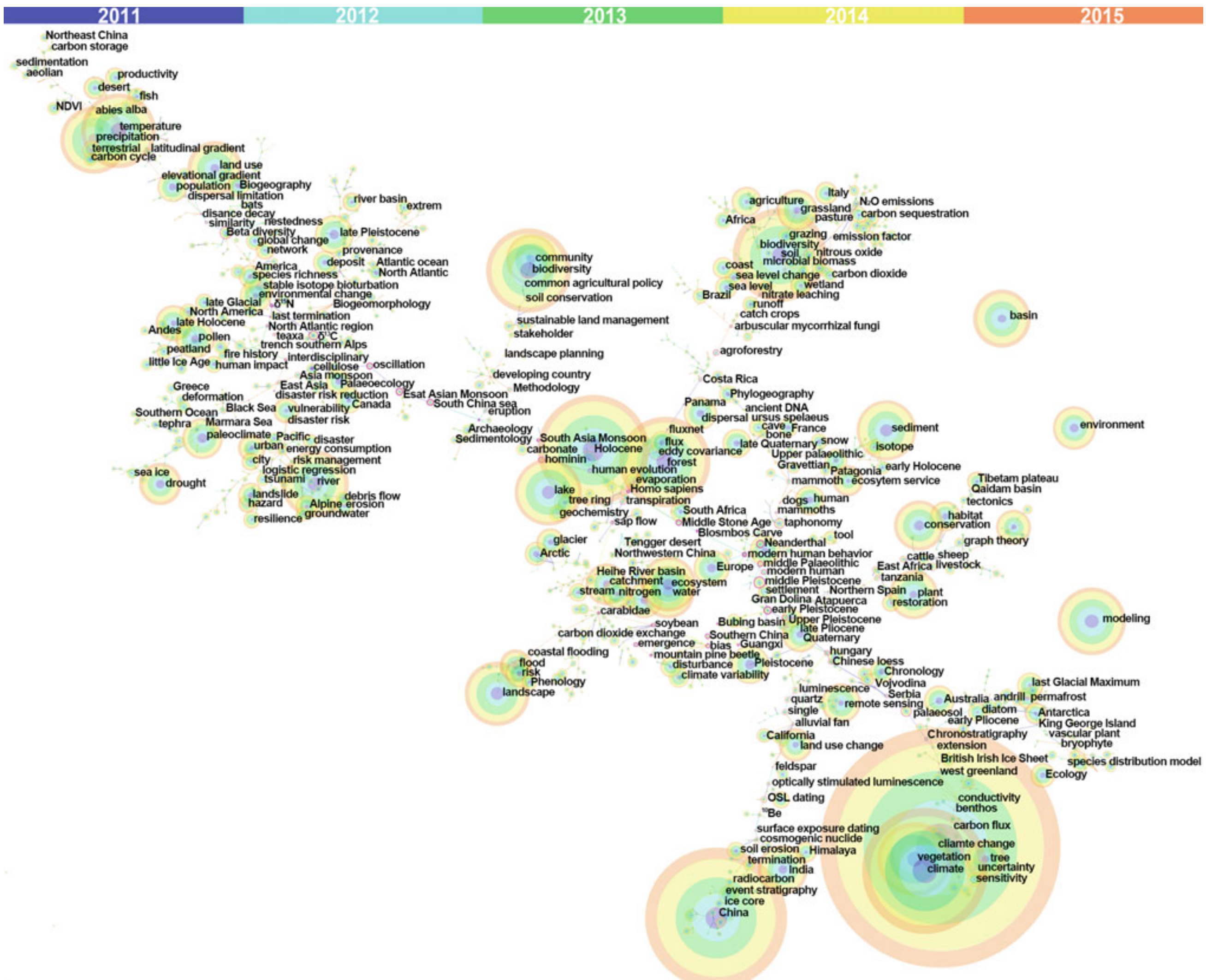


Fig. 4.17 Co-occurrence network of keywords in SCI/SSCI mainstream journals of physical geography during the period 2011–2015

the water cycle and water resources became a major theme of research in physical geography, with the appearance of *runoff* in 2011 in co-occurrence network of keywords. Supported by the National Global Change Major Research Project sponsored by the MOST and various NSFC projects, research on glaciers and permafrost became major research objectives in global change. Accordingly, glacier and hydrologic processes in permafrost also become core processes in studies of the water cycle and variations of water resources in inland river drainages. **Third**, there was further overlap in the themes of temperature and precipitation, and attention was focused on extreme weather and agro-meteorological disasters, as reflected by the emergence of *agroclimatic resources* and *risk assessment* in 2011. (2) Research into **ecosystems** was further combined with climatic, hydrologic, and economic elements, and investigation of ecohydrological processes in arid areas increased unprecedentedly. **First**, the impacts of temperature, precipitation, and soil-water and groundwater fluctuations on habitat selection, drought resistance, and adaptation to salt stress of typical species in temperate deserts under global warming were prominent academic topics. **Second**, inland river drainages within arid regions, such as the Heihe, Tarim, and Shiyang river basins, and keywords related to ecohydrological processes in arid regions, such as *evapotranspiration*, *potential evapotranspiration*, *groundwater*, and *hydrological response*, all became important keyword nodes driven by the MRP of Integrated Research on the Eco-Hydrological Process in Heihe Basin, which was launched by NSFC in 2009. (3) Ecological effects of **land use**

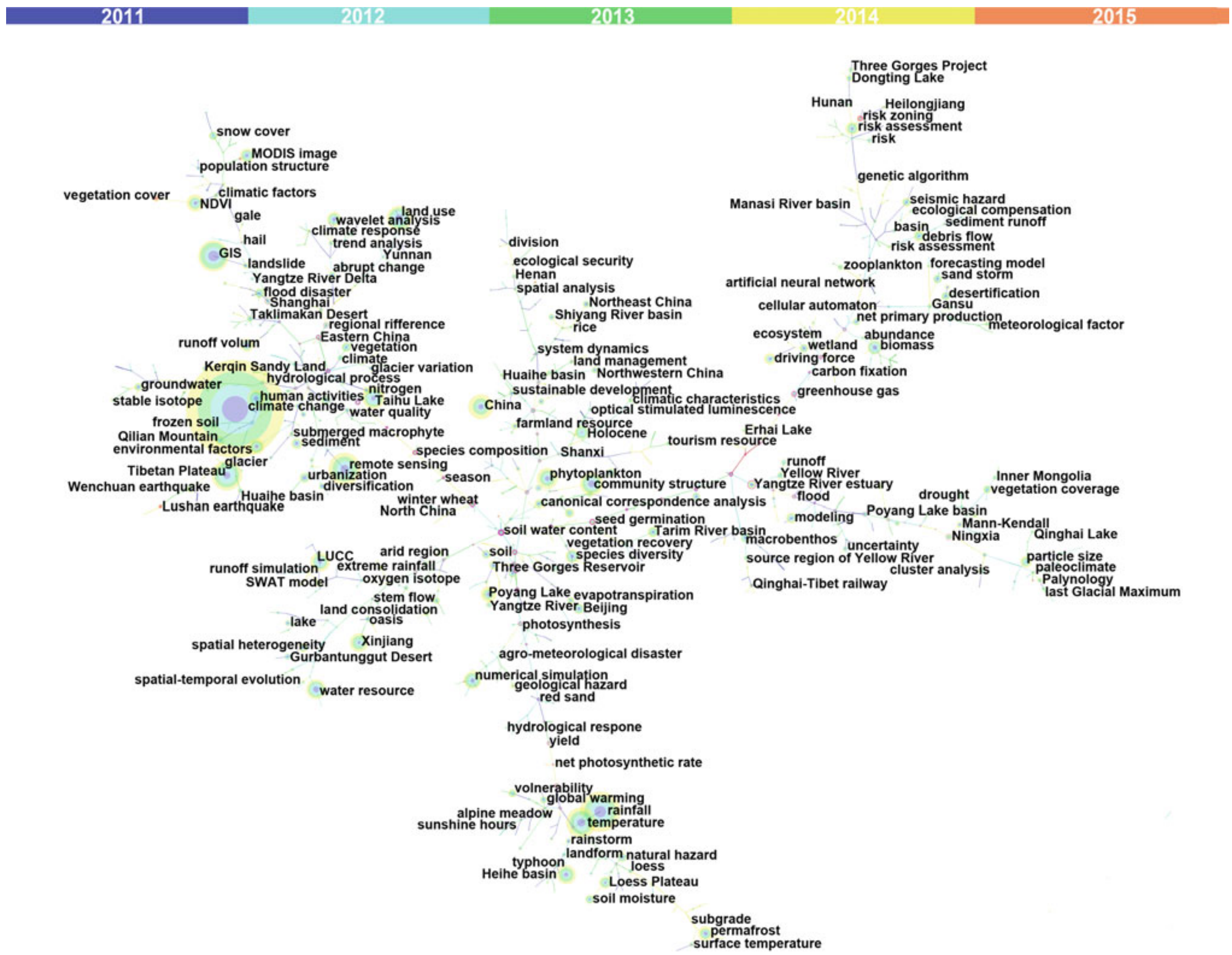


Fig. 4.18 Co-occurrence network of keywords in CSCD journals of physical geography during the period 2011–2015

and LUCC became an important theme, with more comprehensive research associated with management, ecology, and planning. Ecological effects mainly had two aspects. One was the effect on hydrology and the other was the effect on biodiversity. *Land use*, *farmland resource*, *land management*, and *land control planning* were keywords with high centrality. (4) Research on **lake and wetland ecosystems** increased further. The key objects were Poyang, Taihu, and Dongting lakes, and studies of the lake water environment centred on *biomass*, *lake level*, *water quality*, and *cyanobacteria bloom*. *Three Gorges Reservoir* appeared as a critical keyword node, with increased papers using it as a keyword. (5) Research into **water resource** research was refined and became increasingly combined with engineering, management, and ecological issues. This was reflected by frequent keywords such as *water footprint*, *water resource utilisation*, *water quality*, *water resource capacity*, *virtual water*, *water resource management*, *reservoir*, and *water use efficiency*. In addition, keywords such as *water resource use efficiency*, *south-to-north water diversion*, *water resource supply-demand system*, *water right transaction*, *salty water irrigation*, and *water resource allocation* increasingly appeared in papers. (6) Research on **natural hazards** declined compared with that of the previous 5 years, but *vulnerability analysis*, *risk assessment*, *disaster prevention and reduction*, and *emergency management* continued to have high centrality. The major hazards addressed during the period were debris flow and earthquakes, with appearance of the keyword *Lushan earthquake* in 2013.

Figure 4.19 compares major issue keywords in SCI/SSCI journals used by Chinese authors and others during the period 2011–2015 (the diagram description see the note of Fig. 4.7). The average frequency of the top 15 keywords used by the former authors was 59, 1.6 times that of the previous period. The top 15 keywords used by foreign authors all had a frequency in excess of 148. The most

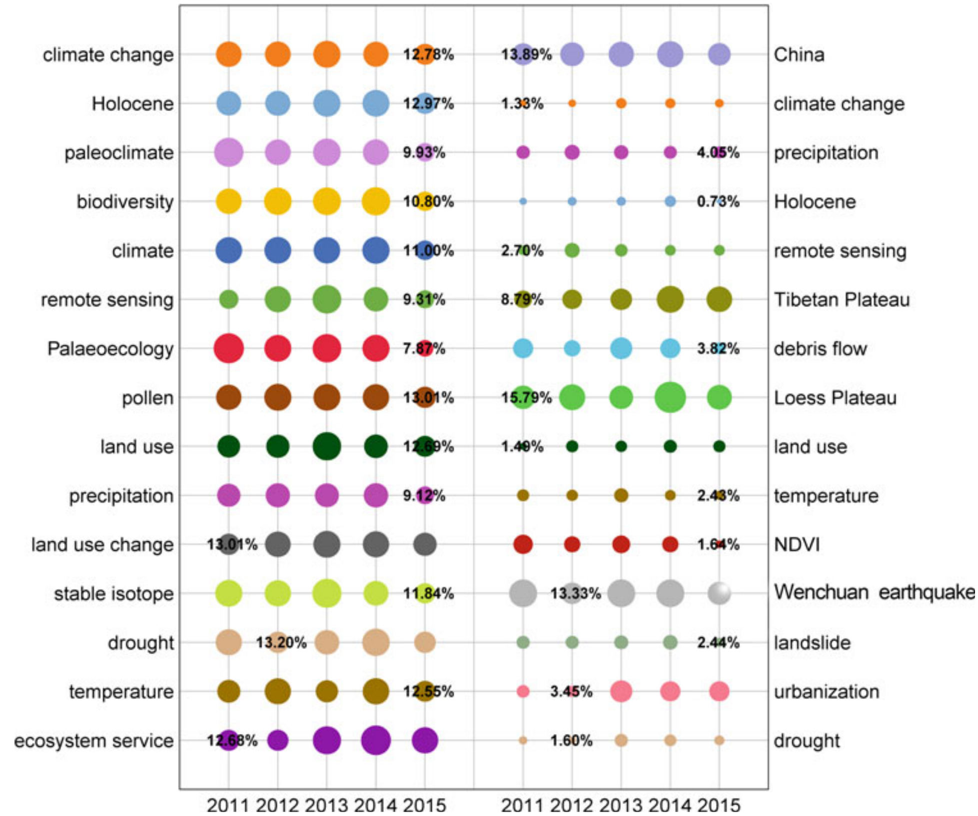


Fig. 4.19 Comparative diagram of prominent keywords by Chinese authors and others in SCI/SSCI mainstream journals of physical geography during the period 2011–2015

frequent keywords were *climate change* and *Holocene*, with frequencies 1241 and 473, respectively, much higher than those of the remaining 13 keywords. Twelve of the 15 keywords had already appeared in the previous 5-year period, showing little change in frequency. Only the frequency of *climate change* increased, by 35.8 %. Newly emerging frequent keywords included *drought*, *land-use change*, and *ecosystem service*. This suggests that global change research had shifted from climate change facts to ecosystem services, disastrous weather, and agriculture and crop production under the influences of climate change and human activity. Such a shift of research theme is closely related to human survival, especially for people in developing countries. Seven of the top 15 frequently used keywords by Chinese authors were the same as those used by foreign authors (these were *climate change*, *precipitation*, *Holocene*, *remote sensing*, *land use*, *temperature*, and *drought*). The proportions of keyword frequency to total frequency all increased. *Climate change* increased by 3.1 %, precipitation by 11.9 % (accounting for 26.2 % of total research), *Holocene* by 3.3 %, and *temperature* by 9.7 % (20.2 % of total research). This pattern indicated that research into physical geography in China not only continued to focus on climate change facts as in the previous period following the international trend, but also began to focus on the new popular topic *drought*, reflected by a frequency proportion of 14.5 %. Compared with research outside China, an additional characteristic of domestic research was a concern for hazards. In addition to *drought*, four of the top 15 keywords were hazard-related, such as *debris flow*, *landslide*, and *Wenchuan earthquake*. The keyword *debris flow* constituted 48.1 % of the total frequency. The proportions of *landslide* and *Wenchuan earthquake* were 23.7 and 93.5 %, respectively. This indicates that geologic disasters and their effects in southwestern China were momentous, becoming critical issues in Chinese physical geography research. Other prominent topics in China included land use and urbanisation. The frequency proportion of *land use* increased 8 % over the previous period. *Urbanisation* was a new keyword that made up 43.5 % of the total frequency of international keywords. The Tibetan and Loess plateaus remained major research regions in China.

4.2.6 Analysis of Driving Factors for Disciplinary Development over the Past 30 Years

The previously analysed evolution of research themes based on the mainstream SCI/SSCI physical geography journals is consistent with the development of global change research. In research during 1986–1995, traces of earlier international research projects could be followed. For example, the

International Biosphere Program (IBP) of 1964–1974 and subsequent Man and Biosphere Programme (MAB) beginning in 1975 were reflected in later research by the major topics of forest and desert ecosystems and nature conservation. Keywords *Diversity* and *Biogeography* began to appear sporadically in 1988 and 1990, and have significantly increased since 1991. This indicates that research development in biodiversity and biogeography may be related to establishment of the International Programme on Biodiversity Science, DIVERSITAS. The International Geosphere-Biosphere Programme (IGBP) initiated by the International Council of Scientific Unions has directly promoted overall development of physical geography in China during the past 30 years. Because this project examines the life-supporting earth system environment, interactions between different system elements, and changes in the system and impacts of human activity, it has facilitated research into physicogeographical processes, interactions between different spheres, and human-land relationships. One of the core plans in the IGBP is Past Global Changes (PAGES), established in 1991, which has promoted the study of environmental change in physical geography. The late Quaternary, last glacial maximum, and Holocene are all focus periods proposed by PAGES. As a result, *Holocene* and *pollen* have significantly increased in international papers on physical geography since 1991. Promoted by the project Global Change and Terrestrial Ecosystem (GCTE) in 1995, research on land-use and land-cover change (LUCC), which investigates changes of earth surface pattern, has been greatly enhanced. *Land* has become a critical keyword since 1996, being one of the 25 most frequent keywords during 1996–2005. Research in LUCC emphasises the close relationship with ecological processes and increases attention to human factors. The Global Land Project emerged from the GCTE, and LUCC study has further facilitated physicogeographical research to have a more comprehensive direction. *Modelling* as emphasised by the IGBP has always been one of the top five keywords in physical geography. *Climate* and *climate change* have been the top three keywords since 1991, being closely related to guidance from the Intergovernmental Panel on Climate Change (IPCC), beginning in 1988. As affected by IPCC reports, the focus of global change research has shifted from an initial focus on global warming, greenhouse effects and atmospheric composition change to the recent focus on earth surface processes, especially the response and adaptation of human society to climate change. The steering role of the IPCC in global change research has been reflected in papers about global change problems, with discussion by international physical geographers. Since the beginning of the present century, China has implemented several large projects on global change. These have been fully represented by research into Chinese regional physical geography, especially in the last decade. Research on regional characteristics like the Asian monsoon, Loess Plateau, and Tibetan Plateau has made China outstanding in the regional physicogeographical field. Interdisciplinary research has also promoted the development of physical geography. As a product of the combination of geography and ecology, landscape ecology has developed vigorously since 1970 and has become a widespread research topic since the late 1980s. The depiction of patterns and processes has fully brought the advantages of geography and ecology into full play, which is also the reason why they have always been important keywords in physical geography. Recent research on ecosystem services has combined physical processes and sustainability, further enhancing the value of the discipline of geography and ecology.

Research topics reflected in the CSCD journals are closely related to the regional response of global change in the country, and coincide with the traditional research direction of Chinese physical geography. With regard to the aforementioned response, impacts on water resources and natural hazards are the most important topics in China, followed by land use and biodiversity. The above three topics are all traditional research directions in the country. Therefore, these topics have become the most common themes in the past 30 years, steered by global change in Chinese physical geography. The lack of focus on the carbon cycle, temperature and precipitation in Chinese papers is largely related to a long-term fine division of disciplines in the country. Taking the carbon cycle as an example, geographers focus on simulations at large scales, whereas carbon emissions by ecosystems are more often investigated by ecologists or pedologists. Although temperature and precipitation were traditional research topics in physical geography, Chinese geographers examined regional characteristics of temperature and precipitation, and their relationships to droughts and floods. In addition, international issues of climate variability were mainly studied by atmospheric scientists in China. Moreover, many regional keywords in Chinese papers not only signify that the regions have clear-cut physicogeographical traits, but that they are also typical regions for global change research. For example, research centred on the Tibetan Plateau, including climate, ecosystems, glacial change, and permafrost and lakes, have fully reflected the importance of the cryosphere in global change. Research on the Tibetan Plateau is closely related to the Holocene environmental changes as reflected by keywords, indicating the importance of earth surface processes in interpreting paleoenvironmental change. Another example is research into Taihu and Poyang lakes, with a focus on eutrophication. Research on the Loess Plateau has focused on soil erosion and ecosystem services. Research on arid and semiarid regions included hydrologic processes, such as runoff, soil water and groundwater, natural hazards represented by sandstorms, and ecosystems represented by wetlands and biodiversity. Keywords representing arid and semiarid regions such as *Mu Us Sandland*, *Badan Jilin Desert*, and *Heihe River Basin* indicate that there has been much physical geography research in these regions.

4.3 Disciplinary Development and Research Teams in China

This section analyses the disciplinary development trend based mainly on the following. (1) The proportions of applications and funded projects in physical geography to total number of those in the NSFC Geographical Sciences; (2) number of applications and funded projects in different branches of physical geography; and (3) characteristics of themes chosen by researchers in NSFC-funded projects. The conditions of teams in research institutions in China were also analysed. We determined (1) the number of institutions with research in physical geography; (2) the number of publications in SCI/SSCI journals per researcher in these institutions; (3) collaborative networks of Chinese authors with publications in SCI/SSCI or CSCD journals; and (4) institutions with which the highly cited SCI/SSCI-indexed articles were affiliated and situations of NSFC-funded projects in these institutions.

4.3.1 Numbers and Proportions of NSFC Applications and Funded Projects for Physical Geography

In the past 30 years, both the number of applications submitted to and those funded by NSFC in physical geography had been increasing, although the 5-year rate of increase had tended to slow (Fig. 4.20). The proportions of applications/funded projects in physical geography to the total in geographical sciences had been decreasing. For example, the application proportion decreased from an initial 50 % to less than 30 % in the last 5 years. Similarly, the proportion of approved applications decreased from more than 50 % in 1991–1995 to less than one third in those 5 years. These data suggest that research teams in physical geography in China had gradually lost their dominant position in geographical sciences, becoming similar to those in other branches of those sciences. The reason for large proportions of projects funded by NSFC to applications submitted in physical geography is tied to the concept of disciplinary development and management measures by NSFC. As the core branch of geographical sciences, physical geography is most closely related to geology, atmospheric science, and marine science. To guarantee the opportunity for physical geography to develop synchronously with other branches of earth science, the Division of Geography in the Department of Earth Science of NSFC gave preference to physical geography when determining the proportion of projects funded, resulting in the higher proportions of projects funded to applications submitted.

The proportions of applications in each branch of physical geography and their variations during the period 1986–2015 are listed in Fig. 4.21. Applications counted included those applying for the General Programme (GP), Young

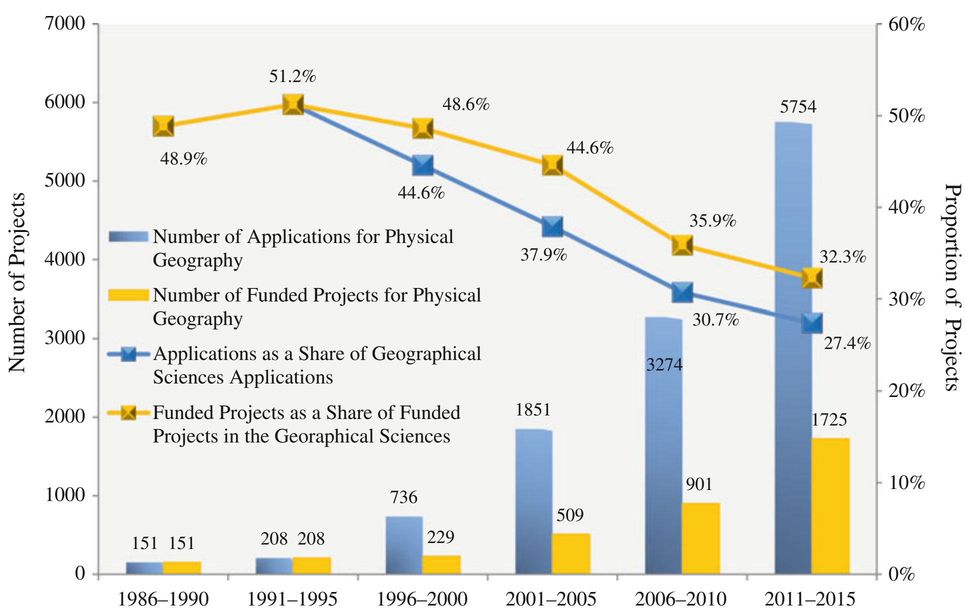


Fig. 4.20 Proportions of NSFC projects for physical geography during the period 1986–2015. *Note* Non-funded proposals from 1986 to 1997 were not recorded in the NSFC database. Therefore, number of applications and NSFC-funded projects are identical from 1986 to 1995, as shown in the figure

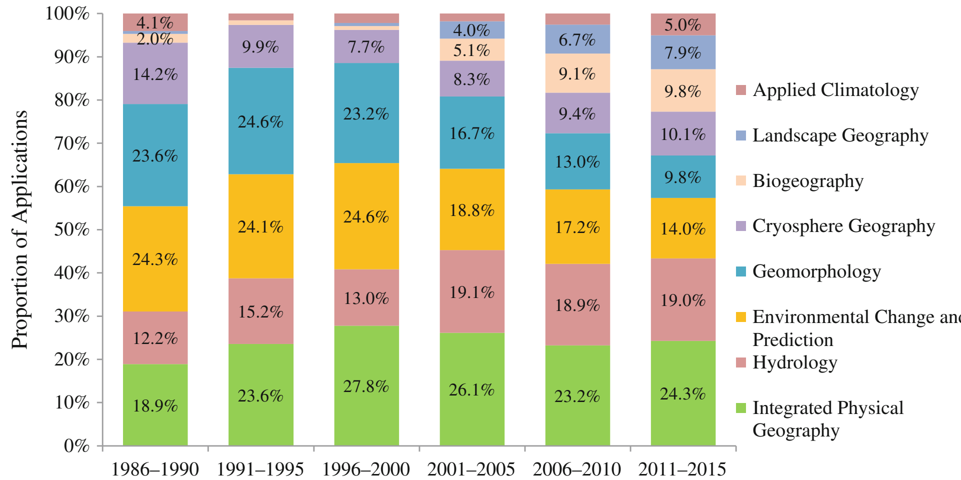


Fig. 4.21 Proportions of NSFC applications of branches of physical geography during the period 1986–2015. *Note* Non-funded proposals from 1986 to 1997 were not recorded in the NSFC database. Therefore, the proportion of applications shown in the figure is the proportion of funded projects during the period

Scientists Fund (YSF) and the Fund for Less Developed Regions (LDR Fund). Results show that the proportion of applications to total applications in physical geography in "Geomorphology" and "Environmental Change and Prediction" had decreased drastically since 2000, while the proportions in "Biogeography," "Landscape Geography" and "Hydrology" had all increased. The proportion of applications in geomorphology decreased from almost a quarter in the first 5 years to less than 10 % in the last 5 years. Analyses of the titles and keywords of applications in 1986–2015 suggest a decrease in number within paleoenvironment and an increase within modern physicogeographical processes and patterns. In addition to the sharp reduction of applications within "Environmental Change and Prediction," proposals with research contents of modern environmental processes indicated by paleoenvironmental proxies increased rapidly. At the same time, over the past 5 years the proportion of applications in biogeography had increased to nearly 10 % and that of hydrology to 19 %. Keywords describing earth surface ecological and physical processes in applications emerged in large numbers, such as *hydrological model*, *isotope hydrology*, *water cycle*, *evapotranspiration*, *biodiversity*, *ecosystem services*, and *soil carbon cycle*, and their frequencies and increase rates were among the largest. There is a wide range of application topics under integrated geography. The proportion of applications in that area was as large as 28 % in 1996–2005 but decreased to ~24 % in the last 5 years. The 2008 adjustment of environmental effects of human activities in integrated geography to environmental geography might have somewhat reduced the number of applications in integrated geography. Applications involved were those studying ecological recovery and environmental effects of major engineering construction. The proportion of applications in cryosphere geography was once near 15 % (in 1986–1990), but this continuously declined and stabilised at the present ~10 %. This is because researchers in cryosphere geography in China are relatively small in number compared with those in other branches of physical geography.

4.3.2 Objects of Studies in NSFC-Funded Projects

During the period 1986–2015, NSFC Geographical Sciences supported 547 projects with 390,162 thousand yuan for the study of 153 rivers nationwide (Fig. 4.22). Of these rivers, a third are third-order and fourth-order rivers, a quarter are second-order, 8.5 % are fifth-order, 1.3 % are first-order and sixth-order, and 0.7 % are seventh-order rivers. These rivers are all over the country and are classified into six levels per the number of NSFC-supported projects (these levels are designated by six colours in Fig. 4.22. Rivers in red indicate that most research projects for these rivers were supported by NSFC. (1) **Rivers with the most research projects supported were the Heihe, Yellow, Tarim, and Yangtze**. Ninety-one projects and 40,256 thousand yuan were assigned to **the Yellow River** for research in geomorphology, hydrology, biogeography, and landscape ecology. Associated research topics were river landform evolution, silt source, and transport, water level fluctuation, flood-drought hazards and their risks, alpine wetlands, and water conservation, ecosystem services, biodiversity in delta wetland, sea water invasion, adaptation to climate change, and vulnerabilities. Eighty-six projects were funded 148,274 thousand yuan for **the Heihe River**, and 41 projects received 23,416 thousand yuan for **the Tarim River**. Those two are the most important inland rivers in the arid region of China. Research topics on the two river drainages included ice and snow in inland river basins in the arid region; permafrost evolution and hydrology; water resource change; transformation of surface water and groundwater and its ecological effects; biological mechanisms of water use and water consumption by plants at different scales; mechanisms of

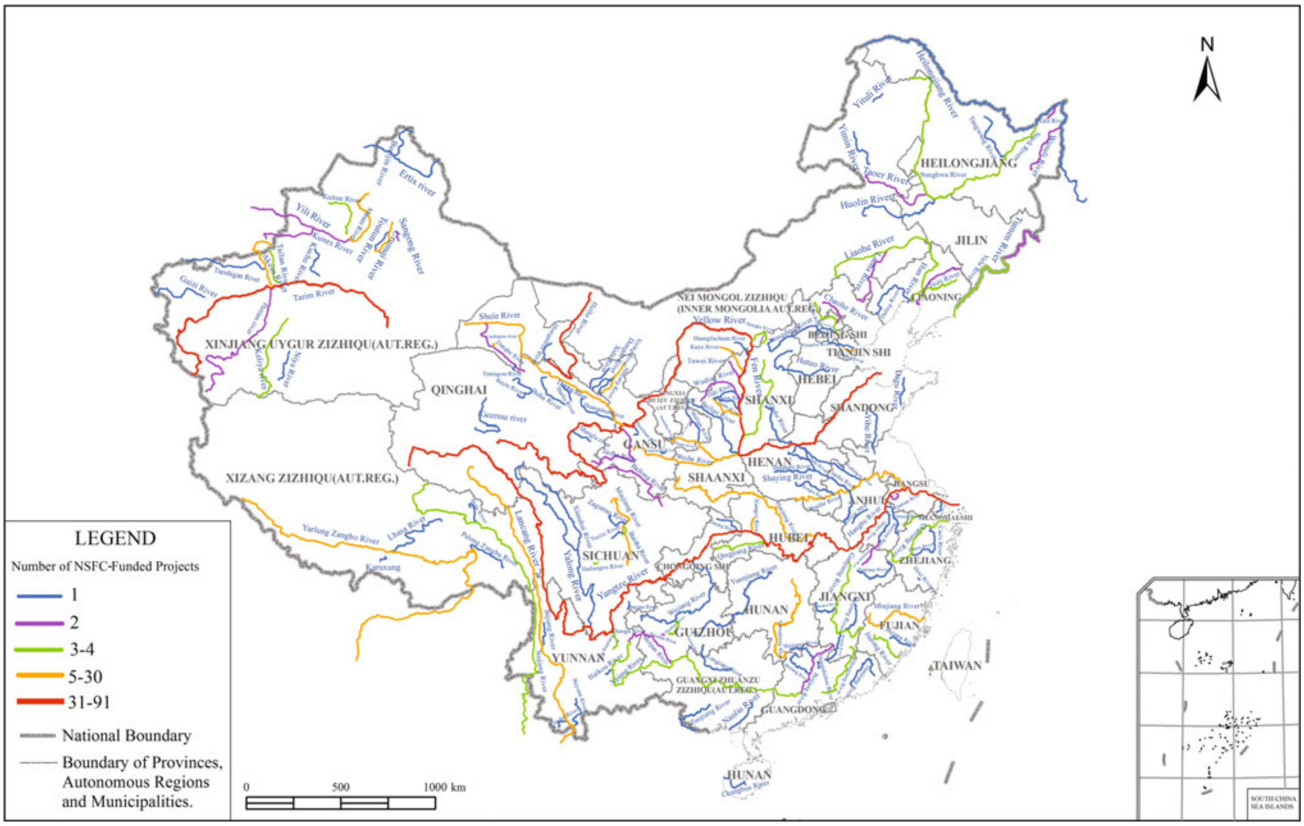


Fig. 4.22 Distribution of rivers studied by NSFC-funded projects in geographical sciences during the period 1986–2015

ecological-hydrological interaction under typical vegetation patterns; economy–ecology–water system evolution at basin scale; and eco-hydrological integrated models and decision support systems at basin scale. Thirty-nine projects were funded a total of 16,182 thousand yuan for research on **the Yangtze River** pertaining to the impacts of climate change on runoff and the water cycle in the catchment; impacts of land use and hydraulic engineering in the drainage basin on hydrologic processes and water-sand variations; river–lake relationships and water system evolution; natural hazards and human–land relationships from the historical period; estuary and coastal geomorphology; and biogeochemical cycles. Another heavily invested river was **the Urumqi**, with 23 projects and 9355 thousand yuan. Studies on this river system were centred on melting and runoff change under global warming (using isotope hydrology methods) and hydrologic processes simulations. Research on the aforementioned five rivers accounted for 44 and 60.9 % of total projects and funding, respectively, for research on all rivers in China. (2) **Rivers with more projects and funds were mainly at the southeast edge of the Qinghai-Tibetan Plateau, arid regions in northwestern China, and the Loess Plateau**. Three rivers in the southeast corner of the Qinghai-Tibetan Plateau, **the Lancang, Yarlung Zangbo, and Minjiang**, were supported by 32 projects and 10,215 thousand yuan for research on multiscale interactions of hydrologic processes between upper and lower reaches, impacts of hydropower exploitation on river silt and aquatic life, and hydraulic effects under climate change and land use. There was also research into glacier and permafrost processes, river geomorphology and river valley aeolian landforms, and geologic hazards. Thirty-five projects and 15,541 thousand yuan were allocated to **the Shiyang, Laohugou, Shule, and Huangshui-Datong rivers** in the arid regions of the northwest. Research on the Laohugou River was mainly about monitoring and simulation of mass balance of glaciers, glacial climate, and hydrologic effects. Research into the Shule and Shiyang rivers included land use, reservoir construction, groundwater change in arid oases, vegetation population, function change in oasis-desert ecotones, grassland degradation and desertification, water use efficiency of drought-resistant plants, ecological-hydrological processes, and ecological water demand, and water right systems and water resource management. The Huangshui-Datong River is in the Qilan mountainous of the northeastern Tibetan Plateau. Research there was centred on distribution change of permafrost and snow and fluvial deposition/erosion cycles. Twenty-one projects with 13,260 thousand yuan were put into research on **the Manas, Akesu, Tailan, Hetian, and Gongnaisi rivers** in Xinjiang, in the arid region of northwestern China. Major themes were extreme climate events affected by both the monsoon and westerly circulations under global change, water resource change and suitable scales of oases, and mountain-oasis-desert systematic evolution. Rivers on the Loess Plateau, including **the Weihe, Jinghe, Yanhe, Kuye, and Fenhe rivers**, were supported by 37 projects and 21,404 thousand yuan. Major themes were land use/land cover change, landscape patterns, eco-hydrological modelling, ecosystem services, flood and drought, water and sand change, and water conservation. Other topics included impacts of climate and tectonic movement since the Holocene on fluvial landforms and river system evolution, and paleofloods. Projects and funds approved for the aforementioned 17 rivers represented 19.7 and 15.5 % of the total number of projects and funding, respectively. **Apart from these rivers**, there was another 41 projects and 22,695 thousand yuan for **the Hanjiang, Haihe, Huaihe, Xiangxi, Minjiang, Xiangjiang and Taojiang rivers**, constituting 6.4 and 5.8 % of the total number of projects and funding. These seven rivers are in the monsoon region of eastern China. Research topics for these rivers were river system change, climate change and its hydrologic effects, wetland processes and species invasion, carbon and nitrogen cycles in wetland, environmental effects of hydraulic construction, water pollution prevention and remedies, and ecological restoration.

From 1986 to 2015, NSFC Geographical Sciences funded 261 projects with 151,092 thousand yuan for 71 lakes, for research in hydrology, water ecology, paleoenvironment, and water environment (Fig. 4.23). Of these lakes, large ones (with area >500 km^2) accounted for 12.7 %. Those with area between 100 and 500 km^2 made up 31 %; 28.2 % had area 10–100 km^2; 11.3 % had area 1–10 km^2; 4.2 % had area <1 km^2. Number of projects for each lake and the research topics are shown in Fig. 4.23. Studied lakes were mainly on the Qinghai-Tibetan Plateau, in arid regions of the northwest, middle and lower reaches of the Yangtze River, Yunnan Province, and Inner Mongolia Autonomous Region. (1) Forty-six and a half percent of the 71 lakes were studied in the field of **hydrology and water ecology**, consuming 49.2 % of the total funding for lakes. Lake projects receiving over 3000 thousand yuan funding were for Poyang, Taihu, Aibi, Yangzhuoyongcuo, Namucuo, Qinghai, Selincuo and Dongting lakes. Relatively large funds were put into projects for Xingkai, Bosteng, Baiyangdian, Ranwu, Chaohu, Longgan, Fuxian, and Dianchi lakes. Research topics were mainly climate change, lake water balance under land use and hydrologic construction, water and sand change, aquatic vegetation community structure, and river recharge and its relationship to lakes. Important new directions in recent years included isotope hydrology, lake evaporation and biodiversity of wetlands around lakes, and soil microorganisms. Focal points varied by region. For example, monitoring research was done for Aibi, a terminal lake in the arid region, to observe oasis–desert interactions. The spatial distribution of permafrost and simulation of its impact on permafrost hydrologic processes were studied for Zhaling Lake, the headwater of the Yellow River. In Taihu, a shallow lake in an intensively urbanised area, research mainly involved lake hydrodynamics, observations, and simulations of light intensity impacts on the ecosystem. (2) Of the 71 lakes, 26.8 % were researched for their **water environment**, and these were mainly in eastern China and Yunnan Province. This consumed about 26.8 % of the total funding for lakes. Lake projects receiving funds of over 3000 thousand yuan included those for Taihu, Chaohu, Poyang, and Dianchi lakes. Other lakes, including Baiyangdian, Nansihu, Dianshan, Yangzonghai, Aibi, Bosteng, and Fuxian, also received substantial funding. Research topics were mainly eutrophication, cyanobacteria bloom, nutrients cycling in the soil-water-sediment interface, pollutant transport and transformation, and environmental risk assessment. Nutrients target nitrogen and phosphorous. Pollutants included heavy metal, persistent organic pollutants and endocrine disruptors, and soil microbial degradation. (3) Sixty-nine percent of the 71 lakes were researched for **paleoenvironment**, and these were mainly in western China, representing 24 % of total funds for lakes. Lakes funded at over 2000 thousand yuan were only Qinghai and Namucuo. Greater funding for paleoenvironmental research was also allocated to Cuo'e, Kanas, Pumoyongcuo, Aibi, Bosteng, Hala, Tangra Yumco, Luobupo, Poyang, and Sugan lakes. Research topics centred on sedimentary processes since the Holocene, the sedimentary environment, climatic significance of environmental proxies, and lake–desert interactions. The pollen, varves, diatoms, phytoliths, halophilic algae, midges, radish snails, margarya mansuyi, carbonates, and clay minerals were all used as environmental proxies for reconstruction of regional paleovegetation and paleoenvironment.

From 1986 to 2015, the NSFC Geographical Sciences supported 761 projects with 402,678 thousand yuan for mountain research. Except for 13 projects without a clear statement of study region, the projects were in the northwest, southwest, and Qinghai-Tibetan Plateau (Fig. 4.24). Major research topics included cryosphere geography, hydrology, biogeography, and geomorphology. There was also

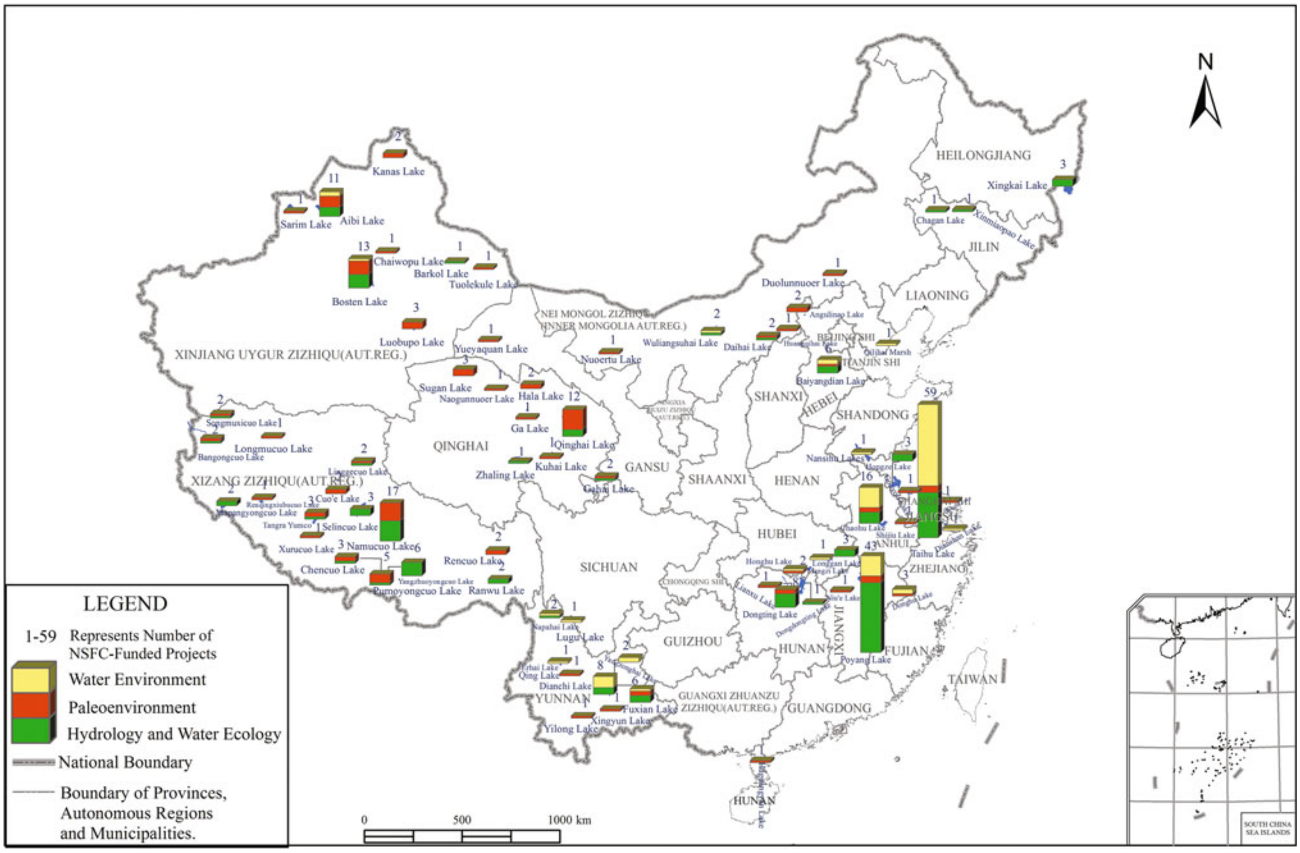
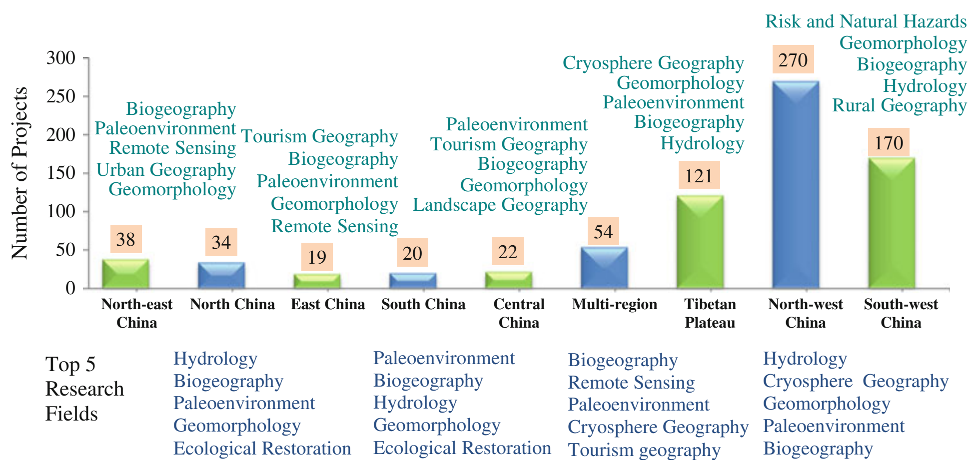


Fig. 4.23 Distribution of lakes studied by NSFC-funded projects in geographical sciences during the period 1986–2015

Fig. 4.24 Distribution of mountains studied by NSFC-funded projects in geographical sciences during the period 1986–2015



substantial research on paleoenvironment, remote sensing, natural hazards and risk assessment, ecological restoration, and tourism geography (Fig. 4.25). Six hundred and three investigators from 159 research institutions or universities nationwide coordinated these mountainous projects supported by Geographical Sciences. Institutions receiving more projects or funds included the Cold and Arid Regions Environmental and Engineering Research Institute of CAS, Institute of Mountain Hazards and Environment of CAS, Institute of Tibetan Plateau Research of CAS, Lanzhou University, Institute of Geographic Sciences and Natural Resources Research of CAS, Peking University, Xinjiang Institute of Ecology and Geography of CAS, Yunnan University, Beijing Normal University, Northeast Normal University, Yunnan Normal University, Nanjing University, and Shenyang Institute of Applied Ecology of CAS.

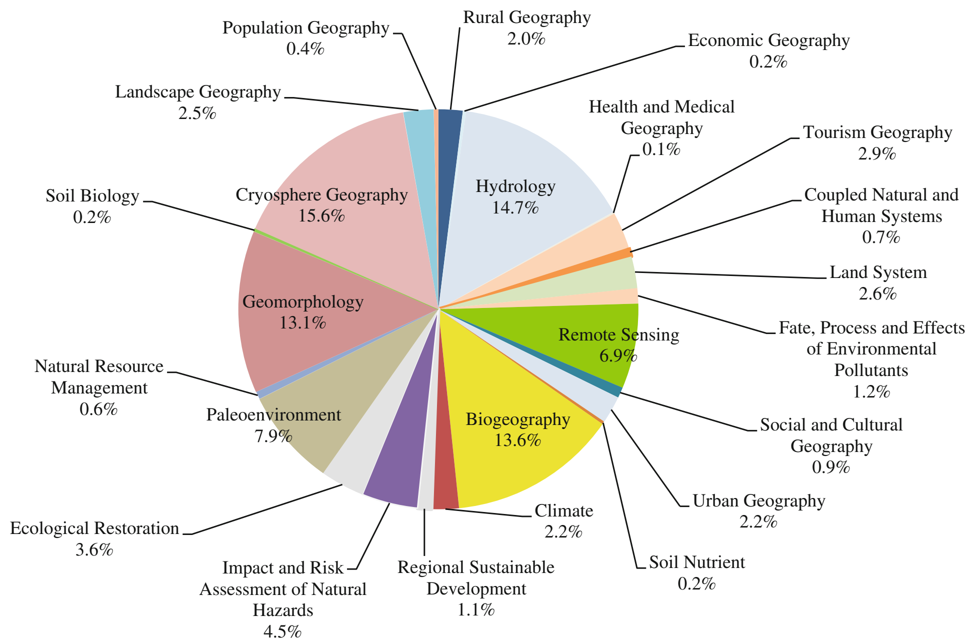


Fig. 4.25 Research topics on mountains studied by NSFC-funded projects of geographical sciences during the period 1986–2015

Research on mountains in northwestern China was largely supported in cryospheric hydrology, general glacial research, biobotany, paleoenvironment, and geomorphology. Research on mountains in southwestern China was mostly funded in the areas of natural hazards, biobotany, and tourism geography. Principal support for research on mountains of the Qinghai-Tibetan Plateau was mainly for glaciers, but there was also support for alpine tree lines and the response to climate change of alpine evergreen shrubs and herbaceous plants. Research on mountains in northeastern and northern China was mainly sustained in the field of biobotany. Research on mountain hydrology constituted a large proportion of mountain research, but the topic varied by region. For example, in the southwest, ecohydrological observation of forest micro-watersheds was the principal topic. In northwestern China, cryosphere hydrologic processes and simulations of the upper reaches of inland rivers were important topics. Research on the Qinghai-Tibetan Plateau focused on climate–hydrology interactions. In northern China, there was research into isotope hydrology of groundwater and ecohydrology in rocky mountainous areas. In the northeast region, the major topic was snow sublimation in the broadleaf Korean pine forest of the Changbai Mountains. Finally, cross-region research included mountainous plant species biodiversity, alpine tree line dynamics, comparative investigation of the vertical spectrum of alpine vegetation, comparison of paleoenvironmental records of the eastern monsoon and western regions, tourism geography of scenic areas in famous mountains, remote sensing of mountain radiative transfer, and the vertical distribution of population in mountainous areas. This research reflected characteristics of large scale or compared various types of mountains.

4.3.3 Research Teams

Analyses of research teams mainly included the following aspects: (1) number of institutions applying for NSFC projects in physical geography; (2) number of institutions publishing papers in SCI/SSCI or CSCD journals; (3) authors and their collaborative networks; (4) average number of papers from institutions supported by NSFC physical geography and the top 5 institutions receiving the most funds from that source; (5) the general situation of the highly cited papers in SCI/SSCI journals published by Chinese authors (top 50 Chinese papers and top 1000 international papers), and the top 10 institutions receiving the most NSFC funds. In the figures of collaborative networks of Chinese authors (in SCI/SSCI and CSCD journals, Figs. 4.27 and 4.28), some author names are marked with abbreviations of their institutions in case of identical names (abbreviations and full names of institutions are listed in Appendix D).

Figure 4.26 shows the number of institutions applying for NSFC physical geography funding and of institutions (all Chinese authors) with publications in SCI/SSCI mainstream journals by 5-year interval from 1986 to 2015. The green line indicates the proportion of number of institutions with publications to all institutions applying for NSFC funds.

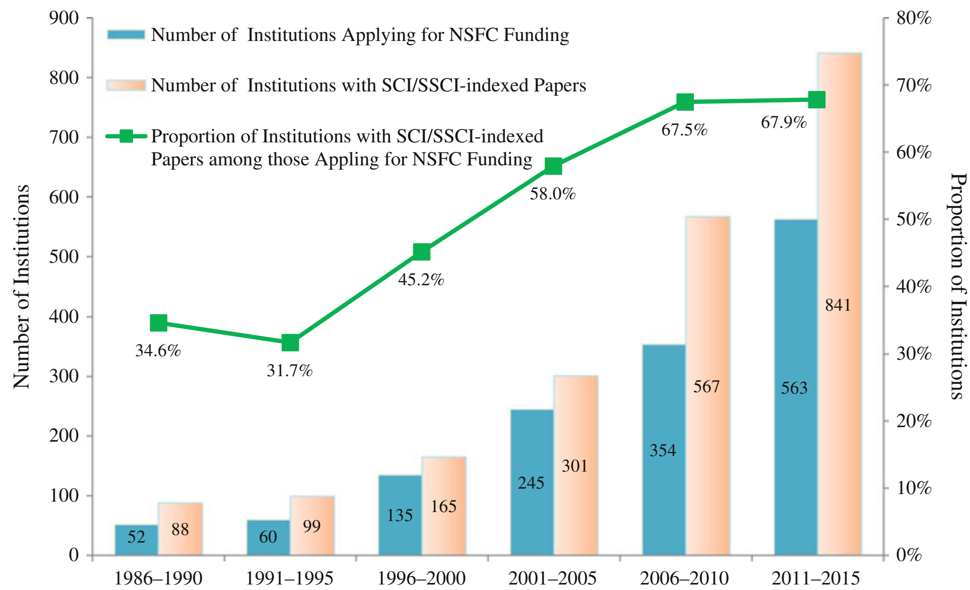


Fig. 4.26 Number of Chinese research institutions on physical geography during the period 1986–2015

Several characteristics are evident from the data shown in this figure. (1) Both the number of institutions applying for NSFC funds and that of institutions with publications in SCI/SSCI mainstream journals had been increasing, revealing that the number of institutions engaged in physical geography research in China was growing and that internationalisation was gradually improving. (2) The proportion of institutions with SCI/SSCI publications to those applying for NSFC funds had increased from an initial 35–68 % over the last 5 years, indicating that the overall research level of institutions applying for NSFC funds had greatly risen. (3) The number of institutions publishing papers in SCI/SSCI mainstream journals had exceeded that of the institutions applying for NSFC funds, and the gap was widening. Several factors were responsible for such a situation. First, investigators in some institutions are performing research that did not rely on NSFC funding. Second, some institutions had only few scientists involved in basic research. Although such institutions were not qualified to apply for NSFC projects, some of their investigators could cooperate with other qualified strong institutions to obtain NSFC funds and published papers. Third, some researchers were conducting interdisciplinary research related to physical geography, but did not apply for NSFC projects in physical geography because of their academic backgrounds. They instead chose other disciplines when applying for NSFC funding.

Figures 4.27 and 4.28 show the collaborative networks of Chinese authors who published papers in the SCI/SSCI mainstream journals and CSCD core journals of physical geography in 1986–2015 (see Appendix D for the names of institutions). Analyses on both networks suggest that the fields for papers in both SCI/SSCI and CSCD journals are generally quite similar. Therefore, we introduce them together. In the past 30 years, Chinese geographers were active in six fields, i.e., cryosphere research, hydrology and water resources, biogeography and ecosystems, geomorphology and Quaternary environment, integrated geography and landscape ecology, and natural hazards and their risks. It is also seen that core nodes of the author collaborative network are mainly important disciplinary leaders in institutions with research characteristics. The main branch nodes are middle-aged and young academic key members. Interactions among branch disciplines in physical geography are obvious. The six major research fields in the author collaborative network are introduced in the following sections.

Cryosphere Research

Research in this field was usually carried out in cold regions, like the Qinghai-Tibetan Plateau, and polar regions. (1) The author collaborative network was centred around the cold environment, glacial hydrology and water resources on the Qinghai-Tibetan Plateau, ice core and paleoclimate research, snow/ice and atmospheric chemistry, polar glacial environmental change and its relationship with climate. Major nodal authors were **Yao Tandong** and **Kang Shichang** in ITP and **Liu Shiyin** (CAREERI). Other nodal authors included **Qin Dahe**, **Ren Jiawen**, **Li Zhongqin**, **Ding Yongjian**, and **He Yuanqing** (CAREERI), and **Xu Baiqing** (ITP). Related papers had been published in the *Journal of Glaciology*, *Quaternary International*, *Hydrological Processes*, *Journal of Mountain Science*, *Global and Planetary Change*, and *Journal of Geographical Sciences*. (2) Another author

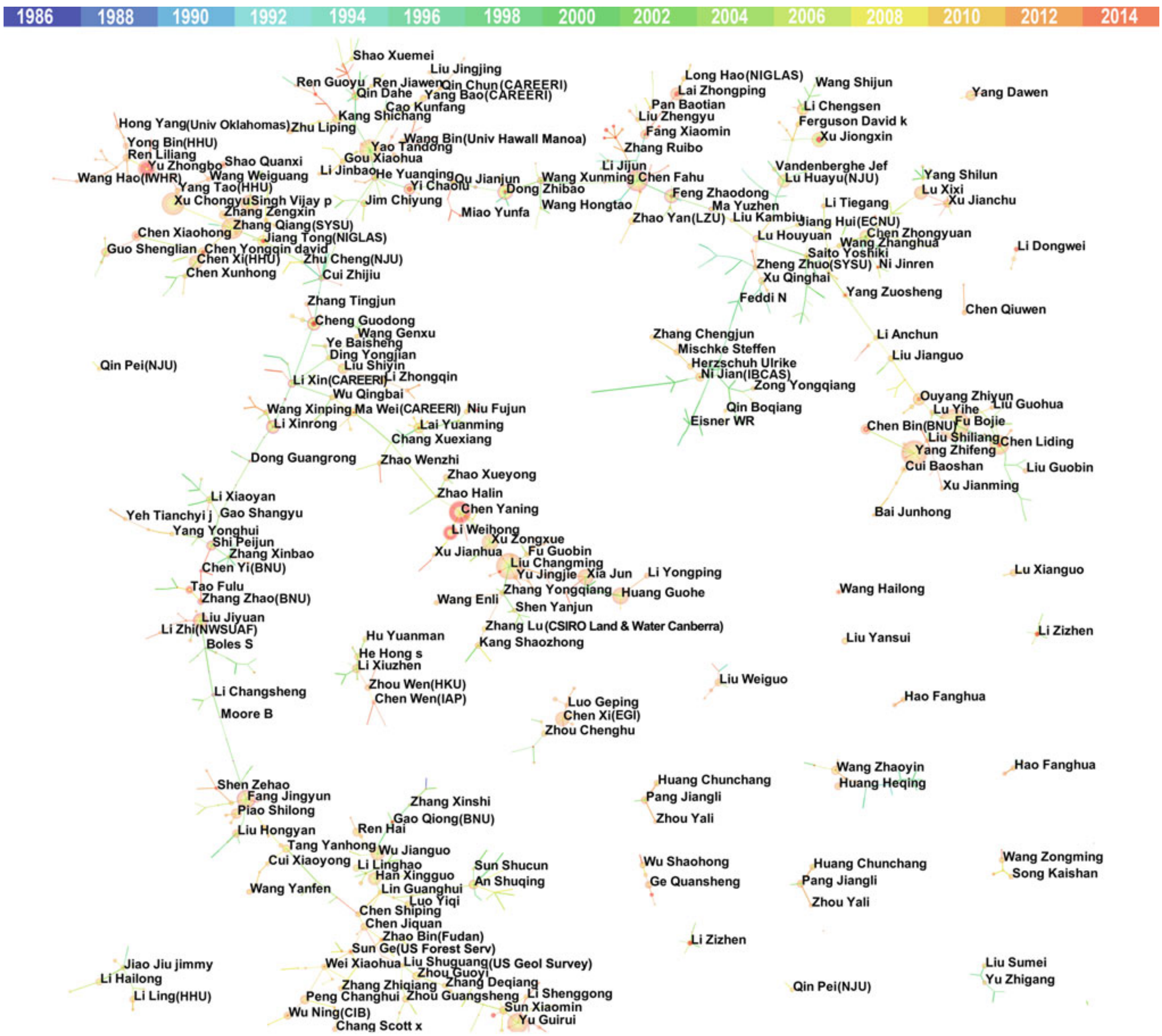


Fig. 4.27 Collaborative network of Chinese authors in SCI/SSCI mainstream journals of physical geography during the period 1986–2015

collaborative network was centred around permafrost on the Qinghai-Tibetan Plateau. Research included frozen soil mechanics, permafrost change under road construction, roadbed stability, and interactions between permafrost and climate change. Major nodal authors were **Cheng Guodong** and **Lai Yuanming** (CAREERI). Other authors of international papers were **Ma Wei**, **Wu Qingbai** (CAREERI) and **Zhang Tingjun** (LZU). Papers mainly appeared in *Cold Regions Science and Technology*, *Permafrost and Periglacial Processes*, and *Arctic, Antarctic and Alpine Research*. In addition, **Cui Zhijiu** (PKU) was an important cooperative node linking research into glaciers, permafrost, geomorphology, and the Quaternary environment.

Hydrology and Water Resources

The author collaborative network was composed of researchers in areas of hydrology and climate, hydrology and engineering, and hydrology and ecology. (1) A network formed around the water cycle, runoff generation and convergence, and impacts of climate change and human activity on the water cycle and water resources. Major nodal authors were **Liu Changming** (IGSNRR) and **Xu Zongxue** (BNU). Nodal authors also included **Zhang Yongqiang** and **Fu Guobin** from Commonwealth Scientific and Industrial Research Organization (CSIRO) and IGSNRR, and **Yu Jingjie** (IGSNRR). Major journals were *Hydrological Processes*, *Journal of Hydrology*, *Journal of Geographical*

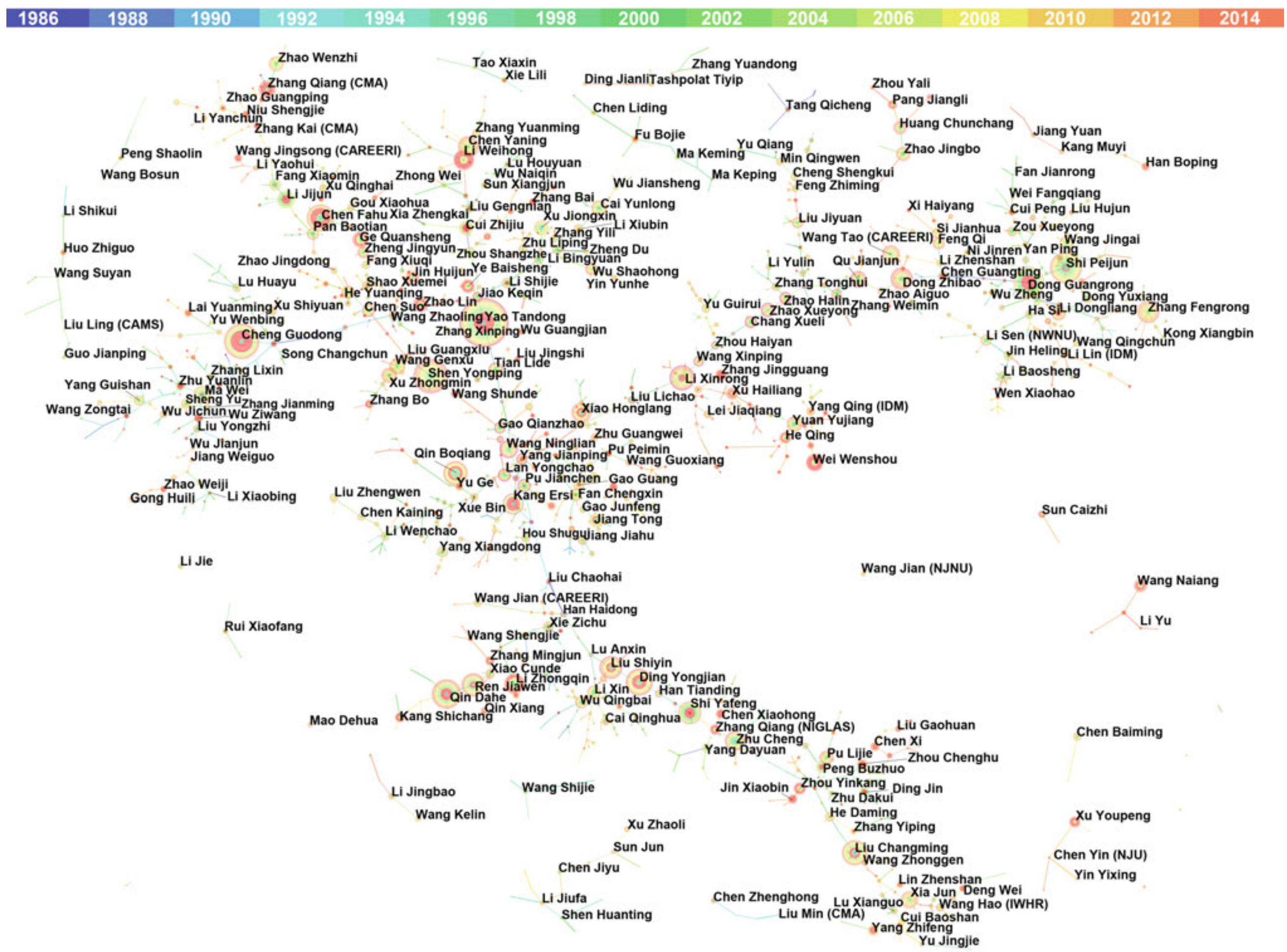


Fig. 4.28 Collaborative network of Chinese authors in CSCD journals of physical geography during the period 1986–2015

Science, and *Water International*. (2) A second network was around hydrologic processes and simulation of hydrologic responses to land-surface change. Major authors were **Yu Zhongbo** (HHU/University of Nevada) and **Chen Xi** (HHU). Other nodal authors were **Ren Liliang** and **Yong Bin** (HHU). Papers were mainly published in the *Journal of Hydrologic Engineering*, *Hydrological Processes*, *Journal of Hydrology*, and *Hydrology Research*. (3) A third network was around hydrologic forecasting, flood prevention and disaster reduction, and water resource management and allocation methods. Major nodal authors were **Huang Guohe** (NCEPU) and **Xia Jun** and **Guo Shenglian** (WHU). Papers were in *Stochastic Environmental Research and Risk Assessment*, *Water Resource Management*, *Journal of Hydrology*, and *Hydrological Processes*. (4) A fourth network formed around analysis of extreme meteorological and hydrological values, extreme climate, mechanisms and prediction of extreme hydrologic events. Major nodal authors were **Zhang Qiang** (SYSU/NIGLAS), **V.P. Singh** from Texas A&M University (TAMU), and **Xu Chongyu** from The University of Oslo (UIO) and NIGLAS. Other authors were **Chen Yongqin David** (CUHK), **Chen Xiaohong** (SYSU), **Yang Tao** (HHU), and **Shao Quanxi** (CSIRO/HHU). Papers were mainly in the *Journal of Hydrology*, *Stochastic Environmental Research and Risk Assessment*, *Hydrological Processes*, *Theoretical and Applied Climatology*, and *Journal of Hydrologic Engineering*. (5) A fifth network was around vegetation pattern processes in the arid region and desert ecohydrological research. Major nodal authors were **Chen Yaning** (EGI) and **Li Xinrong** (CAREERI). Other nodal authors included **Li Weihong** (EGI) and **Wang Xinping** (CAREERI). Related papers were published in *Hydrological Processes*, *Journal of Arid Environments*, *Arid Land Research and Management*, and *Ecohydrology*. (6) A sixth network was around wetland hydrology and ecology and ecological risk assessment. A major nodal author was **Yang Zhifeng** (BNU). Other nodal authors included **Cui Baoshan** and **Chen Bin** (BNU). Papers were principally in *Ecological Modelling*, *Ecological Engineering*, and *Journal of Hydrology*.

Biogeography and Ecosystems

Research networks were mainly centred around carbon storage in terrestrial ecosystems and its response to climate change, vegetation productivity, vegetation distribution and dynamic change, and plant biodiversity. (1) The first network formed around global change biogeography and ecology, including nodal authors **Fang Jingyun** and **Piao Shilong** (PKU) and **Yu Guirui** (IGSNRR). Nodal authors also included **Liu Hongyan** (PKU) and **Peng Changhui** (UQ/Northwest A&F University), **Wu Ning** (CIB), **Sun Xiaomin** (IGSNRR), and **Zhou Guoyi** and **Ren Hai** (SCIB). Papers were mainly published in *Nature*, *PNAS*, *Global Change Biology*, *Agricultural and Forest Meteorology*, *Biogeosciences*, *Global Ecology and Biogeography*, *Global and Planetary Change*, and *Global Biogeochemical Cycles*. (2) A second network formed around distributions of biological communities and their relationships to the environment, vegetation structure and function, and plant biodiversity. Major nodal authors were **Wu Jianguo** (Arizona State University), **Ni Jian** (IBCAS), **An Shuqing** (NJU), and **Huang Yao** (IBCAS). Papers were in *Landscape Ecology*, *Ecological Engineering*, *Journal of Arid Environments*, *Ecological Modelling*, and *Ecological Research*.

Geomorphology and Quaternary Environment

Networks mainly formed around topics of fluvial, eolian, glacial and periglacial landforms, plus Quaternary environmental changes. (1) The first network was around records of paleoenvironmental change (river terraces, lake sediments, pollen, tree rings and historical documents), spatiotemporal evolution of paleoclimate, and proxies of environmental change. Major nodal authors were **Chen Fahu** and **Li Jijun** (LZU), **Feng Zhaodong** (EGI), **Fang Xiaomin** (ITP), **Lai Zhongping** (ISL), **Lu Huayu** (NJU), **Li Chengsen** (IBCAS), and **Ge Quansheng** (IGSNRR). Nodal authors were **Pan Baotian** and **Gou Xiaohua** (LZU), **Zhao Yan** (LZU/IGSNRR), **Jef Vandenberghe** (Vrije University, Amsterdam), **Yang Bao** (CAREERI), **Xu Qinghai** (HBNU), **Zheng Zhuo** (SYSU), **Zhu Liping** (ITP), **Shao Xuemei** (IGSNRR) and **David Ferguson** (University of Vienna). Papers were published in *Quaternary International*, *Quaternary Research*, *Quaternary Geochronology*, *Global and Planetary Change*, *Holocene*, *Quaternary Science Reviews*, and *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*. (2) The second network was around fluvial landforms. Major nodal authors were **Chen Zhongyuan** (ECNU) and **Xu Jiongxin** (IGSNRR). Nodal authors were **Saito Yoshiki** (Geological Survey Japan) and **Wang Zhanghua** (ECNU). Papers mainly appeared in *Geomorphology*, *Estuarine & Coastal and Shelf Science*, and *Holocene*. (3) A third network was eolian landforms, with a focus on mechanisms of dust release, impacts of eolian activities on the composition of eolian deposits, and changes in topography. Major nodal authors were **Dong Zhibao** (CAREERI), and nodal authors included **Qu Jianjun** (CAREERI) and **Wang Xunming** (CAREERI/IGSNRR). Papers were principally in *Geomorphology* and *Journal of Arid Environments*. (4) A fourth network of glacial and periglacial landforms formed around research into glaciers on the Qinghai-Tibetan Plateau and surrounding mountains. The major nodal author was **Cui Zhijiu** (PKU). Nodal authors included **Yi Chaolu** (ITP) and **Zhu Cheng** (NJU). Papers were published in *Quaternary International*, *Permafrost and Periglacial Processes*, *Journal of Glaciology*, *Geomorphology*, and *Journal of Geographical Sciences*.

Integrated Geography and Landscape Ecology

This network was mainly about landscape patterns and processes, LUCC, and water resource and food security. (1) The first network formed around landscape pattern and processes and ecosystem services in the Loess Plateau region. Nodal authors were **Fu Bojie** and **Chen Liding** (RCEES). Nodal authors included **Liu Guohua** and **Lü Yihe** from the same institute. Papers were mainly published in *Catena*, *Progress in physical geography*, *Hydrology and Earth System Sciences*, *Ecological Research*, and *Journal of Hydrology*. (2) There was a second network around LUCC, which formed around **Liu Jiyuan** (IGSNRR) and **Chen Xi** (EGI). Nodal authors included **Zhang Zhao** (BNU), **Tao Fulu** (IGSNRR), **Zhou Chenghu** (IGSNRR), and **Luo Geping** (EGI). Research methods were geographical information system and remote sensing. Papers were mainly in *Ecological Modelling*, *Journal of Arid Land*, *Agricultural and Forest Meteorology*, *Journal of Geographical Sciences*, *Global and Planetary Change*, *Hydrological Processes*, and *Water Resources Management*.

Natural Hazards and Their Risks

Major nodal authors of papers in natural hazards and their risks were **Cui Peng** (IMHE) and **Shi Peijun** (BNU). Papers were published in *Journal of Mountain Science*, *Natural Hazards*, *Ecological Engineering*, *Landscape and Urban Planning*, and *Geomorphology*.

In addition to the abovementioned important nodal authors in the networks appeared in both SCI/SSCI and CSCD journals, there were also some authors form important nodes in the network of CSCD journals. However, because their works were either on regional characteristics in

China or earlier pioneering work when the internationalization level was low. Moreover, their research results were mainly published in Chinese and could not be reflected in the SCI/SSCI journal-based network. Earlier research on glaciers on the Qinghai-Tibet Plateau included that done by **Xie Zichu**, **Shi Yafeng** (CAREERI), **Zhou Shangzhe** (LZU/SCNU) and **Liu Gengnian** (PKU). Nodal authors of researches in ice core or precipitation isotopes in the Qinghai-Tibet Plateau included **Wang Ninglian** (CAREERI), **Tian Lide** and **Wu Guangjian** (ITP). **Dong Guangrong** and **Wang Tao** (CAREERI) were nodal authors in desert environment and desertification in China. Research on the Kerqin Sandy Land and Tengger Desert were carried out by **Zhao Xueyong**, **Zhao Halin** and **Xiao Honglang** (CAREERI). Their studies focused on observations of soil water change, ecohydrological processes, biodiversities and vegetation restoration. **Zheng Jingyun** (IGSNRR) and **Fang Xiuqi** (BNU) were nodal authors carrying out research in extracting paleoclimatic information from historical documents in the fields of environmental change or global change. In the network of integrated geography, researches on LUCC, land systems, sustainable assessment of land use and farmland resource and food security from the perspectives of integrated physical geography were represented by **Cai Yunlong** (PKU) and **Li Xiubin** (IGSNRR). Research focusing on the natural environment of the Qinghai-Tibetan Plateau and its regional differentiations, Chinese ecological and geographical zoning system, and climate change and LUCC, from the perspectives of geobotany and geomorphology was led by **Zheng Du**, **Li Bingyuan**, **Zhang Yili** and **Wu Shaohong** (IGSNRR). **Zhang Yuanming** (EGI) carried out research on desert ecosystems in the inland river basins in Xinjiang and the influence of climate change and exploitation in oases. Ecological security of international rivers was studied by **He Daming** (YNU). The network centred on **Zhang Fengrong** (CAU) indicates researches on farmland protection, rural residential land reorganization and land quality from the perspective of pedogeography using Beijing as a major case. Additionally, **Qin Boqiang, Fan Chengxin** (NIGLAS) and **Lü Xianguo** (NEIGAE) were nodal authors of studies on lakes and wetlands in China. Overall, above nodal authors conducted research pertaining to regional characteristics or earlier pioneering work in China. Their research has been influential in China and played an important role in promoting later research in the international science community.

According to statistics of the top 200 Chinese authors who published papers in the SCI/SSCI physical geography journals during 1986–2015, there were 4461 papers published in 121 journals. Journals with the most papers from Chinese authors were *Hydrological Processes* and *Journal of Hydrology*, with more than 200 papers in both journals, accounting for about 10 % of all 4461 papers. Other journals with numerous publications were *Quaternary International*, *Journal of Climate*, *Journal of Geographical Sciences*, *Ecological Modelling*, *Ecological Engineering*, *Geomorphology*, *Cold Regions Science and Technology*, *Stochastic Environmental Research and Risk Assessment*, *Agricultural and Forest Meteorology*, *Global and Planetary Change*, and *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*. In total, there were 1353 papers in the aforementioned journals, a proportion of 30 %. The remaining 108 journals published about 60 % of the 4461 papers, but the average proportion of each journal was less than 2 %.

Nearly 77 % of authors publishing in the SCI/SSCI mainstream journals and 86 % of authors publishing in Chinese CSCD journals were supported by NSFC projects. Thirty-two authors rank in the top 100 authors with the most publications in both SCI/SSCI and CSCD journals. They were granted 587 projects funded by NSFC. Of the top 100 authors with the most publications in SCI/SSCI journals, 21 were once supported by the Young Scientists Fund (YSF), 24 by the National Science Fund for Distinguished Young Scholar (DYS Fund) (including scholars with foreign citizenship). Six groups, led by **Chen Fahu**, **Fu Bojie**, **Yao Tandong**, **Qin Dahe, Ma Wei** and **Zhou Chenghu**, were supported by the Science Fund for Creative Research Groups (CRG Fund). The sum of funds supporting the Key Programme (KP), Major Programme (MP), and Major Research Plan (MRP) made up 58.2 % of total funds, and this proportion for the General Programme (GP) was 15.8 %. Of the top 100 authors with the most publications in CSCD journals, 68 were granted different types of projects funded by NSFC and 47.8 % of the total funds were granted to them as the Key Programme (KP), Major Programme (MP) and Major Research Plan (MRP). The General Programme (GP) and the Young Scientists Fund (YSF) granted to them account for 33.7 and 7.9 % of the total funds, respectively. The above data suggest that the talent-oriented programmes such as the National Science Fund for Distinguished Young Scholar (DYS Fund) and Science Fund for Creative Research Groups (CRG fund), and the importance-based types such as “Key” and “Major” NSFC programmes have been important to international academic achievements of physical geography in China.

Table 4.2 shows institutions, number of people supported, and the sum of funds for the top five institutions funded by NSFC physical geography by 5-year intervals from 1986 to 2015. The number of people refers to the total of those funded by NSFC within an institution in each 5-year period. The same person was only counted once in the 5 years. In the past 30 years, there were nine institutions entering the top five supported by NSFC, of which four were universities and five were research institutes. Institute of Geographic Sciences and Natural Resources Research of CAS, Cold and Arid Regions Environmental and

Table 4.2 Top 5 institutions with NSFC funding for physical geography during the period 1986–2015

1986-1990			1991-1995			1996-2000		
Institutions	Number of PIs	Funding (10,000 yuan)	Institutions	Number of PIs	Funding (10,000 yuan)	Institutions	Number of PIs	Funding (10,000 yuan)
Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences	21	125.6	Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences	25	432.7	Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences	30	1,170.5
Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences	23	115.8	Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences	29	401.6	Peking University	15	930.5
Peking University	10	45.7	Peking University	11	139.8	Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences	23	488
Northeast Institute of Geography and Agricultural Ecology, Chinese Academy of Sciences	6	40.5	Beijing Normal University	3	126.5	Lanzhou University	8	377
Nanjing University	10	37.5	Institute of Mountain Hazards and Environment, Chinese Academy of Sciences	10	86	Institute of Mountain Hazards and Environment, Chinese Academy of Sciences	7	294
Total of top 5	70	365.1	Total of top 5	78	1,186.6	Total of top 5	83	3,260
Total of non top 5	74	333.4	Total of non top 5	112	884.9	Total of non top 5	118	2,243
Total of physical geography	144	698.5	Total of physical geography	190	2,071.5	Total of physical geography	201	5,503
Sum of geography	294	1,362.3	Total of geography	374	3,840.6	Total of geography	422	9,984.9
2001-2005			2006-2010			2011-2015		
Institutions	Number of PIs	Funding (10,000 yuan)	Institutions	Number of PIs	Funding (10,000 yuan)	Institutions	Number of PIs	Funding (10,000 yuan)
Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences	57	3,780.6	Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences	118	8,801	Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences	176	16,399.2
Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences	47	2,014.9	Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences	62	3,945.5	Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences	106	10,126.6
Lanzhou University	22	1,443	Lanzhou University	35	2,940.9	Institute of Tibetan Plateau Research, Chinese Academy of Sciences	69	9,321.3
Peking University	22	1,402.8	Institute of Tibetan Plateau Research, Chinese Academy of Sciences	34	2,529.8	Lanzhou University	59	6,522.9
Beijing Normal University	22	1,017.6	Peking University	24	1,952.6	Beijing Normal University	46	5,992.4
Total of top 5	170	9,659	Total of top 5	273	20,169.8	Total of top 5	456	48,362.4
Total of non top 5	185	5,862.6	Total of non top 5	450	19,698.7	Total of non top 5	1,006	67,269.5
Total of physical geography	355	15,521.6	Total of physical geography	723	39,868.5	Total of physical geography	1,462	115,631.9
Total of geography	890	33,800.6	Total of geography	2,197	90,823.6	Total of geography	4,821	304,971.3

Engineering Research Institute of CAS and Institute of Tibetan Plateau Research of CAS (established in 2005) had always been within the top five positions, indicating their major advantages in the study of physical geography.

In Fig. 4.29, the per capita SCI/SSCI-indexed articles are those of institutions listed in Table 4.2, calculated by dividing total papers supported by NSFC in the 134 SCI/SSCI mainstream journals by the total number of people supported. The funding proportion is the sum of funds received from NSFC in these listed institutions to total NSFC physical geography funds in each five-year bin. This shows that the funding proportion was rising before 2005 and reached 62.2 % in 2001–2005. However, this figure has dropped rapidly to 41.8 % in recent years. Such a process suggests that with improvement of the overall level of the discipline, traditional advantageous institutions in physical geography had gradually lost their dominance in the acquisition of funding. Per capita publications had been increasing. The number of such publication was less than one before 2000 but had increased rapidly to 2.8 in 2001 and 2005, exceeding the number of other institutions. By 2011–2015, this number reached 5.6, twice that from a decade earlier, further widening the gap between the top five institutions and other institutions. This reflects a rapid improvement in the internationalisation of research in China.

With the increase of per capita publications, the number of highly cited papers in physical geography in China had also increased. Figure 4.30 shows that the proportion of NSFC-funded papers to the top 50 highly cited papers by Chinese authors in SCI/SSCI journals had been increasing, from 48 % in 2000 to 86 % in 2014. This proportion had increased by ~30 % since 2009. The proportions of articles by the top 10 institutions to the top 50 highly cited articles did not fluctuate much, with a minimum of 24 % (in 2010) and maximum of 48 % (in 2006). The proportion of publications from the top 10 institutions (with most NSFC funds) increased from 71.4 % in 2000 to 94.1 % in 2014, indicating that such publications were almost all supported by NSFC in the last 5 years. In conclusion, the top 10 most advantageous institutions had produced ~30 % of influential SCI/SSCI-indexed articles in China. NSFC projects had been important in the publication of these influential papers, as 2/3 of all the top 50 highly cited papers in SCI/SCCI journals were funded by NSFC.

The growth rate of the highly cited papers in China was accelerating, but the number of the highly cited papers has remained limited. Within the top 1000 highly cited SCI/SSCI-indexed articles, Chinese authors contributed 14 in 2000–2004 and 50 in 2010–2014. The top 1000 highly cited papers in various periods (Table 4.3) indicate that the U.S. authors contributed 465 (46.5 %) in 2000–2014, and

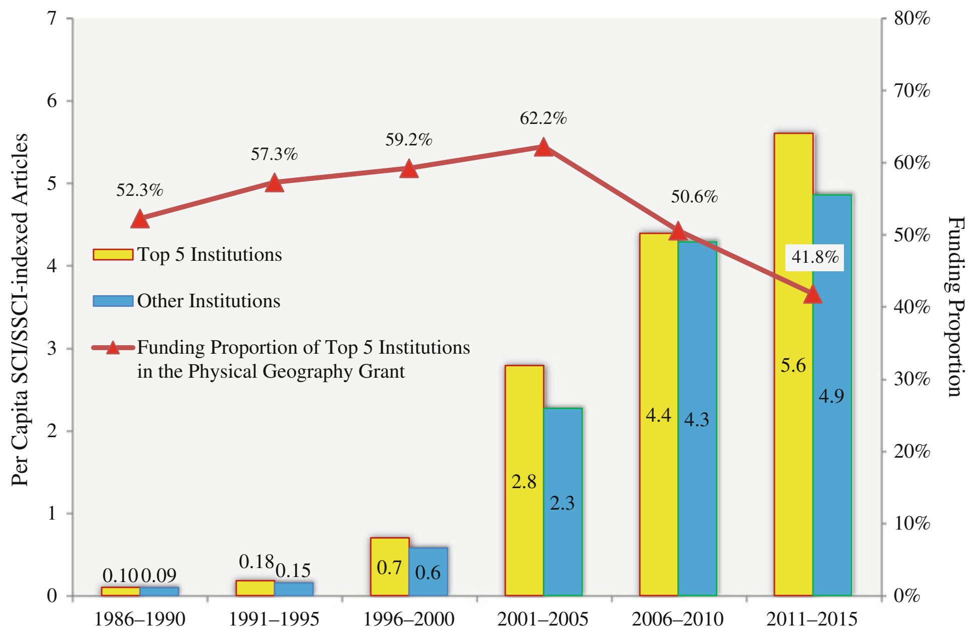


Fig. 4.29 Funding proportion of top 5 NSFC-funded institutions and their per capita SCI/SSCI-indexed articles in physical geography during the period 1986–2015. *Note* Co-authors from different institutions were counted separately

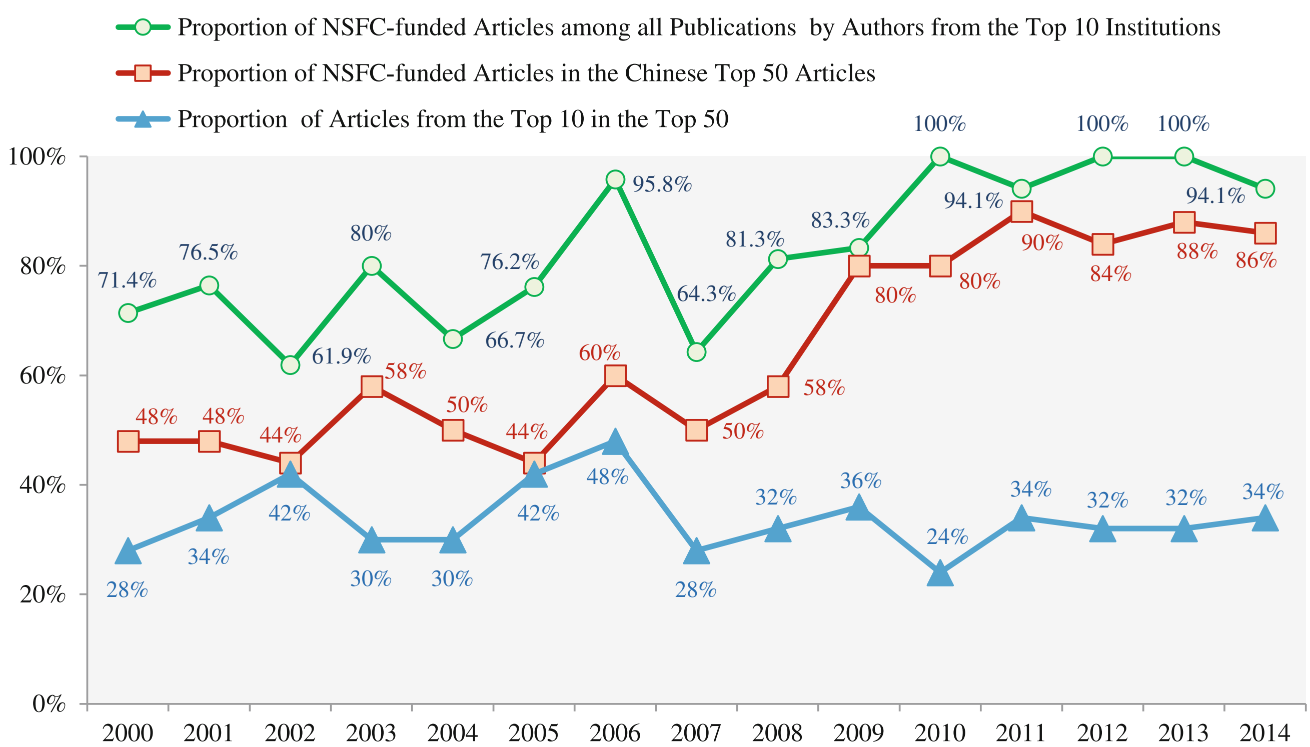


Fig. 4.30 Proportion of NSFC-funded SCI/SSCI-indexed articles in Chinese top 50 citation in physical geography during the period 2000–2014. *Note* The top 10 institutions refer to those with top 10 NSFC's annual funding for physical geography during the period 2000–2014, including the Cold and Arid Regions Environmental and Engineering Research Institute of CAS, Institute of Geographic Sciences and Natural Resources Research of CAS, Institute of Tibetan Plateau Research of CAS, Lanzhou University, Peking University, Beijing Normal University, Xinjiang Institute of Ecology and Geography of CAS, Research Center for Eco-Environmental Sciences of CAS, Nanjing Institute of Geography and Limnology of CAS, Northeast Institute of Geography and Agricultural Ecology of CAS, Nanjing University, and Institute of Mountain Hazards and Environment of CAS

Table 4.3 Analysis of top 1000 highly cited SCI/SSCI articles in physical geography during the period 2000–2014

Periods	% of articles by American authors	% of articles by Chinese authors	% of articles with NSFC funding by Chinese authors	% of articles from Top 10 institutions with NSFC funding to articles by Chinese authors	% of articles from Top 10 institutions with NSFC funding to articles funded by NSFC
2000-2004	47.6	1.4	42.9	35.7	60.0
2005-2009	42.0	2.7	55.6	22.2	100.0
2010-2014	31.9	5.0	80.0	32.0	93.8
2000-2014	46.5	0.9	33.3	44.4	50.0

Note The Top 10 institutions refer to those with top 10 NSFC's annual funding for physical geography during the period 2000–2014, including the Cold and Arid Regions Environmental and Engineering Research Institute of CAS, Institute of Geographic Sciences and Natural Resources Research of CAS, Institute of Tibetan Plateau Research of CAS, Lanzhou University, Peking University, Beijing Normal University, Xinjiang Institute of Ecology and Geography of CAS, Research Center for Eco-environmental Sciences of CAS, Nanjing Institute of Geography and Limnology of CAS, Northeast Institute of Geography and Agricultural Ecology of CAS, Nanjing University, and Institute of Mountain Hazards and Environment of CAS

Chinese authors contributed 9 (0.9 %). In the past 15 years, the proportion of papers by the U.S. authors decreased by 15.7 % and that by Chinese authors increased by 3.6 %. For the papers published by Chinese authors, the proportion of those supported by NSFC had been increasing, from 42.9 % in 2000–2004 to 80 % in 2010–2014. The proportion of papers published by the top 10 institutions decreased from 35.7 % in 2000–2004 to 22.2 % in 2005–2009 and 32 % in 2010–2014. Of the papers funded by NSFC, the proportion of those published by the top 10 institutions increased from 60 % in 2000–2004 to 93.8 % in 2010–2014. The above data show that high-quality research results in physical geography in China, which are recognised internationally, had increased rapidly in the last 5 years. Eighty percent of these results were supported by NSFC projects. Ninety percent of the highly cited papers supported by NSFC were from the top 10 institutions funded by NSFC physical geography projects, and highly cited papers from those institutions accounted for more than 30 % of all highly cited papers published by Chinese authors.

For further analysis of the relationship between research themes of the highly cited papers from Chinese authors and themes in their NSFC projects, the top 10 most frequent keywords by those authors were selected from the top 1000 highly cited papers in physical geography. The proportion of the top 10 most frequent keywords to total number of papers published by Chinese authors was calculated (referred to as the "paper-based top 10 keywords"). The proportion of top 10 most frequent keywords in projects supported by NSFC was also determined (referred to as "project-based top 10 keywords"). Comparison of the paper-based and project-based keywords (Fig. 4.31) shows that 50 % of the two types of keywords were identical, including *climate change*, *model*, *Tibetan Plateau*, *Holocene*, and *environmental change*. This indicates that NSFC projects had provided a basis for highly influential research outputs in Chinese physical geography and had been at the frontiers of development of the discipline. The keywords *climate change* and *Holocene* already had a place in NSFC-funded projects during 2000–2004, but did not appear in the highly cited papers until 2005–2009. This indicates a lag from research to publication and in becoming a highly cited paper. It also demonstrates the importance of the accumulation of research results. The distribution of the paper-based top 10 keywords shows that physical geography in China had produced influential research results in climate change, the Qinghai-Tibetan Plateau, Holocene environmental change, and hydrology. The project-based top 10 keywords had correspondence with the paper-related top 10 keywords, further indicating the substantial attention paid by basic research in Chinese physical geography to major global topics, methodology, and basic scientific issues. Of all the keywords, *LUCC* represents substantial attention to the impacts of global (not just climate change and human activities). *Isotope hydrology* represents strong emphasis on the methodology of hydrology. *Scale* and *scale effect* represent an emphasis on scientific issues. Proportions of keywords in different periods show that paper-based keywords such as *precipitation, water*, *carbon*, and *model* have increased in the last 5 years. Project-based keywords *climate change*, *model, hydrological model*, and *water cycle* also increased, revealing that simulating the impact of climate change on the water and carbon cycles had become a frontier of research in physical geography in China. **Piao Shilong** from Peking University, **Liu Junguo** from Beijing Forestry University, **Zhang Qiang**

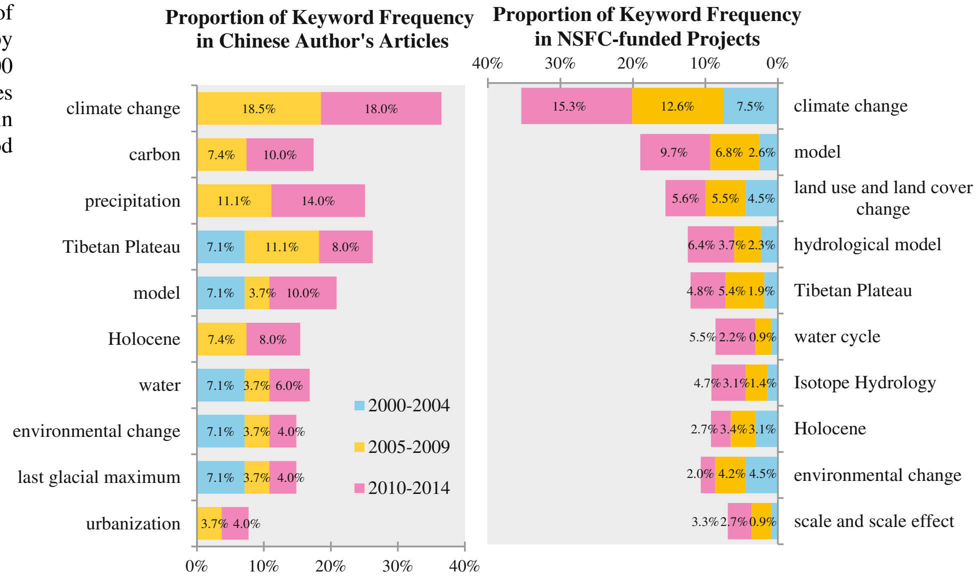


Fig. 4.31 Comparative diagram of prominent keywords in the articles by Chinese authors among the top 1000 highly cited SCI/SSCI-indexed articles with those in NSFC-funded projects in physical geography during the period 2000–2014

from Sun Yat-sen University, and **Yang Tao** from Hohai University had all published highly cited SCI/SSCI-indexed articles focusing on the aforementioned topics.

4.4 Summary

In the past 30 years, with the promotion of many international major scientific programmes, research into physical geography in China has gradually developed a main line of research guided by global change and the comprehensive pattern of the earth surface. Disciplinary-exclusive research is weakening. Instead, question-oriented research is gradually becoming dominant and physical geography is developing toward multi-element and comprehensive research. Frontier research in China has followed trending global topics in the water cycle and water resources, terrestrial ecosystems, LUCC, and cryosphere evolution. However, faced by regional environmental problems, Chinese scholars have done substantial research in permafrost engineering and the permafrost environment, natural hazards and risk, lake ecosystems and eutrophication, and ecohydrological processes and water resource utilisation in arid regions. This research was aimed at resolution of the associated problems. Overall, comprehensive research on the Qinghai-Tibetan Plateau, arid regions of northwestern China, Loess Plateau, and Taihu Lake has reflected research characteristics of physical geography in China and promoted international academic influence. In 1986–2015, the number of papers published in the SCI/SSCI mainstream journals and CSCD journals of physical geography had rapidly increased. Half of these papers were published in the last decade. The proportion of papers published by Chinese authors in the SCI/SSCI mainstream journals reached 12.9 % in the last 5 years. The per capita publication figure was 5.3, 2.1 times that of 10 years ago. Average citations of the top 100 highly cited papers of each country in the SCI/SSCI mainstream journals show that the United States has stabilised at the top, and China has risen to number 8. However, the average citations of all papers published by Chinese authors remain less than the average of the top 20 countries (regions).

NSFC has played an important role in Chinese physical geography research. In the past 30 years, of the top 100 authors with the most publications in the CSCD journals, 86 % were supported by projects granted by NSFC. Of the top 100 authors publishing in the SCI/SSCI journals, 77 % were supported. There were 32 researchers among the top 100 authors with the most publications, in both the SCI/SSCI and CSCD journals. In the last 10 years, 76.4 % of papers by Chinese authors in the SCI/SSCI journals and 73 % in the CSCD journals were supported by NSFC projects. Of the top 50 highly cited papers in SCI/SSCI journals published by Chinese authors in 2010–2014, 85.6 % were supported by NSFC projects, 1.7 times that in 2000–2004. In 2010–2014, the proportion of the top 1000 highly cited SCI/SSCI-indexed articles from Chinese authors increased by 3.6 % compared with 2000–2004, and 80 % of those authors were supported by NSFC projects. Institutions receiving greater funding include Institute of Geographic Sciences and Natural Resources Research of CAS, Cold and Arid Regions Environmental and Engineering Research Institute of CAS, Institute of Tibetan Plateau Research of CAS, Peking University, Beijing Normal University and Lanzhou University. They have not only become the most advantageous research institutions in Chinese physical geography but have also been increasingly important in major international scientific programmes and global comprehensive research.

Human Geography

5

Shuying Leng, Canfei He, Zhigang Li, Ying Wang, Fengkui Qian, Desheng Xue, Geng Lin, Ye Liu, and Yuqi Liu

Abstract

Human geography is a major geographical discipline that is mainly concerned with the spatial differentiation or spatial organization of human activities, and the ways in which people use natural resources. Human geographers not only examine the issues of population, society, culture, economy, and politics but also their related impacts upon regions, cities, and rural areas, as well as the society-nature relationships such as resource management. According to the NSFC, human geography is partitioned into four divisions: economic geography, social and cultural geography, urban geography, and rural geography. This chapter is based on an examination of 84 mainstream SCI/SSCI-indexed human geography journals, together with 12 Chinese (CSCD) core journals. Chinese human geographers have conducted a large number of studies into land use and management, urbanization and urban systems, regional sustainable development, and tourism. They also have paid particular attention to industrial agglomerations, foreign direct investment, international trade, global cities, and other key international topics. From 1986 to 2015, there have been substantial increases in the number of papers published in the mainstream SCI/SSCI-indexed human geography journals and in the Chinese human geography journals. About one-half of these papers are published over the last decade. Papers published by Chinese scholars in the mainstream SCI/SSCI-indexed journals account for 5.6 % of the total. On average, each Chinese author published about 1.5 SCI/SSCI-indexed articles, five times more than 10 years ago. The NSFC has played a significant role in Chinese human geography research. Over the last three decades, 84 % of the top 100 authors with the most publication in the Chinese journals and 63 % of the top 100 Chinese authors with the most publications in the SCI/SSCI journals have received funding for NSFC geographical sciences' projects.

Keywords

Human geography • Research topics in human geography • NSFC-funded projects for human geography • Chinese scholars and institutions of human geography

Human geography is a major geographical discipline that is mainly concerned with the spatial differentiation or spatial organization of human activities, and the ways in which people use natural resources. Human geographers not only examine the issues of population, society, culture, economy, and politics but also their related impacts upon regions, cities, and rural areas, as well as fields relevant to society-nature relationships such as resource management. According to the NSFC, human geography is partitioned into four divisions: economic geography, social and cultural geography, urban geography and rural geography. Although it is considered a part of the field of environmental

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geography, regional sustainable development is also closely connected with human geography. This section is based on an examination of 84 mainstream SCI/SSCI-indexed human geography journals, including 38 comprehensive journals and 46 specialised journals, together with mainstream Chinese journals (CSCD-indexed journals).

Figure 5.1 shows the number of articles published in the 84 mainstream SCI/SSCI-indexed journals from 1986 to 2015 to which Chinese scholars contributed. The total number of human geography articles was 88,439 (papers in some journals published before 1990 were not counted), of which 58 % were published in the last decade. The total number of papers published by Chinese authors was 2466 (which accounted for 2.9 % of papers worldwide). Of these papers, 87.3 % were published in the last 10 years. Over the last 10 years, Chinese authors contributed 4.2 % of papers worldwide. Over the last 5 years, the percentage increased to 5.6 %. Among papers published in the SCI/SSCI journals written by Chinese authors, there were 1005 NSFC-funded articles in geographical sciences, of which 95.8 % were published in the last ten years. NSFC sponsored 40.8 % of SCI/SSCI-indexed articles over the last 30 years. The proportion of SCI/SSCI-indexed articles sponsored by NSFC increased from 14.1 % in the period of 2001–2005 to 48.5 % in the period of 2006–2010, decreasing to 43.2 % of 2011–2015. Human geography research is affected by factors such as social and economic development, political, cultural, institutional context, and decision-making requirements. Scholars from different countries have different value orientations. There are a number of reasons why the international academic profile of Chinese scholars has risen rapidly in less than two decades. The theoretical development and practical requirements of China's market reform and opening up over the last three decades, NSFC's support of the free exploration of academic frontiers, the increasing frequency of international academic exchanges, and the introduction of overseas talent have all played important roles in raising Chinese human geography to world standards. However, the decreasing proportion of NSFC sponsored papers in the total SCI/SSCI-indexed articles suggests that it is necessary to guide and support basic and cutting-edge research.

Figure 5.2 shows the quantity of papers published in 12 CSCD and Chinese core human geography journals and the share of papers supported by the NSFC over the past 30 years. The 12 CSCD and Chinese core human geography journals were *Resources and Environment in the Yangtze Basin*, *City Planning Review*, *Scientia Geographica Sinica*, *Acta Geographica Sinica*, *Geographical Research*, *Areal Research and Development*, *Economic Geography*, *Human Geography*, *China Population Resources and Environment*, *China Land Sciences*, *Resources Science*, and *Journal of Natural Resources*. A total of 19,102 human geography articles had been published over the past three decades, of which 51.1 % were published in the last 10 years. There were 7050 NSFC-funded CSCD-indexed articles, of which 66.7 % were published in the last 10 years. The proportion of NSFC-funded articles in the last 30 years was 36.9 %, less than 35.4 % in 2001–2005; this increased to 45 % in 2006–2010 and reached to 51.2 % in 2011–2015. For papers published in CSCD human geography journals over the last three decades, the average number of citations per paper sponsored by NSFC geographical sciences programmes was higher in every successive 5-year period than the average for

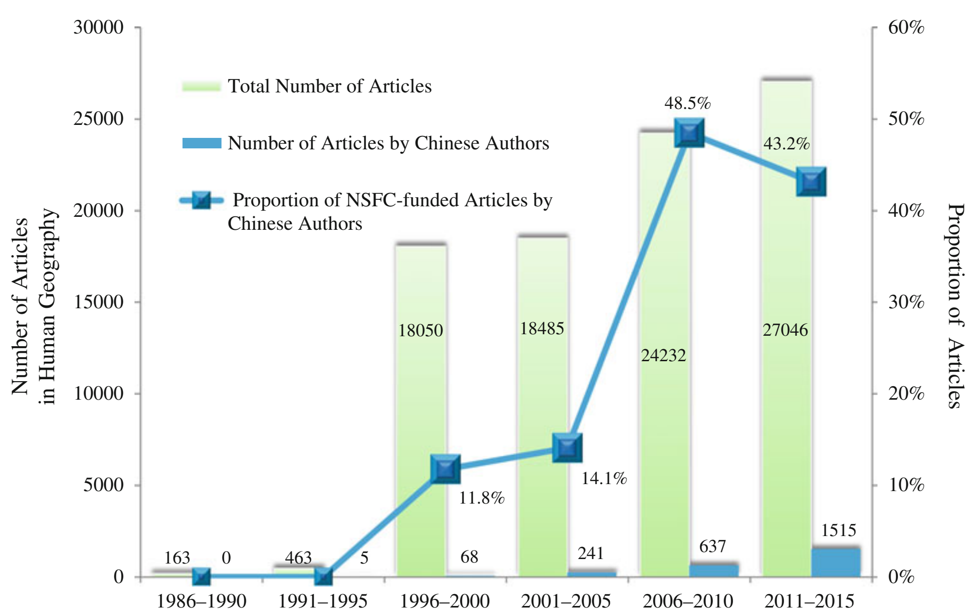


Fig. 5.1 Number of SCI/SSCI-indexed articles and proportion of NSFC-funded articles by Chinese authors in human geography during the period 1986–2015

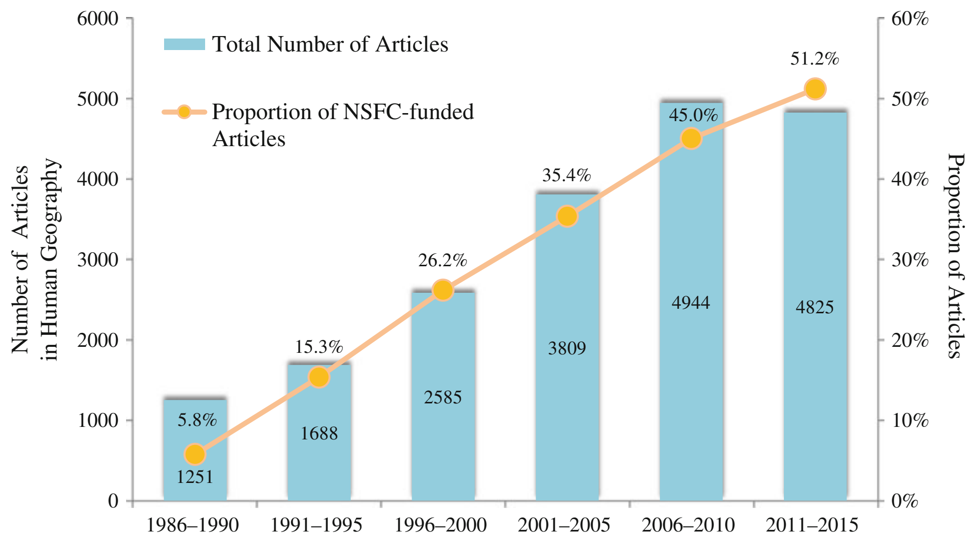


Fig. 5.2 Number of CSCD-indexed articles and proportion of NSFC-funded articles in human geography during the period 1986–2015

papers without the support of the NSFC. Papers sponsored by the NSFC were cited 21.2 times on average, compared with an average of 8.4 for papers without the support of the NSFC. Between 1996 and 2000, the average citation of papers sponsored by NSFC was 41.9, which was 17 times more than that for non-NSFC funded papers. On average, research sponsored by the NSFC tended to generate high-quality outputs and, therefore, attracted more academic attention.

Table 5.1 shows the average number of citations per paper among the 100 most cited papers in each country in mainstream SCI/SSCI human geography journals. This indicator is an important index of the international impact of research in human geography in each country. Before 1990, more than half of the top 20 nations had no statistics on published papers, yet the country with the highest citation rate per highly cited paper was Canada. From 1991 to 1995, Germany exhibited a rapid growth in influence: highly cited German papers had higher average citation scores than papers for any other country. South Africa, the United States of America (USA), the United Kingdom (UK), and the Netherlands also saw their influence grow rapidly. In the 20 years since 1995, the USA and UK had maintained a leading position in terms of citations per paper for the top 100 articles. In the last decade, average citations per paper from the UK exceeded that of the USA. In the same period, the average citations per paper fluctuated for papers from China, with China's overall ranking ranging from 6th to 9th. The gap in average citation narrowed compared with the Canada, Australia, and the Netherlands. If we considered all published papers from China, the average citations per paper were 14.9 and 8.7 in 2001–2005, and 2006–2010, respectively, which was relatively lower compared with the average scores for the top 20 countries (15.6 and 9.2).

5.1 General Characteristics of the Research Topics Over the Past 30 Years

This section focuses on leading research topics as reflected by keywords in SCI/SSCI journals and CSCD journals from 1986 to 2015. It investigates the co-occurrence network of leading keywords and delineates the characteristics of human geography research in the past 30 years.

Analysis of the overall characteristics of popular keywords for papers published in mainstream SCI/SSCI human geography journals since 1986 (Fig. 5.3) shows that authors focused on a wide range of topics, including politics, economy, culture, history, population, and traffic. Studies on geographical scale ranged from analyses at the community to the city, regional and global scales. The US, the UK, some other countries such as Netherlands, Canada, China, and South Africa were among the hotspot research regions. Research methods included modelling, case studies, and discourse analysis. In the discussion of human geography, great importance was attached to the application of various theoretical perspectives, including the institutional, political economy, and neoliberal. *Space*, *place*, *policy*, *network*, and *globalization* were some of the high-frequency keywords that drew common attention from sub-disciplines in human geography. Keywords such as *landscape*, *climate change*, *global environmental change*, *pollution*, and *risk*, which embodied the contribution of human geography to the study of comprehensive issues in geographical sciences, were also high-frequency keywords.

Regarding the overall characteristics of popular keywords of papers published in CSCD and Chinese core human geography journals since 1986 (Fig. 5.4), the main study topics were *land use and land management*, *urbanisation and urban planning, sustainable development* and *tourism*. Land

Table 5.1 Top 20 countries (regions) of average cites per paper for highly cited SCI/SSCI-indexed articles in human geography during the period 1986–2015

Rank	Countries (Regions)	1986-1990	1991-1995	1996-2000	2001-2005	2006-2010	2011-2015
1	UK	5.2	15.3	164	158.4	106.3	22.1
2	USA	4.7	14.4	181.1	173.5	87.8	19.8
3	Canada	11.4	8.1	57.9	65.3	57.1	13
4	Australia	5	9.2	49.7	42.6	45.7	12.1
5	Netherlands	-	12.3	43.2	70.1	47.8	12
6	China	-	4	23.8	30.5	29.9	10.1
7	Germany	-	25.8	24.1	64.3	33.9	8.7
8	Sweden	1.1	5	16.2	28.5	33.6	7.1
9	Spain	-	-	14.9	29.1	24	6.2
10	Italy	-	-	14.2	19.5	24.1	6.2
11	France	7	3.5	19	31.2	20.9	5.9
12	Norway	-	5.5	18.9	19.1	20.9	5.2
13	Belgium	-	-	17.8	35.7	21.4	4.4
14	Denmark	-	0	15.5	19.8	20.3	4.3
15	Switzerland	-	1.2	15.6	18.8	16.6	3.9
16	Austria	-	7.1	13.5	12.9	9.9	3.3
17	Japan	1	1.4	12.4	19.3	18	3.2
18	South Africa	-	17	9.7	10.8	13.6	2.9
19	Taiwan, China	-	-	11.7	11.5	9.6	2.6
20	South Korea	-	1.7	11.5	9.1	8.3	2

Note Top 20 countries (regions) were selected based on average cites of the top 100 highly cited articles in each county (region) out of 25 countries (regions) with the largest number of articles from the 84 SCI/SSCI mainstream journals in human geography; that is, total cites of the 100 articles were divided by 100, with listing by descending order for the period 2011–2015 in the last column

was the key object of study. The perspective of human-land relations infiltrated many subjects. However, *industrial structure, industrial agglomeration*, *foreign direct investment*, *international trade,* and other leading issues with which the international academic community had been concerned were also investigated in some Chinese papers, though such papers accounted for a smaller proportion of the total. (1) With respect to the study of **land**, scholars tended to study land resources, land use, land management, land planning, and changes in land use/land cover from the perspectives of development strategy, driving forces, the market and macro-regulation, sustainable demographic development, and arable land resources. (2) Research topics regarding **cities** were centred on urbanisation: urbanisation development mechanisms, urbanisation level measurement, urbanisation development paths, and regional differences in urbanisation. Urban fringes that emerged during the process of urbanisation, urban and regional development, and the protection and development of farming land, villages, and towns of historical and cultural interest had also been examined. A large number of case studies were carried out into topics such as urban expansion, urban agglomeration, urban morphology, and urban systems. (3) Geographers studying **tourism** had focused on tourism resources, tourism destinations, tourism planning, eco-tourism, the tourist economy, and the tourism industry. (4) One distinctive feature of Chinese human geography research was its close **connection with the requirements of the state and with practical issues**. Keywords such as *Western development*, *economic reform*, *rural homestead*, *land transfer*, and *old industrial bases in northeast China* appeared with high frequency in Chinese papers. Comprehensive studies of important regions and cities such as the *Pearl River Delta*, *Yangtze River Delta*, *Beijing*, *Shanghai*, and *Guangzhou* were also prominent.

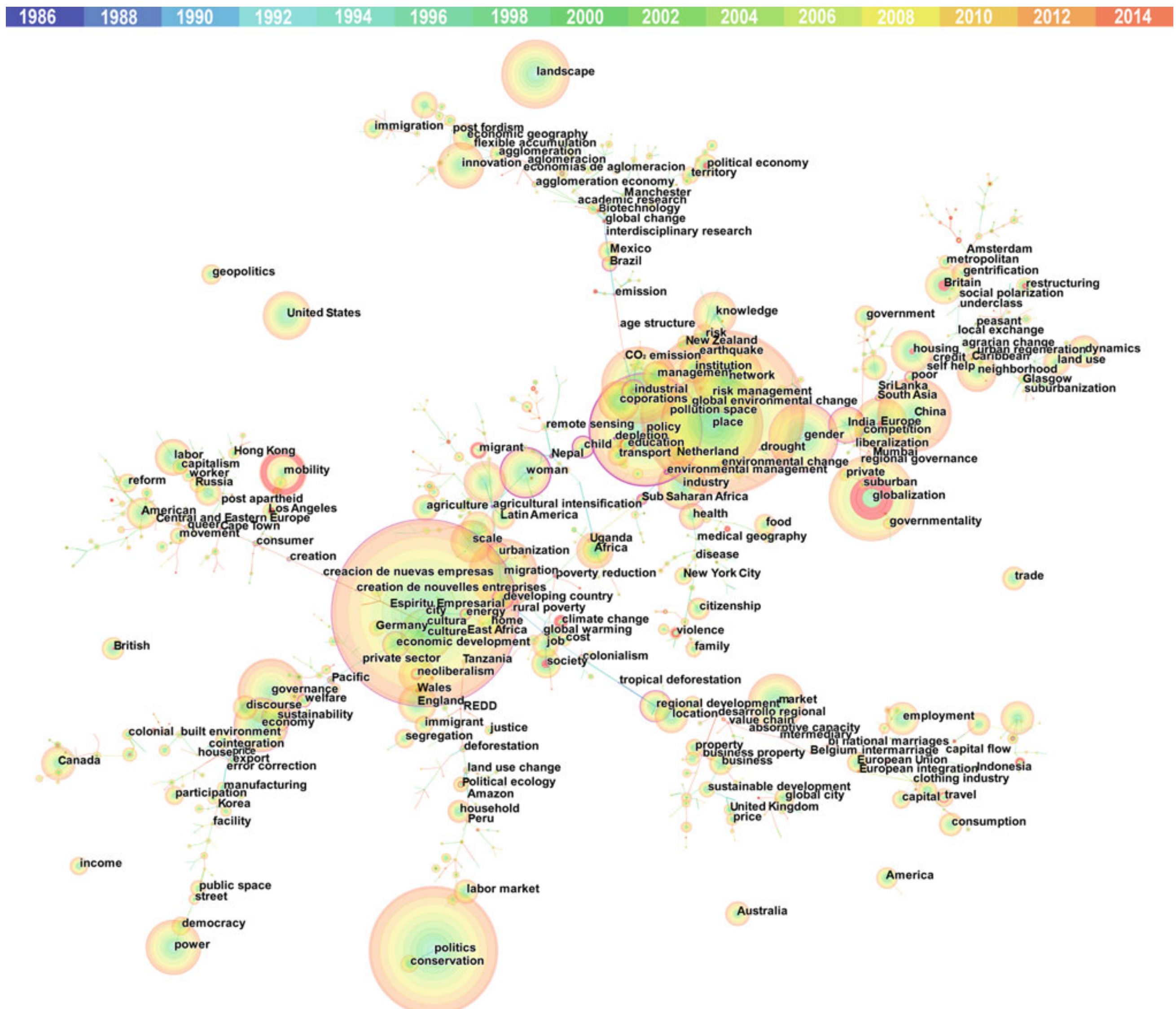


Fig. 5.3 Co-occurrence network of keywords in SCI/SSCI mainstream journals of human geography during the period 1986–2015

5.2 Change of Research Topics in Various Periods

This section divides the period 1986–2015 into several 5-year (or 10-year) segments, and investigates the main themes of SCI/SSCI-indexed and CSCD journals. In addition, it examines the difference between Chinese authors and international authors in terms of their research focus by investigating the SCI/SSCI-indexed articles published by these two groups of authors.

5.2.1 Period of 1986–1995

The number of papers published in SCI/SSCI mainstream journals of human geography from 1986 to 1995 was extremely limited. Hence, the high-frequency keywords shown in Fig. 5.5 reflect the comprehensive characteristics of geographical studies, and did not warrant further analysis.

Figure 5.6 shows leading keywords from papers published in CSCD and Chinese core human geography journals from 1986 to 1995. The figure shows that the main lines of research

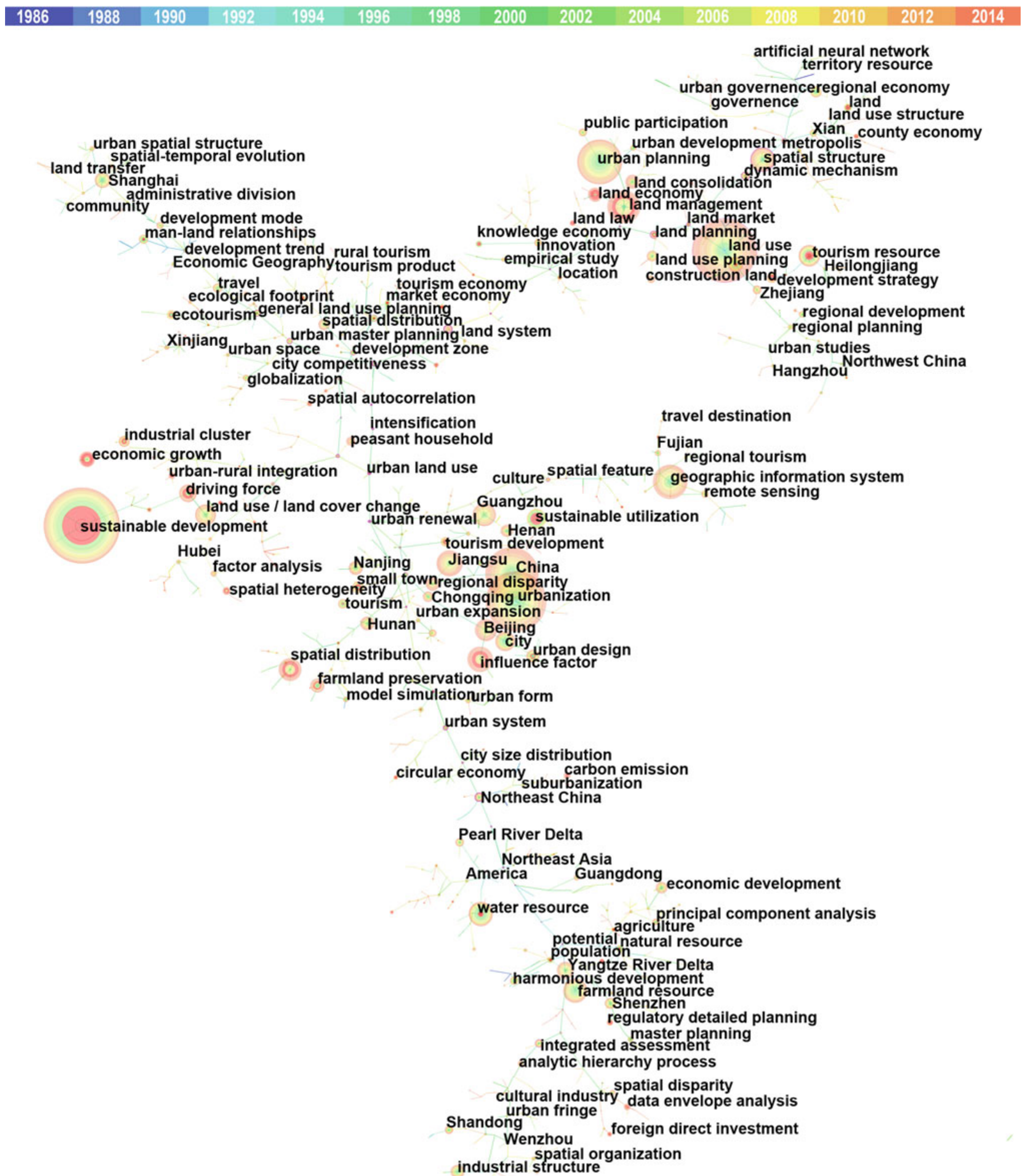


Fig. 5.4 Co-occurrence network of keywords in CSCD journals of human geography during the period 1986–2015

were land–population–mineral resources and water resources. (1) The use of three keywords in this period—*land use*, *macro-regulation*, and *market economy*—indicates the great change that occurred in terms of **land use** against the background of the new market economy in the early stages of reform and opening up. They also indicate that, in human geography, a large number of studies were carried out on micro-management, macro-regulation, model optimisation, and land planning to maintain the balance between land resources and the land market. Studies also targeted another aspect of land resources: the natural properties of land, including land production potential, comprehensive development, and agricultural land use. (2) Research on mineral and water resources focused on **resource development** and the rational utilisation of resources. As the main users of resources, people, and related population issues were the core objects of study. An important nodal keyword, *population*, was connected with other keywords such as *carrying capacity,* manifesting the connections and contradictions between natural resource utilisation and population growth. (3) Between 1986 and 1995, the study of **urbanisation and urban systems** was by no means at the core of the study of human geography in China. However, at the end of the period, there were an increasing number of papers on urbanisation. This indicates that the reality of China's urbanisation provided new topics in the study of human geography. Conversely, the occurrence of keywords in Chinese papers on urban studies, such as *population urbanisation* (1989), also reflected features of China's urbanisation process.

Figure 5.7 compares popular keywords in papers published by Chinese authors and others in mainstream SCI/SSCI-indexed human geography journals from 1986 to 1995. The total number of articles and journals in this period was limited, and the total keyword frequencies were low. The keyword that appeared most frequently appeared 13 times. In particular, Chinese authors published few papers during this period. Among articles published by non-Chinese authors in this 10-year period, the top two most frequent keywords worldwide were mentioned over ten times and reflected human geography's attention to global warming issues (*greenhouse*, *carbon dioxide*, *energy use*, *methane*) and to *population* issues. *Policy* and *economy*, which have traditionally been investigated in human geography, also ranked high in the list of the top 15 keywords. The relationships of the other keywords to research topics were not explicit, merely reflecting concerns about human activity and its influence on the environment.

5.2.2 Period of 1996–2000

Figure 5.8 shows that the most frequent research topics of papers published in mainstream SCI/SSCI human geography journals included city, policy, politics, economy, culture, and globalisation. The list of popular topics includes several that were independent of each other. Northern Ireland, East Asia, and the unified Germany were focus areas in geographical terms. *Income inequality*, *Medical Geography*, and *social polarisation* were important nodal keywords, reflecting common concerns across the sub-disciplines of Human Geography over social issues. (1) **Economic geography** held the dominant position as the effects of economic globalisation emerged. Studies on policy mainly examined the economy, industry, innovation, and government.

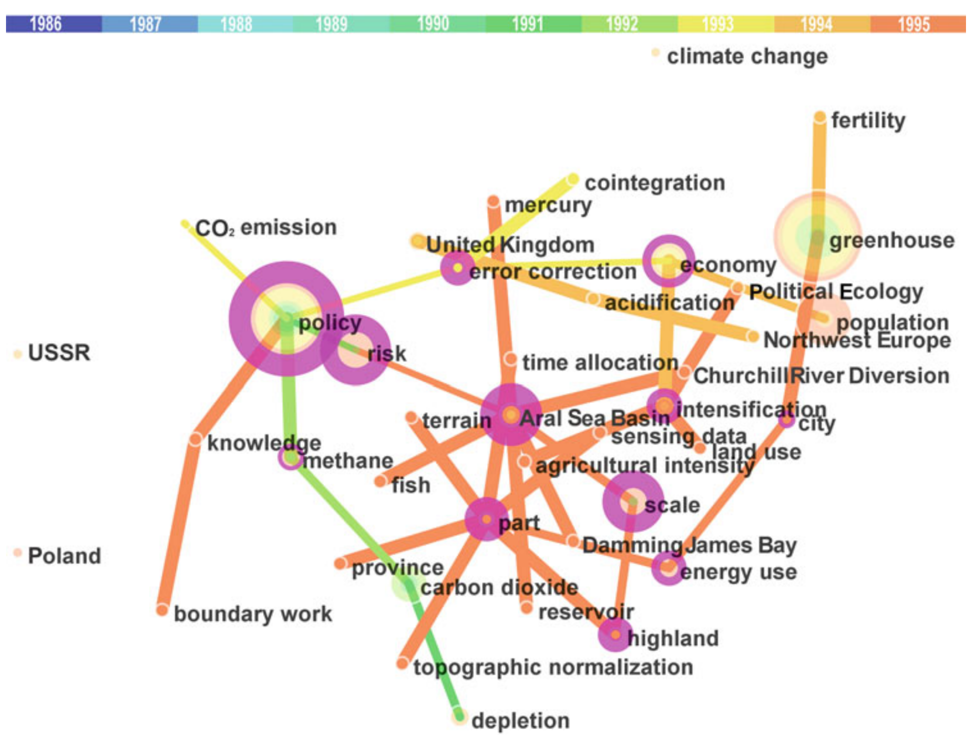


Fig. 5.5 Co-occurrence network of keywords in SCI/SSCI mainstream journals of human geography during the period 1986–1995

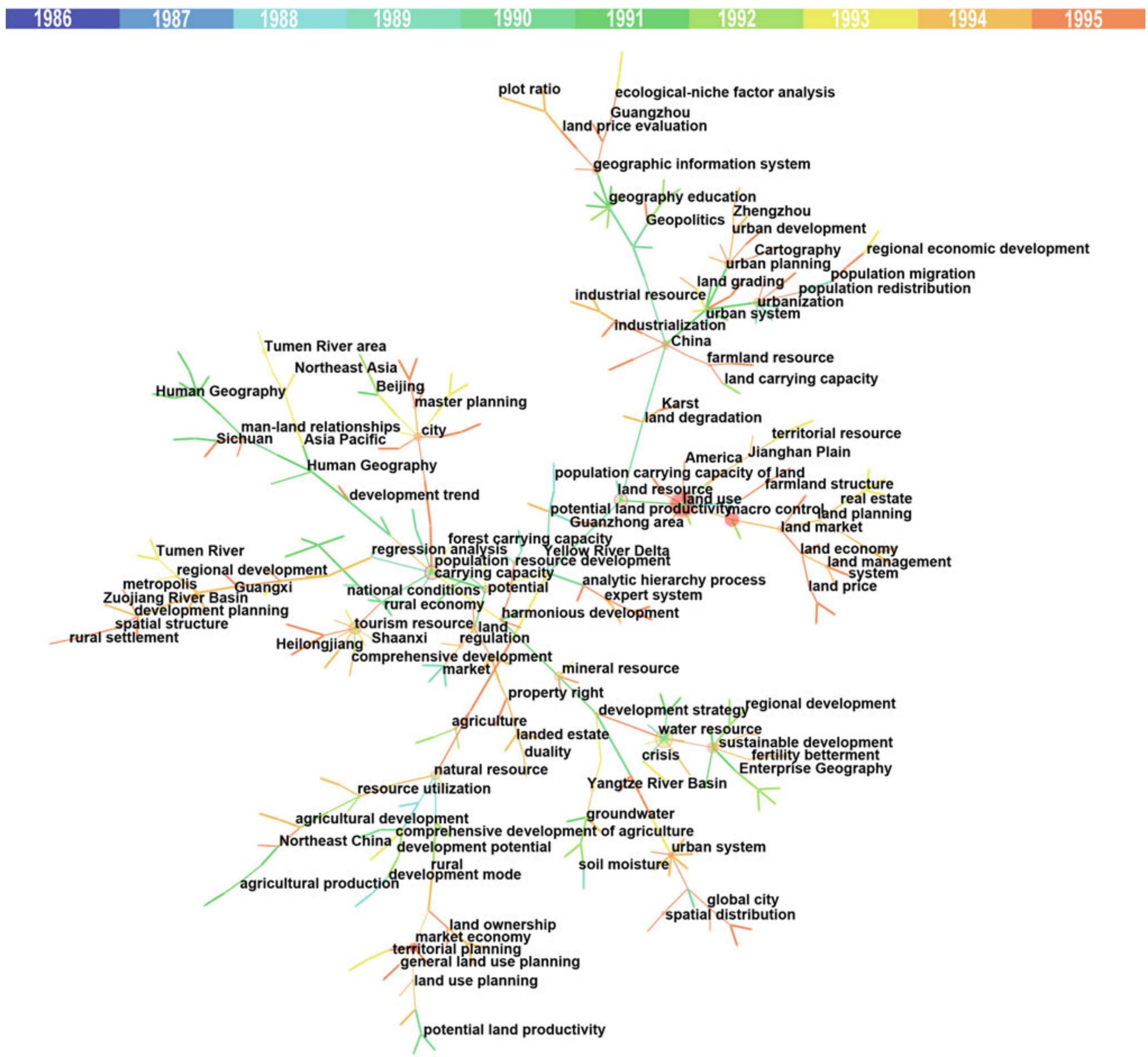


Fig. 5.6 Co-occurrence network of keywords in CSCD journals of human geography during the period 1986–1995

Production system and specialisation were highly central keywords, reflecting the fact that both institutional and economic forces have major impacts upon globalization. Keywords such as *regional policy*, *reform,* and *crisis*, clustered within the study of *market*. Keywords such as *economic reform*, *business*, *environmental protection*, and *industrial*, clustered with the keyword *China*. International business and investment environment also became major topics in economic globalization studies. (2) The themes of **political geography, social and cultural geography, and population geography** are usually inter-related. This is reflected in the agglomeration of keywords such as *race*, *conflict*, *population, migration*, *territory*, *gender*, *women*, and *society*. This suggests that political, social, cultural, and population geographers focus on critical social topics such as racial issues and gender imbalance. (3) Papers in **urban studies** were mainly on *land use*, *travel*, and *population*. This suggested that urban study researchers focused on topics relating to urban economics and spatial behaviour.

Figure 5.9 shows that in terms of research focus, papers published in CSCD and Chinese core human geography journals from 1996 to 2000 focused on the core framework of the regional economy and coordinated development, of which research into cities and urbanisation, natural resources, and tourism were sub-fields. (1) Research on regional economies, the investment environment, industrial distribution, and

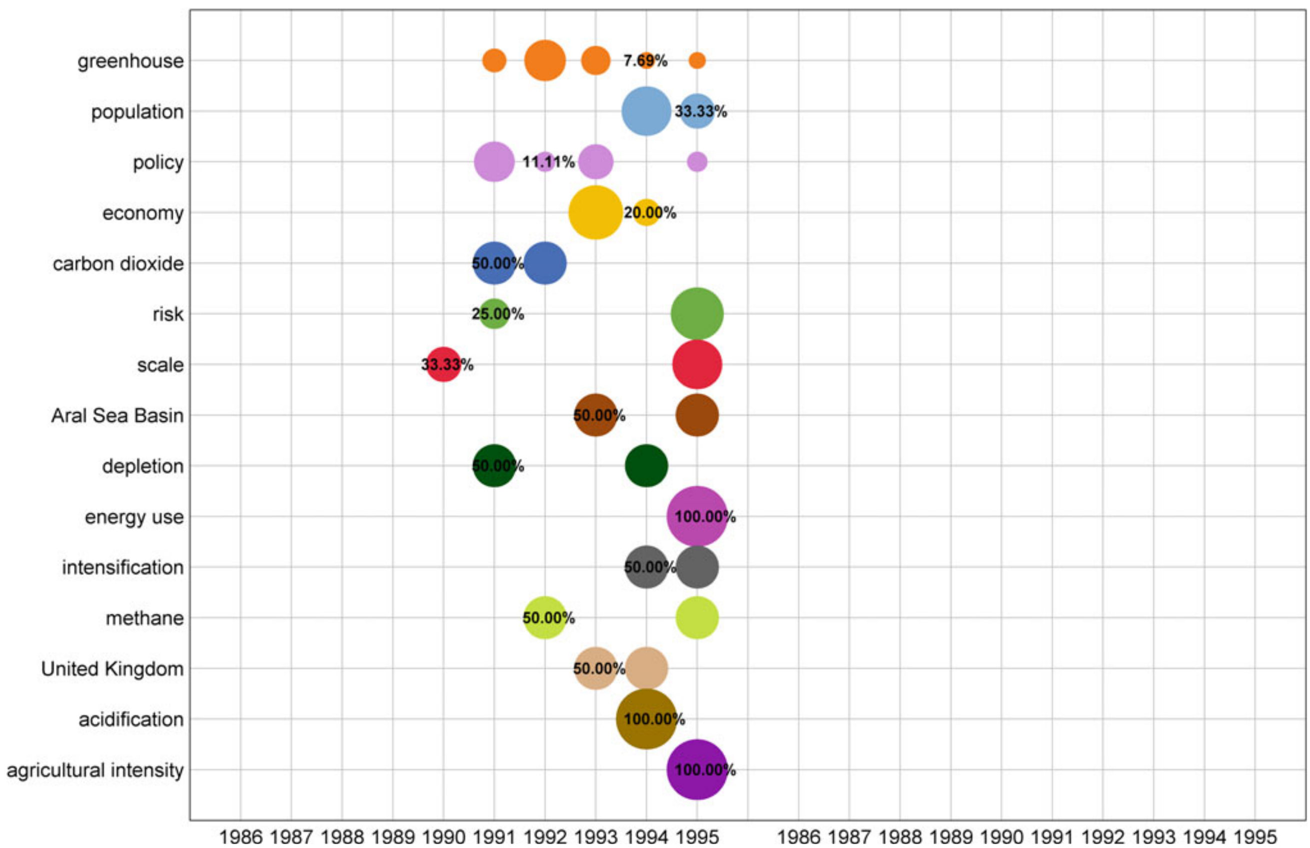


Fig. 5.7 Comparative diagram of prominent keywords by Chinese authors and others in SCI/SSCI mainstream journals of human geography during the period 1986–1995. *Note* Right panel shows keywords used by Chinese authors and left panel shows those used by the authors from other countries (regions). Size of circles represents the proportion of keyword frequency in a single year to its total frequency in 1986–1995. Each keyword has the same colour. Keywords are listed in descending order according to their total frequencies in the above period. There is no Chinese data for this time period

industrial structure focused on eastern coastal areas that were developmentally advantaged, such as Jiangsu and Shandong. Within the study of rural urbanisation and rural industrialisation, urban fringe areas were important case study areas. *Knowledge economy* became a high frequency keyword in 1999. (2) Studies of urban systems were carried out in regions of high and rapid economic development and urbanisation and regions in which obvious contradictions between the population and arable land resources had emerged, such as the Yangtze River Delta. Research was also carried out on such topics as urban spatial structure, suburbanisation, and the internationalisation of Shanghai, Chongqing, and other cities. There was a significant increase in studies on managing the integration and planning of Hong Kong, Shenzhen, and the Pearl River Delta between 1996 and 2000. (3) Research on urban locations, urban positioning, urban development, and urban–rural integration brought natural resource limits, regional development goals, urban design, and overall urban planning into consideration. (4) Under the influence of economic development and the urbanisation process, studies of land use and management, arable land protection, and regional development planning had keywords such as *small cities and towns*, *land*, *rural industrialisation*, *market economy*, and *urbanisation level*. These studies addressed problems faced by regions at different levels of economic development and urbanisation. (5) From 1996 to 2000, the study of tourism showed rapid development. These studies mainly focused on topics such as the evaluation and development of tourism resources, urban tourism, and strategies for tourism development. The study of strategies for tourism development was closely linked with the study of regional development. (6) The rational and sustainable use of water resources was also a major topic in human geography research in this period.

Figure 5.10 compares the popular topic keywords of papers published by Chinese authors and others in mainstream SCI/SSCI human geography journals from 1996 to 2000 (The diagram description see the note of Fig. 5.7). In this period, human geography journals and articles significantly increased in number, the total frequency of keywords increased, and the keyword that appeared with the highest frequency, *gender*, appeared 70 times. Among the papers published in SCI/SSCI journals by Chinese authors, the keyword that appeared most

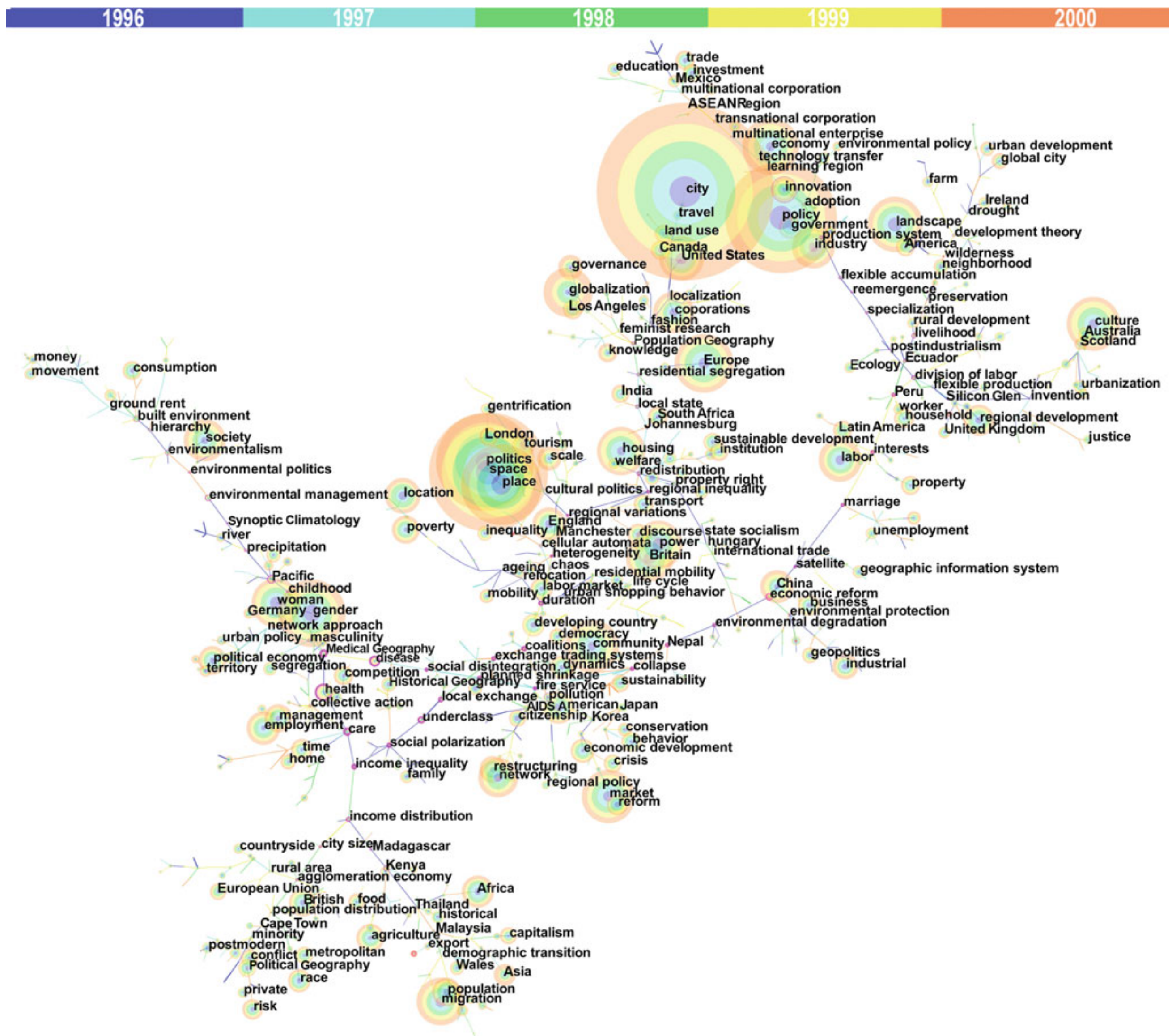


Fig. 5.8 Co-occurrence network of keywords in SCI/SSCI mainstream journals of human geography during the period 1996–2000

frequently out of the top 15 keywords appeared eight times. Among the papers published by non-Chinese authors in this 5-year period, the top 15 high-frequency keywords appeared more than 32 times. The high-frequency keywords in this period reflected a change since 1986–1995: in contrast with 1986–1995, *gender*, *globalization*, and *development* were leading research topics. In addition, substantial attention was paid to the comprehensive topics of *climate change* and *environment.* Many traditional topics in human geography pertaining to agriculture and poverty also appeared among the high-frequency keywords. Though they were not top-ranked in total word frequency, two or three characteristic terms in the study of cultural geography (*migration*, *identity*, and *place*) appeared among the top 15 keywords, showing that cultural geography research was receiving substantial attention in this period. In addition, the high frequency of research on certain regions showed that concern was growing in human geography with less-developed and developing parts of the world like *Africa*, *Asia*, *Latin America*, and *China*, and that these areas had become much more important foci of research in human geography.

Among the keywords ranked in the top 15 in terms of frequency worldwide, Chinese authors in this period only published articles with the keywords *China*, *Asia*, and *environment*, indicating that Chinese authors were not concerned with the issues that dominated the mainstream study of human geography globally or with issues outside Asia. Meanwhile, keywords such as *regional development*, *suburbanisation*,

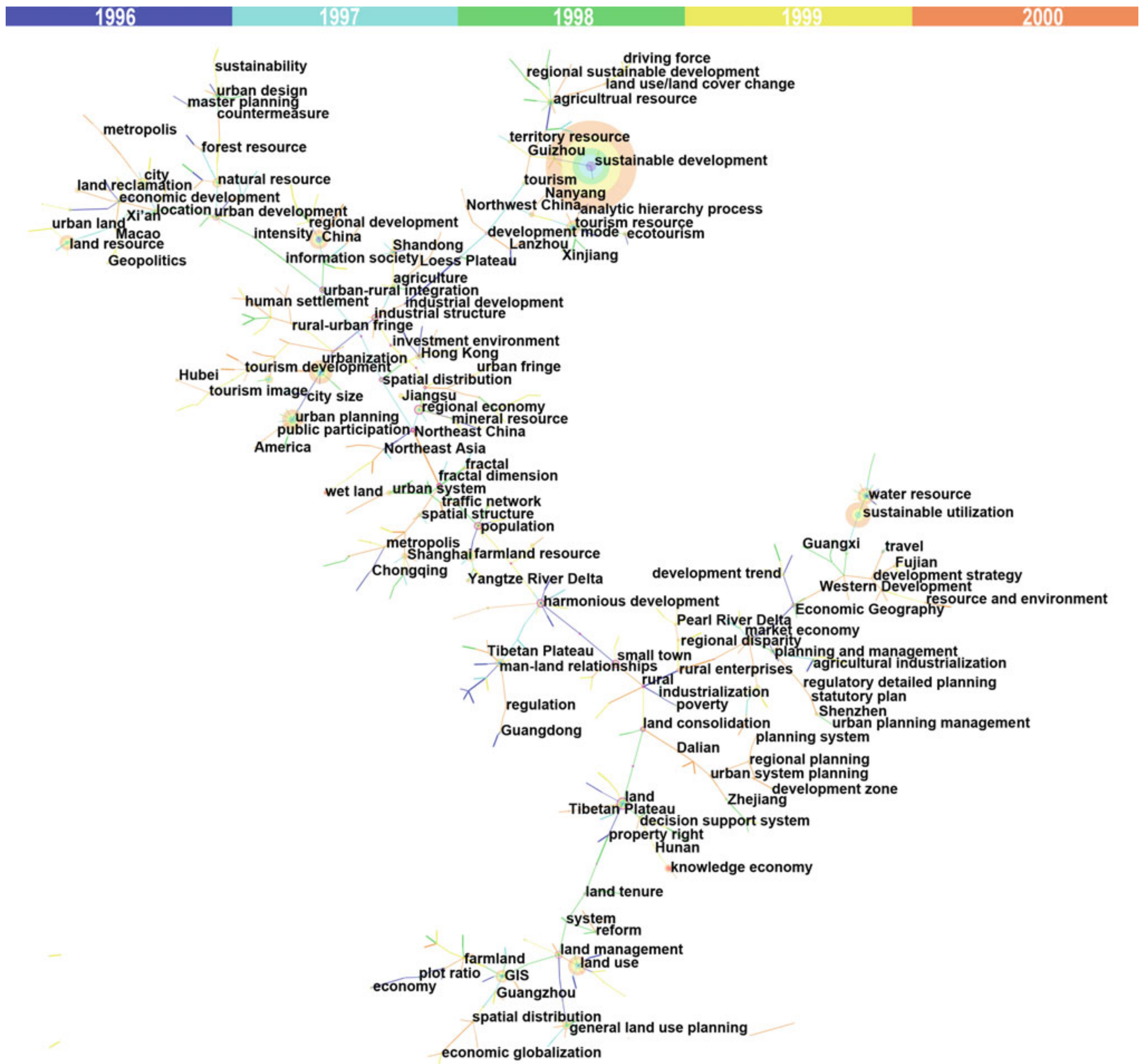


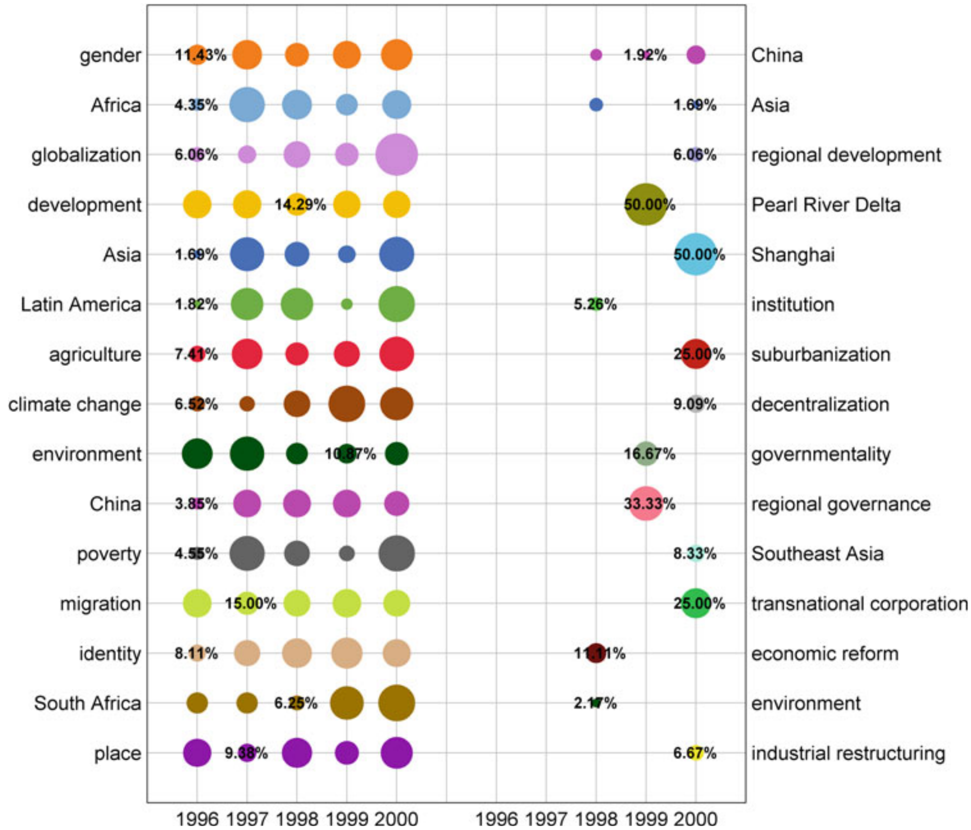
Fig. 5.9 Co-occurrence network of keywords in CSCD journals of human geography during the period 1996–2000

economic reform, and *industrial restructuring*, which were closely linked with China's development and social and economic problems, appeared among the top 15 keywords in Chinese publications. In this period Chinese scholars had started to orientate their studies of local issues toward an international academic audience. In addition, the appearance of certain keywords related to systems and political topics in Chinese authors' papers (*institution*, *decentralisation*, *governmentality*, and *regional governance*) indicates the lifting of the traditional prohibition in Chinese human geography on research into institutions and politics. During this period, although they did not carry out studies of globalisation, Chinese scholars began to pay attention to *transnational corporations*—one of the main drivers of globalisation.

5.2.3 Period of 2001–2005

Figure 5.11 shows the leading research topics in papers published in mainstream SCI/SSCI-indexed human geography journals from 2001 to 2005. Although the topics in this period and those in 1996–2000 did not differ substantially, significant changes occurred in terms of the concrete content of research. (1) Global research was closely linked with

Fig. 5.10 Comparative diagram of prominent keywords by Chinese authors and others in SCI/SSCI mainstream journals of human geography during the period 1996–2000



economic development, *knowledge*, *innovation*, *state power*, *the European Union*, and *agricultural policies*, reflecting economic geography's concern with economic globalisation. At the same time, *localisation* and the *agglomeration economy* were also important topics in economic geography research and *small business* became a high-frequency keyword in 2002. (2) In urban studies, there were agglomerations of *space*, *community*, *policy*, and *governance*. Keywords such as *global cities*, *world cities*, *world city network*, *American city*, *European city*, *London*, and *Bangkok* indicates that urban studies focused on typical regions or cities. In addition, *gentrification*, *inner city*, and *public space* were also important topics. (3) Many topics were explored on the basis of common political, economic, cultural, and social perspectives. *Mobility*, *migration* and *immigration* were mainly explored in Europe, Latin America, and Asia, but with different foci, often linked with issues such as economy or natural disasters. The study of immigration issues in *metropolises* tended to be connected with *race*, *young people*, and *advanced producer services*. Network studies tended to be linked with social geography topics, such as *health*, *rural areas*, *chronic poverty*, *equality*, *social welfare*, *child labor*, and *disability*.

Figure 5.12 shows the leading research topics in papers published in CSCD and Chinese core human geography journals from 2001 to 2005. With the rising impact of globalisation, studies of economic geography and urban geography began to accumulate. National development strategy and policy-oriented issues remained important topics in the study of human geography. (1) The number of studies of **globalisation** began to increase. The keyword *globalization* started to appear in papers in 2001. Although it had appeared in Chinese papers as early as 1999, *economic globalization* was not a nodal keyword with high centrality until 2001. *Governance*, *World Trade Organization*, and *economic transformation* successively began to appear as keywords. Empirical studies were first carried out in the Pearl River Delta and along the New Eurasian Continental Bridge (China's New Eurasian Continental Bridge Economic Belt and the industrial belt along the East Longhai Line). *Guangzhou*, *Dongguan*, and *Hong Kong* were all keywords of relatively high centrality. Research topics encompassed urban governance, urban competitiveness, world cities and regional economic integration. After 2004, enterprise clusters and technological innovation began to attract attention. The appearance of keywords such as *Tokyo*, *Asia-Pacific region*, *South Korea*, and *Western countries* indicates that the study of human geography in China had started to become concerned with the outside world. (2) The study of **regional economies** became an important research direction in human geography in this period. With approaches such as model simulation and from the perspective of

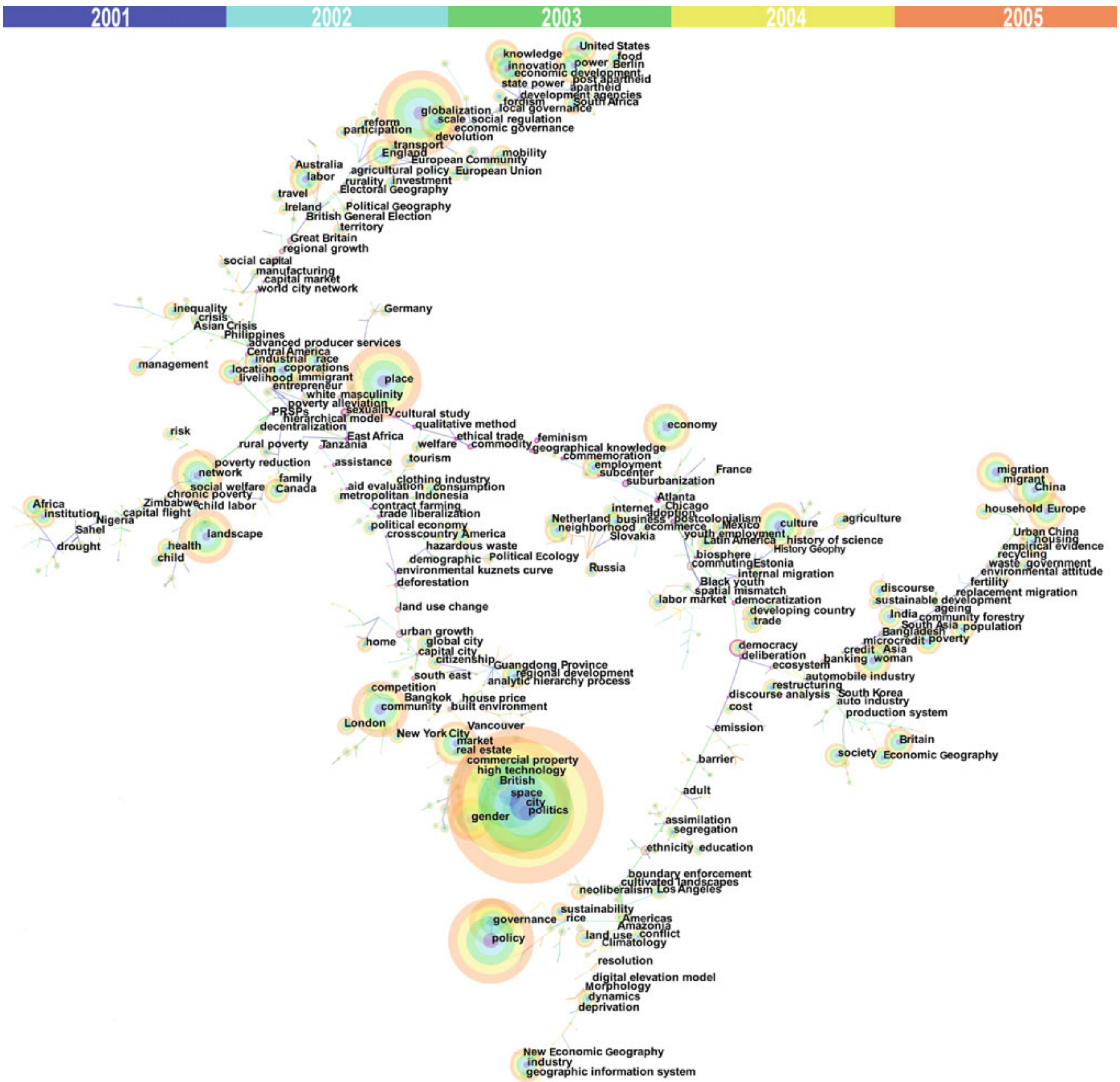


Fig. 5.11 Co-occurrence network of keywords in SCI/SSCI mainstream journals of human geography during the period 2001–2005

new economic geography, researchers studied topics such as *spatial organisation*, *the investment environment*, *industrial structure readjustments*, *spatial agglomeration*, *self-organisation*, and *leading industries*. Many empirical studies were conducted in northeast China, China's old industrial base; coastal areas in Shandong Province; and Inner Mongolia. Studies of industrial structures were centred on urbanisation, industrialisation, land prices, and comparative advantages. *Industrial agglomeration* began to draw attention in 2004. *The rise of central China*, *Central Henan Urban Agglomeration*, and *Western region of China* were common keywords in these studies. *Spatial structure* became a keyword of high frequency and *pole-axis system theory* appeared as a keyword in 2005. (3) In studies of the **urbanisation** processes in small cities and towns, perspectives based on institutional innovation systems became important. The studies in Wuhan, Heilongjiang, Zhejiang, Guangxi, and other regions researched innovation systems in the context of the urban economy, rural economy, urban traffic, urban planning, public policy, the market for water, and water rights. (4) Studies of **traffic** exhibited a rapid increase. From 2001 to 2005, the number of papers on traffic increased

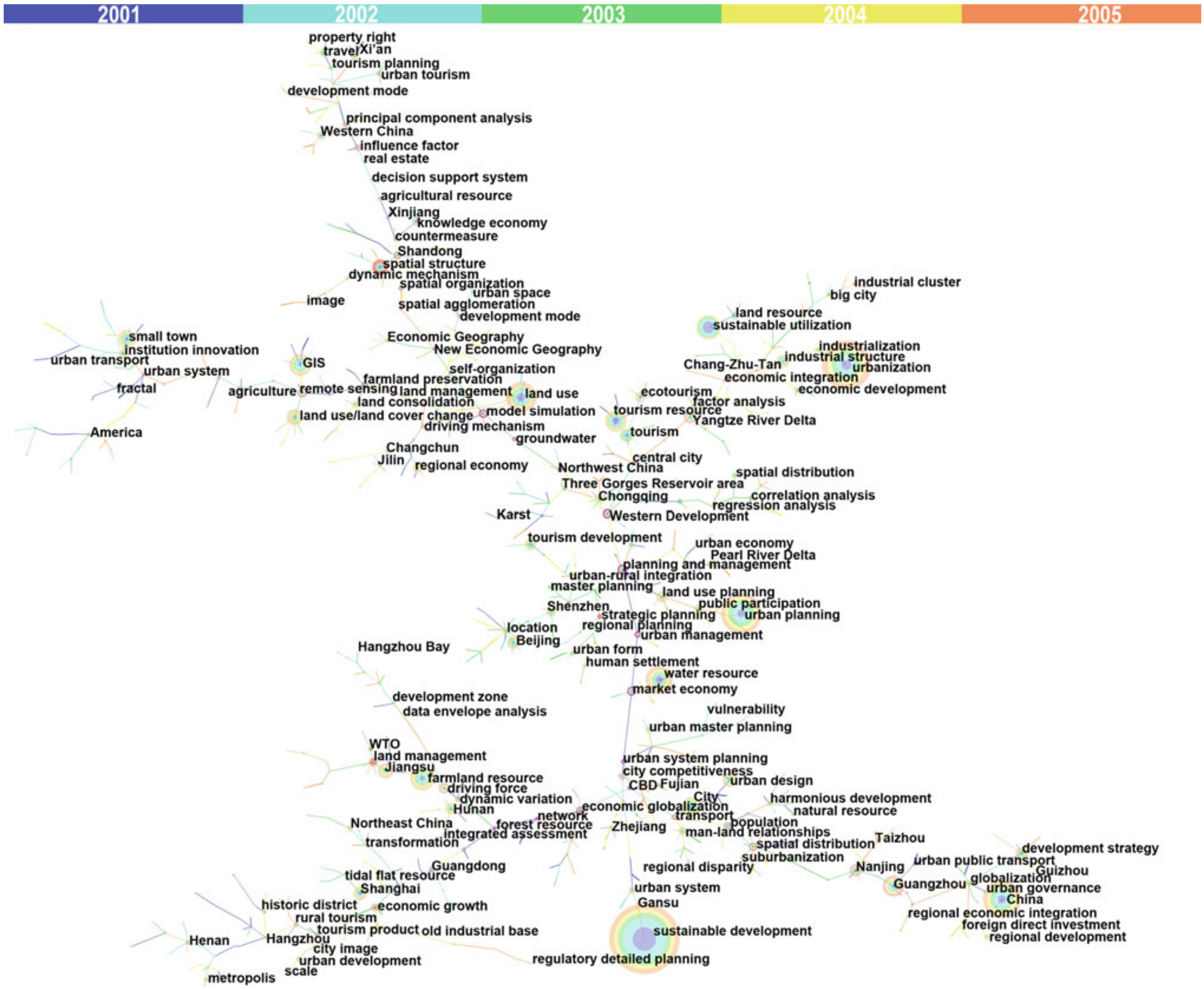


Fig. 5.12 Co-occurrence network of keywords in CSCD journals of human geography during the period 2001–2005

almost threefold. Traffic studies linked the issues of the city, natural resources, tourism, non-farming construction land, and international trade together, for instance, *rail transit* and *Qinghai-Tibet railway* appeared in papers in 2002 and 2005, respectively. (5) The study of **tourism** was also an important topic in the study of human geography in this period. Tourism was studied from many points of view, such as resource assessment, environmental capacity, tourism economy, ecotourism, development and planning, tourism image, and natural reserve areas. Many studies were carried out on tourism in Tibet. (6) **Urban planning, tourism planning, land use planning, regional planning, and territorial planning** remained key topics in the study of human geography. Strategic planning and land management became popular research topics in this period.

Figure 5.13 compares popular keywords in papers published by Chinese authors and others in mainstream SCI/SSCI-indexed human geography journals from 2001 to 2005 (The diagram description see the note of Fig. 5.7). During this period, increases were again seen in the number of journals and papers and the total frequency of keywords. For instance, the keyword with the highest frequency, *globalization*, appeared 146 times. Chinese authors had papers published in SCI/SSCI journals, and among the top 15 keywords, the keyword that appeared with the most frequency appeared 18 times. Of the papers published by non-Chinese authors in this 5-year period, the top 15 keywords all appeared more than 53 times. Leading research topics as reflected in the high-frequency keywords differed from the earlier 1996–2000 period as follows: globalization became the most important research topic in human geography, and key topics pertaining to globalization, such as *innovation and network*, attracted attention; studies of *poverty* and *migration* continued to increase; *gender*, *development*, *climate change*, and *identity* continued to attract attention. However, papers on these topics did not increase in number, and India became an emerging hotspot for study. The keyword *India* appeared more times than the keyword *China*. *Globalization*, *poverty*, and *migration* exhibited the most marked increase in frequency in this 5-year period.

Of all the high-frequency keywords used by human geographers in other regions in this period, only the keywords *China*, *Asia,* and *climate change* appeared with high frequency in the papers published by Chinese authors, showing that Chinese human geographers' attention to the study of climate change increased about 5 years later than that of their international counterparts. Conversely, Chinese scholars came to be substantially concerned in this period with real urban and urbanisation problems such as *urbanisation*, *suburbanisation*, *urban form and metabolism*, *land use*, and *Political Economy*. In addition, among economic globalisation topics, *foreign direct investment* and *global production networks* also started to attract attention. In terms of regional studies, the Pearl River Delta became the most prominent area for case studies (*Hong Kong*, *Pearl River Delta*, and *Guangzhou*).

5.2.4 Period of 2006–2010

Figure 5.14 identifies the leading research topics in papers published in mainstream SCI/SSCI human geography journals from 2006 to 2010. Compared with 10 years earlier, the most significant change was the fact that globalisation attracted attention beyond the field of economics; its influence expanded to the study of other areas, such as the city, culture, and politics. (1) Against the background of globalization, urban studies became concerned with issues such as politics, culture, and governance; a concern with *neoliberalism* was also prominent. Studies of urban governance were closely linked with keywords such as *globalization*, *place*, *politics*, and *governance*. Studies of urban social geography were closely linked with keywords such as *gender*, *woman*, *homelessness*, and *feminist*. The studies of population were closely linked with such keywords as *immigrant*, *mobility*, *housing policy*, *community*, *conflict*, *neighborhood*, and *urban form*. Moreover, the keywords *migration*, *housing*, *industry*, *segregation*, and *residential mobility* were also clustered. (2) The study of economic geography was mainly concerned with the perspective of networks, examining issues of *innovation*, *knowledge*, *corporations*, *labor*,

Fig. 5.13 Comparative diagram of prominent keywords by Chinese authors and others in SCI/SSCI mainstream journals of human geography during the period 2001–2005

market, and *industry*. They often targeted the relationship between industrial clusters and agglomerations. Keywords such as *economic globalization*, *global value chain*, *global production network*, and *income inequality* became the major keywords for economic globalization studies. *Transport*, *transportation*, *airport*, and *airline* became the major topics connecting urban social studies and urban economic studies.

Figure 5.15 shows the popular research topics in papers published in CSCD and Chinese core human geography journals from 2006 to 2010. Urban studies underwent unprecedented development, land research continued to be vigorous, the study of industrial agglomeration developed, and studies of the modern service sector, cultural geography, urban social geography and main functional areas started to attract attention. (1) Analysing the **city** became an important research objective in human geography. A large number of empirical studies of urban spatial structure, urban system, urban expansion, urban form, urban agglomeration, metropolitan area, urban planning and urban design were carried out. A large number of studies of *urban agglomerations*, such as the agglomerations of *central Liaoning*, *central Henan*, *the Yangtze River and Huai River*, *Guanzhong*, and *Chang-Zhu-Tan*, were undertaken, giving a major stimulus to the study of the city and regional development. (2) The study of **land** also continued to develop. Focusing on such issues as *land resource management*, *arable land protection*, *land market*, *land property rights*, and *land compensation*, a large number of empirical studies were conducted in moderately developed regions such as Henan, Chongqing, Shaanxi, and Jiangxi, where the process of urbanisation had accelerated. (3) **Industrial agglomeration** research continued to develop and the manufacturing and service sectors attracted increasing academic attention. The study of *industrial agglomeration* tended to be closely associated with the topics of *industrial structure*, *industrial transfer*, *industrial policies*, *foreign direct investment*, and the *regional economy* in such regions as Zhejiang, Fujian, and the northeast. (4) The **service sector**, particularly the modern service sector, began to attract attention in regions with advanced service sectors such as Jiangsu and the Pearl River Delta. A number of empirical studies were conducted into *spatial organisation*, *location selection*, *the employment of women*, *living space*, *industrial competitiveness*, and *consumption*; these studies often took perspectives based on cultural geography and urban social geography. (5) **Main functional area** appeared as a keyword in human geography papers in 2007. Meanwhile, *urban-rural planning*, *development models*, and *overall urban planning* attracted substantial attention. (6) The study of **tourism** continued to develop. Topics such as competitive advantages in regional tourism, and relations between tourism and the circular economy became key areas of focus. *Ecotourism* appeared in 2006 and soon became a high frequency keyword. *Red tourism* became a nodal keyword in 2007.

Figure 5.16 compares leading keywords in articles published by Chinese authors and others in mainstream SCI/SSCI-indexed human geography journals from 2006 to 2010 (The diagram description see the note of Fig. 5.7). This period again saw increases in the number of journals and papers and the total frequency of keywords. *China* was the keyword with the highest frequency and appeared 225 times. Articles by Chinese authors published in the SCI/SSCI journals markedly increased in number; of the top 15 keywords, the keyword that appeared most frequently appeared 56 times. Among articles published by non-Chinese authors in this 5-year period, the top 15 keywords all appeared more than 84 times. The high-frequency keywords indicate that *climate change* was the most common research topic in human geography, showing that in the sub-disciplines of Geography awareness regarding comprehensive and global issues had greatly increased. *Globalization* remained the most important research topic in human geography. Owing to the influence of the ideology of *neoliberalism*, *governance* ranked among the top 15 keywords, appearing 84 times. Though *gender* went relatively unmentioned in the period 2001–2005, the study of gender became a popular topic and the number of gender-related studies increased by a factor of 1.2 in this period. The number of studies of *migration* continued to grow; the number of studies of *poverty*, *development*, and *identity* also continued to increase. In terms of research regions, *China* became the leading area for studies. *India* began to attract attention in 2001–2005, while *Africa*, *Latin America*, and *Asia* continued to attract attention. Russia also became important, with *Russia* jumping into the rank of the top 15 keywords. The keywords that increased most markedly in frequency in this 5-year period were *climate change*, *governance*, and *neoliberalism*. In addition to the keywords of *China* and *Asia*, among the top 15 keywords in papers published by Chinese authors during this period, *climate change* and *globalization* appeared. However, climate change and globalization were already two of the most critical topics in international human geography. In contrast, Chinese scholars' enthusiasm for *foreign direct investment* remained on the rise. In addition, practical issues such as *urbanisation*, *land use*, *regional development*, *Political Economy*, and *institution* remained among the foci of Chinese scholars. In regional studies, *Beijing* and *Shanghai* became focus regions for case studies in addition to *Hong Kong*, *the Pearl River Delta*, and *Guangzhou*.

5.2.5 Period of 2011–2015

Figure 5.17 shows the popular research topics in papers published in mainstream SCI/SSCI-indexed human

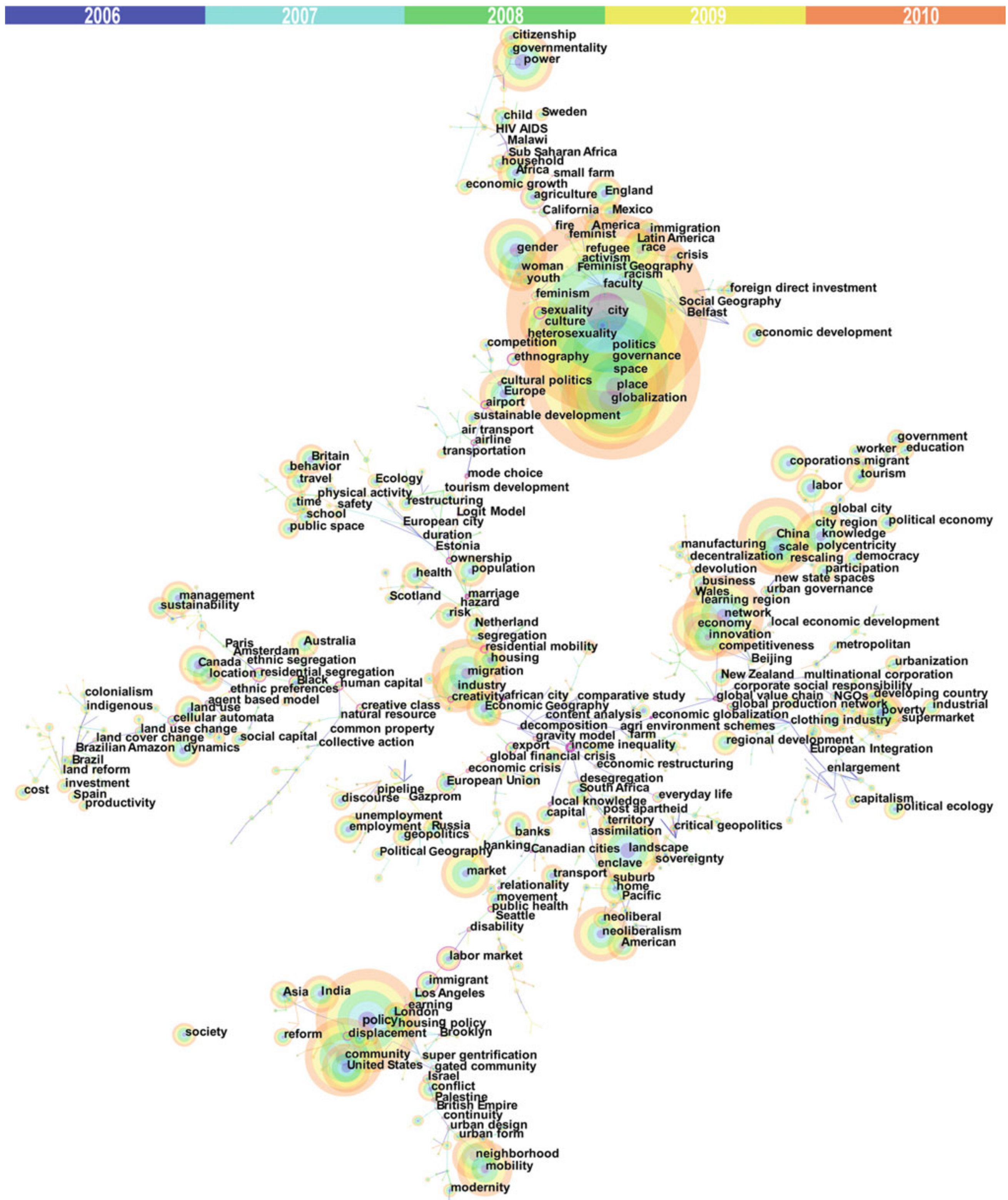


Fig. 5.14 Co-occurrence network of keywords in SCI/SSCI mainstream journals of human geography during the period 2006–2010

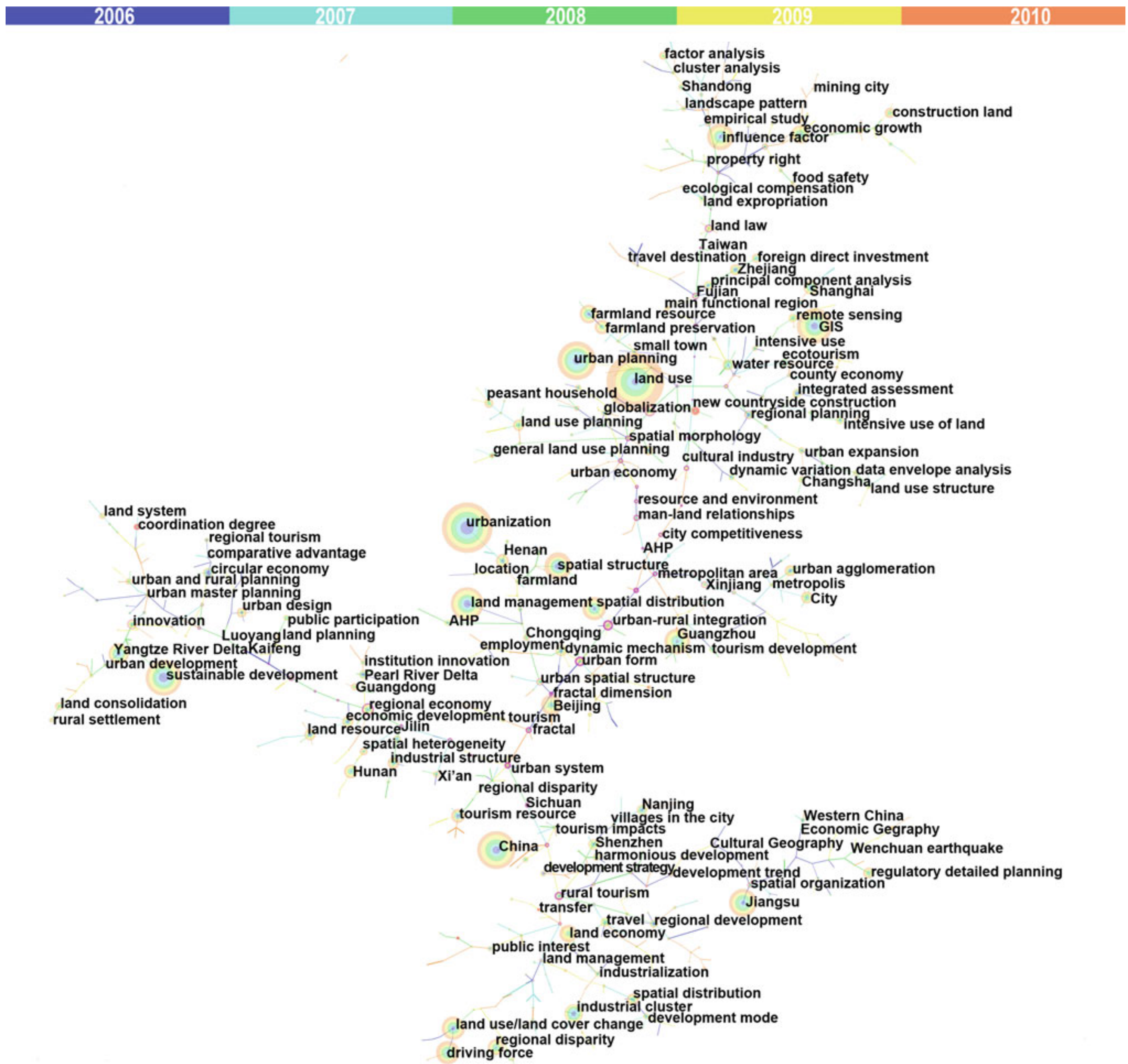


Fig. 5.15 Co-occurrence network of keywords in CSCD journals of human geography during the period 2006–2010

geography journals from 2011–2015. Concern with neoliberalism and liberalization became more prominent; studies of economic globalisation decreased; comprehensive studies of human-land relationships increased; the interconnections of social, cultural and political factors expanded; and overall research topics further diversified. From **the perspective of integrating both physical and human geography**, the following research topics received high attention. (1) The study of urban spatial transformations and their impacts on natural environments, as indicated by the clustering of keywords such as *urbanisation*, *land use*, and *wildland urban interface*, the agglomeration of keywords such as *urban sprawl*, *CO_2 emission*, and *suburbanisation*, and the grouping of keywords such as *green buildings*, *smart city*, and *urban studies*. (2) The impacts of climate change, as indicated by the agglomeration of such keywords as *climate change*, *economy*, and *sustainability*. (3) The relationships between natural reserve and development and utility, as indicated by the agglomeration of keywords such as *conservation*, *tourism*, and *effectiveness*. (4) The models of mountain area development, shown by the clustering of keywords such as *landscape*, *community*, *governance*,

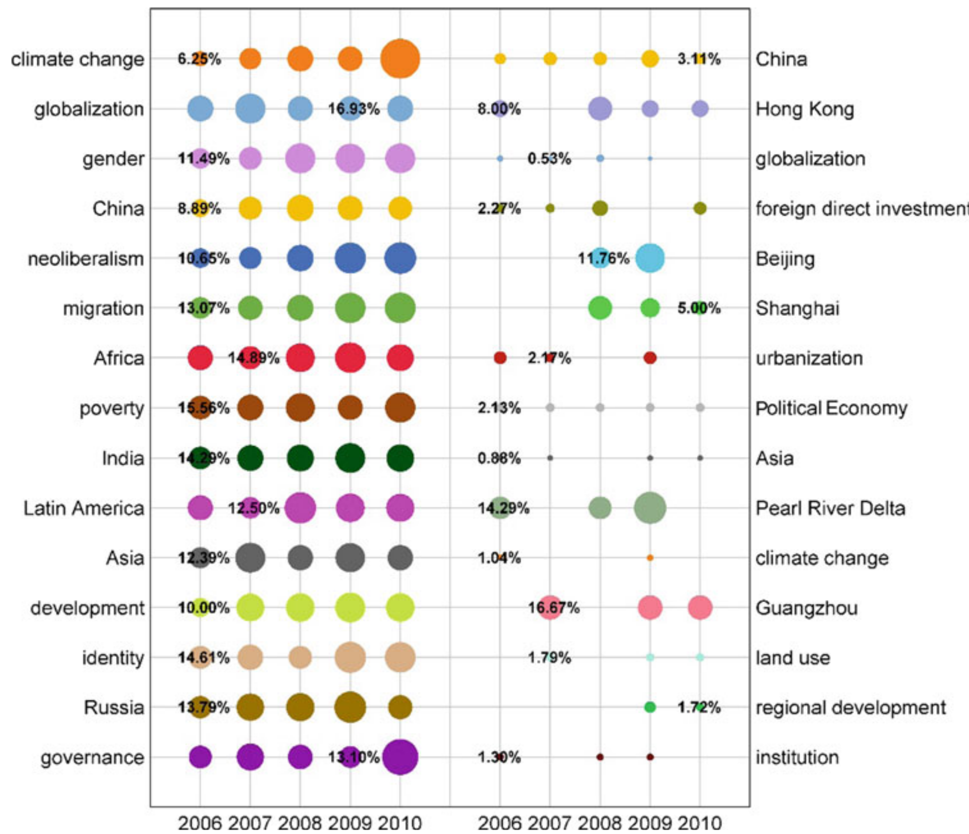


Fig. 5.16 Comparative diagram of prominent keywords by Chinese authors and others in SCI/SSCI mainstream journals of human geography during the period 2006–2010

policy, *market*, *hazard*, *flood*, *insurance*, *India*, *Nepal*, and *Himalaya*. (5) Poverty studies, as indicated by the agglomeration of keywords including *poverty*, *risk*, *household*, and *land reform*. From **the perspective of integrating social, cultural and political factors**, the following topics were popular. (1) The study of urban residential space, as indicated by the agglomeration of keywords such as *neighborhood*, *residential segregation*, *welfare*, and *income inequality*. (2) The study of migration and residential mobility, as indicated by the grouping of keywords such as *migration*, *migrant*, *home*, and *suburban*, the clustering of keywords such as *mobility*, *employment*, and *labor market*, and the agglomeration of keywords such as *gender*, *innovation higher education*, *international student*, *transnationalism*, *second home*, and *sense of place*. (3) The study of ethnical conflicts, as indicated by the grouping of keywords such as *Palestine*, *Caucasus*, *violence*, and *conflict*. **From the perspective of economic globalisation**, the study of local-global relations was a research focus, as indicated by the agglomeration of keywords such as *globalization*, *neoliberalism*, *entrepreneurialism,* and *growth machine*, the agglomeration of keywords such as *industry network*, *creativity*, *housing*, *land development*, *China*, and *politics*; and the agglomeration of such keywords as *institution* and *knowledge*.

Figure 5.18 shows the popular research topics in papers published in CSCD and Chinese core human geography journals from 2011 to 2015. The figure indicates that human geography studies of the economy, the city, and resources began to include ecological, environmental, and social perspectives. The distribution of keywords suggested, first, that human geography studies were marked by the name of specific regions or cities, and second, that there was a trend of integration of physical and human geography. Detailed analysis is presented as followed. (1) ***Land*** remained the most popular topic. In-depth studies were carried out in several major areas such as *land use*, *land management*, and *arable land resources*. Studies of intensive land use concentrated on *development zones* and *industrial areas* in large cities. Studies of land management focused on *land resources*, *land assessment*, *land contracts and management rights*, and *land acquisition conflicts* in the process of transforming rural collective lands into land for urban construction. Studies of land resources mainly explored the influence of *urban networks*, *urban forms*, and *urban systems* on arable land management, as well as the spatial evolution of basic farmland in *urban fringe areas*. Studies of land ecology centred on such topics as the *sustainability of farmers' livelihoods*, assessing the *value of the cultural landscape*, and *ecological compensation*. Studies of *land*

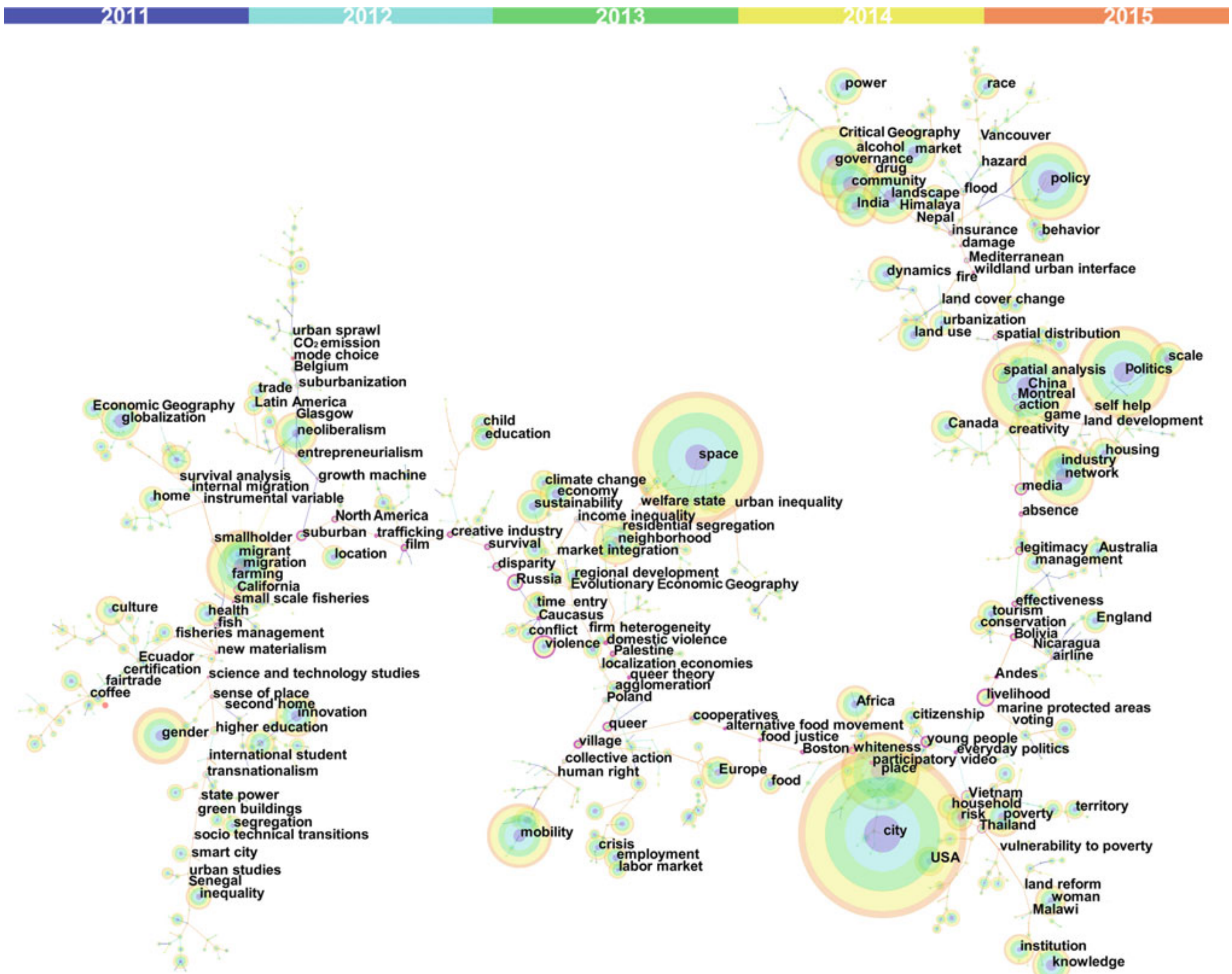


Fig. 5.17 Co-occurrence network of keywords in SCI/SSCI mainstream journals of human geography during the period 2011–2015

consolidation focused on *levels of willingness among farmers*, *rural agglomerations*, *rural homesteads*, *rural transformation and development*, and *new construction in the countryside*. (2) Studies of **cities** remained a popular topic for human geography studies. The keyword of urban studies and *urbanisation* appeared in over 120 papers during this period. Topics covered such issues as the relationships between urbanisation, information, industrialization, and conflicts between land use expansion and agricultural land resources. Also as a focus topic of urban studies, *urban planning* involved over 60 papers, covering the topics of *urban planning* and *land use planning*, *spatial planning*, *urban-rural planning*, and their relationships. In addition, the popular topic of *urban design* involved over 20 papers. Researchers moved from addressing *public participation*, *tourism*, and *urban image* during last period, to focusing on studies of *urban renewal* under the impacts of global and local forces, the issue of *historical areas* in cities, and related *stakeholders* during the process of urban design. *Urban management* was another high-frequency keyword in 2011. In addition, other key topics in urban studies included *urban form*, *urban agglomeration*, *urban spatial structure*, and *city network*, and the *Wuhan agglomeratio*n became a high frequency keyword in 2012. (3) The major concerns of **economic geography** included *economic growth, economic development*, *regional (county) economy*, *industrial structure*, *clusters*, and *industrial relocations*. The topics of *manufacturing sectors*, *cultural industry*, *tourism industry*, and *creative industr*y were popular research topics *Rail transit* also drew attention. Beyond the concerns over the conversion of farmland, during this period studies of rail transit focused on issues such as *industrial structure*, *urban spatial structure*, *accessibility*, and *service sectors*.

Figure 5.19 compares popular keywords in papers published by Chinese authors and others in mainstream SCI/SSCI-indexed human geography journals from 2011 to

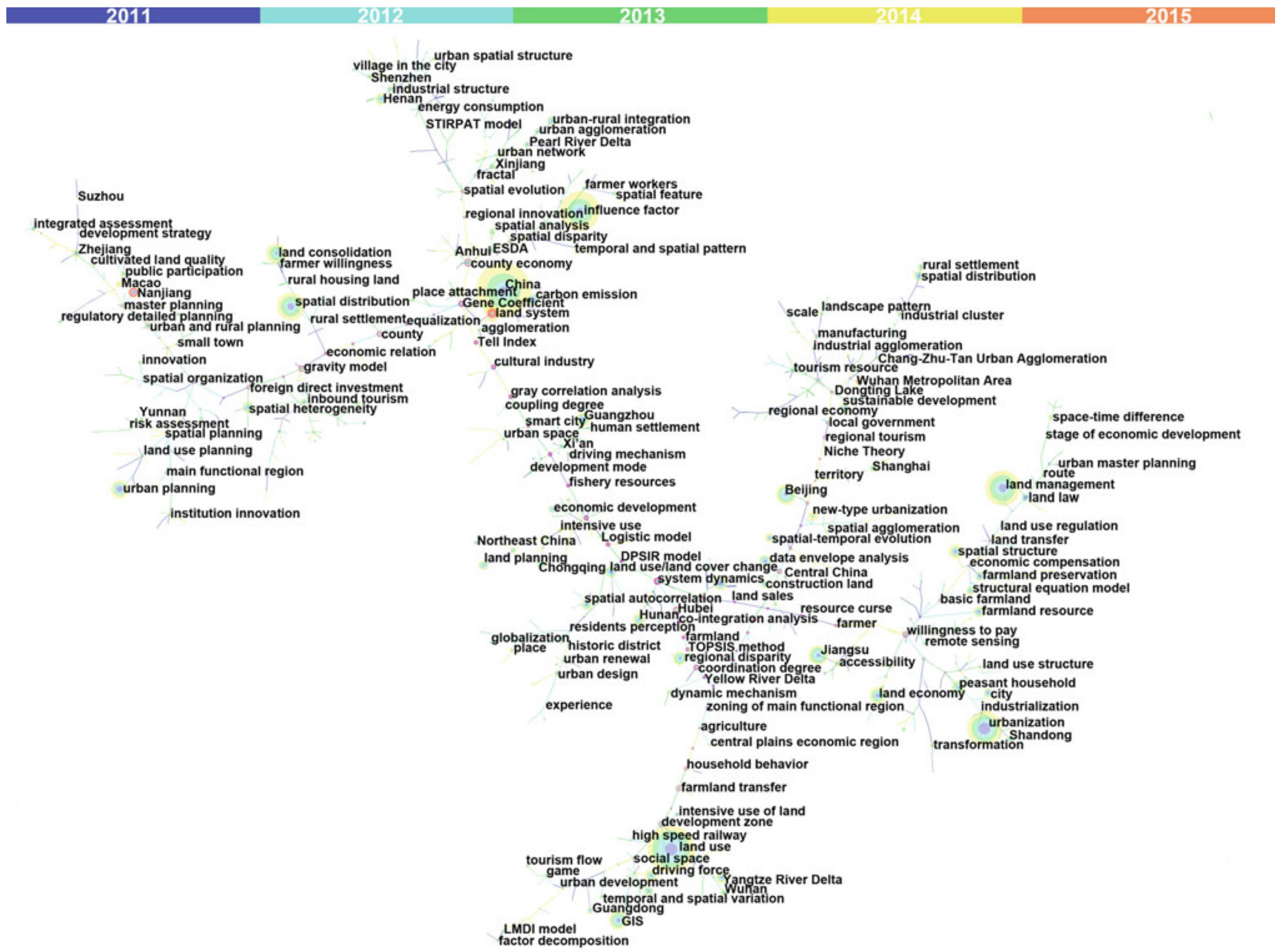


Fig. 5.18 Co-occurrence network of keywords in CSCD journals of human geography during the period 2011–2015

2015 (The diagram description see the note of Fig. 5.7). Again, increases were seen in the total number of journals and papers as well as in the total frequency of keywords. *Climate change* was the most frequent keyword, appearing 329 times. The number of articles published by Chinese authors in SCI/SSCI-indexed journals grew rapidly: the most frequent of the top 15 keywords appeared 88 times. In this period, the top 15 keywords in papers published by non-Chinese authors all appeared more than 88 times. The most common research topic in human geography measured by the highest frequency keyword remained climate change. Studies on *adaptation and vulnerability* to climate change started to expand. As concern with the impact of neoliberalism on global-local relationship studies, studies of *globalization* slightly decreased while *governance* and *institution* increased. The number of studies of migration and development continued to increase, and, for the first time, *sustainability* ranked among the top 15 high-frequency keywords. *Mobility* began to attract attention in migration studies. *Gender* and *poverty* remained one of the 15 leading keywords. In terms of regions researched, *China*, *Africa*, and *India* remained of interest, but a markedly higher number of papers were on China and India rather than on Africa. The keywords that increased most markedly in frequency in this 5-year period were *governance*, *institution*, *vulnerability*, and *mobility*. Of the top 15 keywords in papers published by Chinese authors in this period, *China* and *migration* were also common keywords for authors outside China. *Migration* became a popular topic in international human geography in 1996, but Chinese human geographers did not pay more attention to migration until 15 years later. However, Chinese scholars continued to be enthusiastic about the study of *urbanisation* and the *Chinese city*. The keyword *urbanisation* increased more than one time as frequently as from 2006 to 2010. Chinese scholars, influenced by Swedish and Japanese human geography, began to investigate the *geography of time* and *gated communities*, with the aim of meeting the realistic demands of the development of large Chinese cities. In this period, Chinese human geography also attached importance to the application of spatial methods

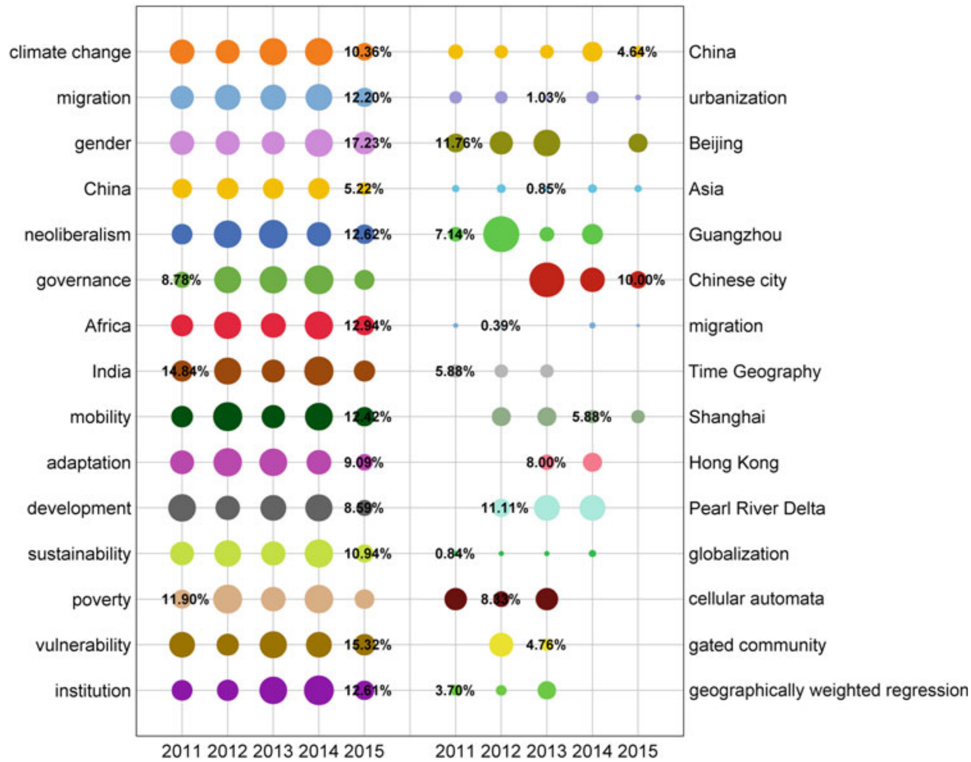


Fig. 5.19 Comparative diagram of prominent keywords by Chinese authors and others in SCI/SSCI mainstream journals of human geography during the period 2011–2015

such as *cellular automata* and *geographically weighted regression*. *Hong Kong*, *the Pearl River Delta*, *Guangzhou*, *Beijing*, and *Shanghai* were the focus regions for case studies.

5.2.6 Analysis of Driving Factors for Disciplinary Development over the Past 30 Years

This analysis of the evolution of the subjects examined, popular topics, and research perspectives in articles published in mainstream SCI/SSCI-indexed human geography journals of over the past three decades shows significant changes over time and marked differences between domestic Chinese and international research.

The evolution of subjects examined in papers published in mainstream SCI/SSCI-indexed human geography journals occurred as a result of two driving factors. First, this evolution was largely the result of social, political, and economic transformations and ideological changes. Development in the 20th century was defined by constant shifts between the market and planning. This was not only reflected in ideology but also in the selection by various countries of political and economic systems. With the crisis of social-democratic compromise in western countries in the 1980s, the market finally "defeated" planning. Most former socialist countries and developing countries adopted the ideology of private property and market economy and entered the process of liberalisation, privatisation and internationalisation. Many developed Western countries further emphasised capitalism. Countries characterised by variegated forms of capitalism engaged in fierce competition. Attempts were made to increase regional integration, and global governance issues became prominent. Multinational companies, together with various international organisations such as the World Trade Organization, World Bank, and International Monetary Fund, promoted a new international division of labour. Western countries became post-industrial societies and formed knowledge-intensive industrial systems defined by innovation and creativity, which were influenced by non-economic institutional, cultural, and relational factors. The dominance of the global economy by developed countries was strengthened by the high mobility of their capital, knowledge, and technology. Countries with economies in transition, together with selected developing countries, were soon melded with the global economic system. A number of them industrialised largely by means of market scale and resource advantages, and most of them experienced rapid urbanisation, promoting urban development and socioeconomic transition. In the early 21st century, globalisation increased in scope and depth. Capitalism's exposure of deep-seated problems caused a global economic crisis. Along with the reshaping of geopolitics and the world economy, the world entered a new era of political and economic competition. International terrorism came to pose a serious threat to international security. New issues such as social reform, population flows, the widening income gap, global city development, economic globalisation, the growth of China, and global environmental change brought about by political and economic transitions provided an excellent opportunity for human geographers to examine political, economic, social, and cultural transitions and related problems in the contemporary world. Neoliberal, institutional, cultural, political, and economic perspectives in human geography are rooted in the aforementioned political and economic trends. In short, the development of human geography had been promoted by social, political, and economic change and the evolution of social ideologies in the past three decades.

Second, a need arose for human geography to be combined with other disciplines in the social and natural sciences. In the era of globalisation, locality became extremely important, greatly influencing social, economic, and cultural behaviour. Since the 1990s, the spatial focus in international social sciences has meant that many disciplines, such as sociology, economics, politics, management, cultural studies, and anthropology, have increasingly addressed the spatial dimensions of social phenomena. Such studies have introduced new perspectives, enriching the understanding of the spatiality of social phenomena. Human geography overlapped with, and borrowed theories, methods, and perspectives from, these disciplines. This has significantly enhanced the study of human geography. Meanwhile, studies of the physical geography, ecology, and climatology of the global environment, global climate change, and land-use change have increasingly addressed comprehensive human factors, creating research opportunities across both human geography and these disciplines. Human geography has made important contributions to extending models and to the study of politics, governance, management, and planning. Human geography research into regional sustainable development, global climate change, and environmental issues indicates that there is a need for collaboration with physical geography and other disciplines.

In this period, Chinese human geography made great progress and contributed significantly to the development of knowledge. Three main factors driving the development of Chinese human geography can be identified. First, China underwent reform and its economic system was opened up. Since 1980, alongside urbanisation, China has experienced marketisation, globalisation, decentralisation, and rapid industrialisation. Rapid economic development has triggered dramatic social and economic change. The emphasis on economic growth has led to serious problems, including tension between population and land, environmental degradation, regional disparities, metropolitan problems, and rural decline. Chinese human geographers carried out in-depth examinations of these new phenomena, problems, factors, mechanisms, and driving forces. Chinese human geography has addressed globalisation, urbanisation, tourism, and rural, land, resource, and environmental problems.

Second, national development strategy and local development planning in China generated a demand for information. An important feature of Chinese human geography is that its development was driven by practical tasks and its vitality stemmed from its combination with practice. China's vast and differentiated territory, complex relations between the population and the land, and rapidly changing social and economic structure provided human geography with crucial opportunities to engage with central and local decision-makers. Human geographers successively addressed practical issues and important theories in the opening up of coastal and border areas and the establishment of development zones, as well as regional coordinated development, Western development strategy, planning for the main functional areas, the upgrading of old industrial areas in northeast regions, and territorial development. The study of urban geography and economic geography was closely linked with the practical needs of urban, regional, and territorial planning.

Third, there were relevant trends in the development of international human geography. With China's successful integration into the world economy, Chinese human geographers have gradually appeared on the international stage: they have significantly increased their active participation in international academic exchanges; they have studied theories, methods, and academic standards in international human geography; and they have investigated leading research topics and theoretical frontiers in international human geography. This is evidenced by the number of Chinese studies of transnational companies, foreign direct investment, urban transition, global cities, industrial agglomerations and clusters, regional innovation, gentrification, and climate change. These studies have not only enriched international human geography, but have also accelerated the development of Chinese human geography.

5.3 Disciplinary Development and Research Teams in China

This section focuses on the change in the proportion of applications and awards for human geography projects in the NSFC Geographical Sciences as a whole, the change in the number of project applications and awards in each sub-discipline of human geography, the average number of papers published on SCI/SSCI-indexed journals by different research institutions, the collaborative networks of authors publishing in SCI/SSCI-indexed or CSCD journals, and the affiliation and NSFC sponsorship of highly cited SCI/SSCI-indexed articles.

5.3.1 Numbers and Proportions of NSFC Applications and Funded Projects for Human Geography

Over the last three decades, human geography projects had secured a declining proportion of NSFC geographical sciences funding. Funding for human geography reached its peak in the period from 1996 to 2000, when it accounted for 20 % of funding (Fig. 5.20). Since then, the share had declined steadily. Nevertheless, the number of human geography applications and projects funded by NSFC had increased substantially, indicating that the study of human geography had remained vital.

Figure 5.21 shows the change in the proportion of applications for funding for General Programme (GP), for Young Scientists Fund (YSF), and for Fund for Less Developed Regions (LDR Fund) for each sub-discipline of human geography from 1986 to 2015. Within the funding system of NSFC, economic geography and urban geography have maintained a dominant position, connected with the fact that Chinese human geography has paid substantial attention to practical issues. Project applications in economic geography and urban geography, at one time, exceeded 60 and 40 %, respectively. Over the last decade, with the diversification of urban geography, the proportion of urban geography projects had decreased falling to 27 % in 2011–2015. At the same time, with 30 years of economic reform and development, social and environmental problems had become salient issues, even surpassing economic factors. Factors such as society, politics, and culture have gradually exerted an influence on Chinese human geography. The number of project applications in social and cultural geography is now equal to that for urban geography, and economic geography applications were 20 % lower than from 1986 to 1990. In the last two decades, international human geography paid more attention to issues in social and cultural geography. The enhancement of communication has had a significant impact on Chinese human geography. As a result in 2008 the NSFC established social and cultural geography as a sub-discipline in which applications could be made, and further promoted studies in this area.

5.3.2 Objects of Studies in NSFC-Funded Projects

Figure 5.22 shows the distribution of human geography projects with case studies that were funded by the NSFC. The yellow points represent 539 projects at the provincial scale. The green points represent 523 projects at the scale of prefecture-level cities and the administrative units below them. The points are located at randomly selected positions within the administrative units. Areas with a greater density of points have a higher number of projects. At the provincial scale, the largest number of projects can be found in Beijing and Shanghai, both over 100, followed by Jiangsu, Yunnan, Henan, Guangdong, Zhejiang, Xinjiang, Ningxia, Chongqing, and Tianjin, each with 20–50 projects. At the scale of

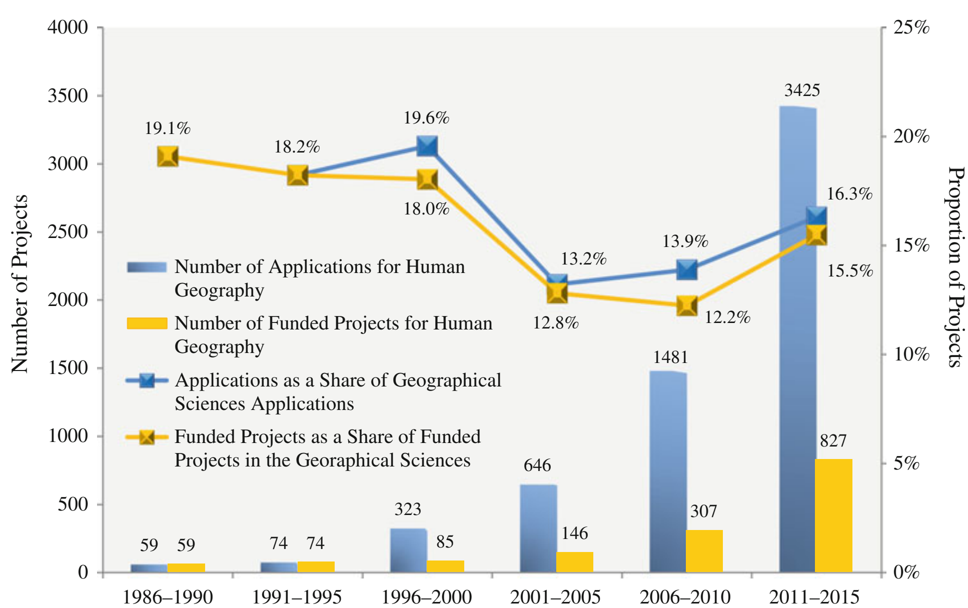


Fig. 5.20 Proportions of NSFC projects for human geography during the period 1986–2015. *Note* Non-funded proposals from 1986 to 1997 were not recorded in the NSFC database. Therefore, number of applications and NSFC-funded projects are identical from 1986 to 1995, as shown in the figure

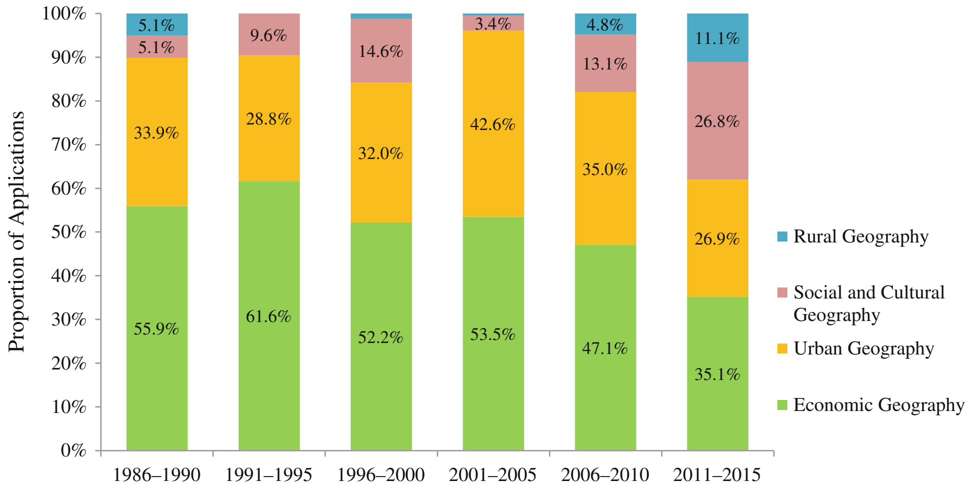


Fig. 5.21 Proportions of NSFC applications of branches of human geography during the period 1986–2015. *Note* Non-funded proposals from 1986 to 1997 were not recorded in the NSFC database. Therefore, the proportion of applications shown in the figure is the proportion of funded projects during the period

prefecture-level cities and the administrative units below them, the largest number of studies was in Guangzhou (about 100) followed by Nanjing, Shenzhen, Xi'an, Wuhan, Hangzhou, Suzhou, Chengdu, Dalian, and Shenzhen, each with about 20–50 projects. These results indicate that human geography studies were concentrated in the regions of rapid economic development, high levels of urbanisation, or high concerns with national developmental strategies, such as Beijing-Tianjin-Tangshan, Yangtze River Delta, or Pearl River Delta. (1) About 263 studies were carried out in Beijing and Shanghai, the global city of China, the funding of which amounted to 77,595 thousand yuan, or about 35.7 % of the total funding input at the provincial scale. Most focused on economic geography, including industrial networks (enterprise, knowledge, and transportation), multinational corporations, and financial service sector clusters, and on urban geography, such as urban spatial structure or social space. There were also studies of topics relating to tourism, time costs, rural migrant workers, and the identity of place. (2) Approximately 106 studies were carried out in Jiangsu, Guangdong, and Zhejiang provinces, the funding of which was 31,151 thousand yuan, or about 14.3 % of the total funding at the provincial level. Within these three provinces, there were about 325 projects in prefecture-level cities/counties, the funding of which amounted to about 78,587 thousand yuan, of 39 % of the total funding in prefecture-level cities/counties. At the provincial level, the topics mainly included issues such as the industrial economy and industrial ecology, and land use. At the scale of prefecture-level cities/counties the topics mainly included urban space, and urban functions. On both scales, there was interest in tourism and culture. (3) In contrast to studies in eastern regions, which focused on the city and industry, human geographers researching western regions paid more attention to people-land relationships within the context of the low level of economic development and urbanisation in the western regions. For example, studies in Chongqing, Shaanxi, and Sichuan focused on people-land relationships in mountainous and rural areas, with regard to issues such as climate change, low-carbon economic development, and farmers' livelihoods. Studies in the Xinjiang Uygur Autonomous Region were mainly concerned with the relations between urbanisation and the development of oasis economies. (4) Liaoning Province, as the most typical old industrial base of China, received a total of 55 projects, costing about 12,552 thousand yuan, in prefecture-level cities/counties, which was over six times that for the projects funded at the provincial scale. Among these projects, Dalian and Shenyang each took up about 40 %. These studies focused on industrial ecology, industrial heritage, brownfields, the low-carbon economy, urban space, and urban renewal with a view to the sustainable development of these industrial regions. There were also a few studies of tourism cities, border cities, and harbour cities.

Statistical results show that different branches of human geography had different preferences for the geographical scale of research. At the provincial scale, economic geography, resources, environment, and sustainability, urban geography, social and cultural geography, and rural geography accounted for 29, 24, 19.6, 19.6, and 7.9 %, respectively, of awarded NSFC grants. At the county/city scale, social and cultural geography, urban geography, economic geography, resource, environment, and sustainability, and rural geography accounted for 25.6, 25.4, 22, 20.4, and 6.6 %, respectively, of awarded NSFC grants. The results show that researchers studying economic geography and regional sustainability preferred to conduct research at a macro scale, while researchers interested in social, cultural, and urban issues preferred meso- or micro-scale research.

Further analysis of research in Guangdong, Jiangsu, and Zhejiang showed that of studies carried out at the provincial scale, economic geography, resources, environment, and

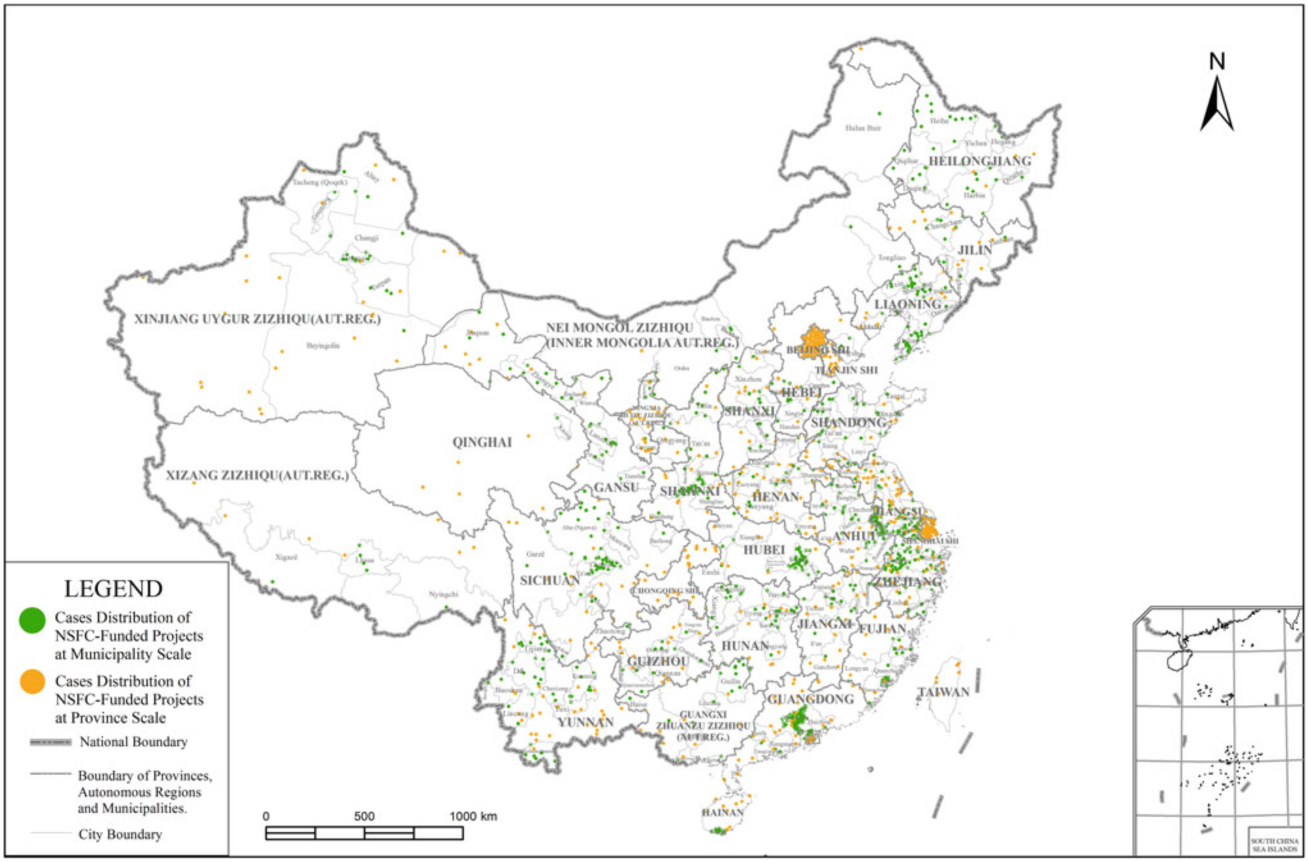


Fig. 5.22 Distribution of provinces and cities studied by NSFC-funded project in human geography during the period 1986–2015

sustainability, rural geography, social and cultural geography, and urban geography accounted for 39.6, 23.6, 14.2, 12.3, and 10.4 % of awarded NSFC grants, respectively. Of studies carried out at the county/city scales, urban geography, social and cultural geography, economic geography, resources, environment, and sustainability, and rural geography accounted for 36.9, 24.6, 23.1, 10.8, and 4.6 % of awarded NSFC grants, respectively.

Statistical results based on the above three provinces confirm that some branches of human geography are concentrated in research at a particular scale, and that the research focus of human geography fits the economic and social development stage of China.

5.3.3 Research Teams

The analysis of research teams in this section uses the following indicators: the number of institutions applying for NSFC's human geography projects, the number of Chinese institutions publishing papers in the SCI/SSCI journals and CSCD journals, Chinese authors in the field and their collaborative networks, the average number of SCI/SSCI-indexed articles of NSFC sponsored institutions and the advantage of the top five NSFC-funded institutions, high-impact SCI/SSCI-indexed articles authored by Chinese scholars and the advantage of the top ten NSFC-funded institutions. In the graphs of the collaborative networks of Chinese authors of papers in SCI/SSCI-indexed and CSCD journals, to distinguish between authors with the same name, we added the abbreviations for Chinese and English authors' affiliations to their names. Appendix D shows the full names and the abbreviations of the affiliations.

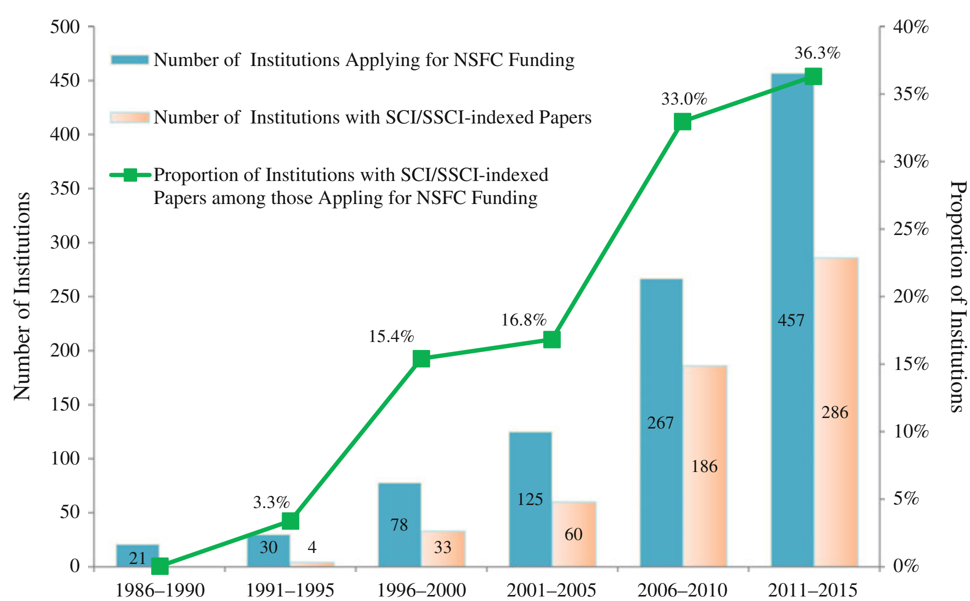
Figure 5.23 shows the number of institutions applying for NSFC's human geography projects and the number of institutions (of all Chinese authors) publishing papers in mainstream SCI/SSCI-indexed human geography journals in five year periods, from 1986 to 2015. The green line represents the proportion of institutions applying for NSFC human geography projects that published papers in mainstream SCI/SSCI-indexed journals. As the chart shows, the number of institutions increased, but the growth rate in the number of institutions applying for projects was noticeably higher than that of institutions publishing papers in mainstream SCI/SSCI-indexed journals. Meanwhile, the number of institutions publishing papers was less than the number lodging applications, regardless of the time period. On the one hand, this indicates that in China the number of institutions participating in basic human geography study was increasing. On the other hand, it indicates that a considerable share of human geography institutions had not published papers in English, making it difficult for China's human geography research to integrate into international academic circles. This situation was further confirmed by the data recording the proportion of institutions publishing papers on mainstream SCI/SSCI-indexed human geography journals. Although in the last 5 years, among institutions applying for NSFC human geography projects, the proportion of institutions publishing papers in SCI/SSCI mainstream journals reached 36 % (almost 10 times higher than before 1995), more than two-thirds of institutions applying for NSFC funds did not publish papers in mainstream SCI/SSCI-indexed journals. Several factors are responsible for such a situation. (1) Chinese scholars focused on local problems and rarely analysed them from an international perspective. (2) As a discipline that crosses the boundaries between geography on one hand and human, economics, sociology and management science on the other hand, human geography required higher English writing skills, which was a disadvantage for researchers in China. (3) The weakness of research methods and the lack of credible data undermined the rigor of some research conducted in China.

Figures 5.24 and 5.25 show the collaborative network of Chinese authors publishing papers in the mainstream SCI/SSCI-indexed and CSCD-indexed human geography journals from 1986 to 2015 (please refer to Appendix D for the abbreviations index). During the last thirty years, the papers published by Chinese human geographers in mainstream journals focused on the following five fields: (1) urban studies; (2) economic geography and regional science; (3) rural geography and the resource environment; (4) tourism development and management; and (5) transportation geography. First, scholars in the same field in China and abroad showed strong collaborative relationships, while domestic scholars often cooperated with colleagues from the same research institutions. Moreover, due to the proximity of institutions or the location of study areas, distinctive research directions formed among different higher education or research institutions. Examples included the study of urban and regional sustainable development at the Institute of Geographic Sciences and Natural Resources of CAS (IGSNRR), the study of urban social space at Sun Yat-sen University (SYSU), and the study of housing, transportation and infrastructure at The University of Hong Kong (HKU). In addition, collaborative networks had interdisciplinary characteristics and were made up not only of human geographers but also of scholars in such fields as remote sensing and geographical information science, landscape ecology, physical geography, economics, and urban planning.

Urban Studies

Collaborative networks in the field of urban studies are characterized by the following. (1) **Urban research and the study of cities** was the most important theme of papers published in mainstream journals by Chinese human geographers during the last three decades. Urban research was large in volume and wide in scope, and was made up of a series of independent sub-networks. The main research regions were on the Pearl River Delta, Yangtze River Delta, and in megacities, such as Hong Kong, Guangzhou and Shanghai. The main collaborative networks included: the study of urban development, with associated networks involving **Shen Jianfa** (CUHK), **Zhao Simon Xiao Bin**

Fig. 5.23 Number of Chinese research institutions on human geography during the period 1986–2015



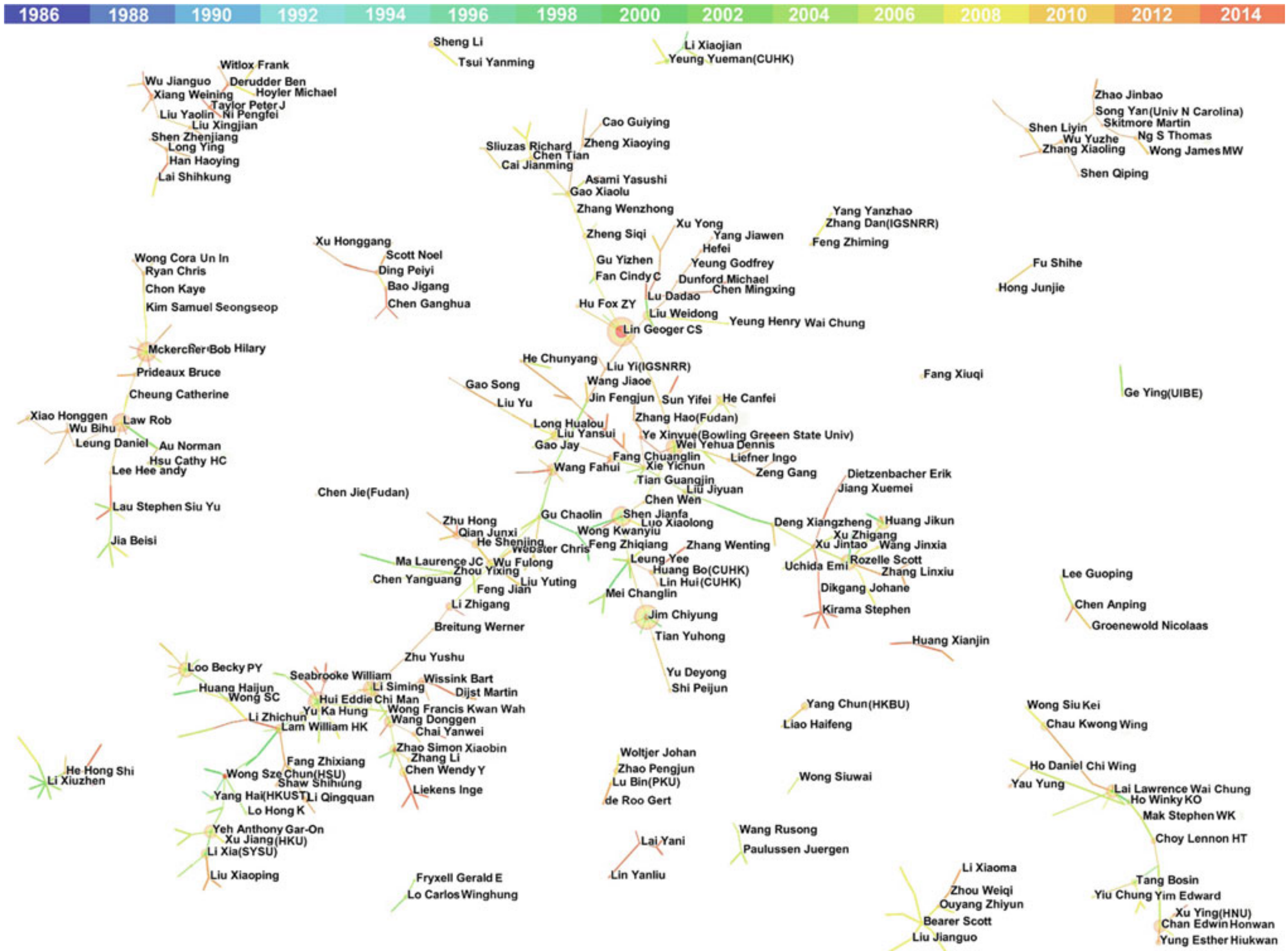


Fig. 5.24 Collaborative network of Chinese authors in SCI/SSCI mainstream journals of human geography during the period 1986–2015

(HKU), **Fang Chuanglin** and **Chen Tian** (IGSNRR), serving as the nodes. Urban studies focused on the relationships between population, economy, and industry, and examined vertical links, evolutionary paths and urban planning and governance. Articles on these subjects were mainly published in *Urban Geography*, *Cities, Habitat International*, *Geoforum*, *Regional Studies*, *Journal of Geographical Sciences*. (2) **Urbanisation and urban systems** included the collaborative networks in which **Zhou Yixing** (PKU), **Wu Fulong** from the University College London (UCL), and **Gu Chaolin** (TSINGHUA) served as nodes. These studies paid attention to the analysis of the driving mechanisms of urbanisation, urban system evolution, urban transforming features and their influences at different scales, and dissected the reasons for, and characteristics of a number of conflicts in urbanisation. This group's papers were published in *Urban Studies*, *Urban Geography*, *Habitat International*, *Environment and Planning A & B*, *Cities*, *Eurasian Geography and Economics*, and *Regional Studies*. (3) **Urban space and social cultural space** included the collaborative networks whose nodes were **Li Zhigang** (SYSU/WHU), **He Shenjing** (SYSU/HKU), **Zhu Hong** and **Qian Junxi** (SCNU), and **Gao Xiaolu** (IGSNRR). These studies mainly concentrated on the characteristics of urban space and their developments, urban social segregation, and the formation and evolution of social cultural space, with related papers published in *Environment and Planning A & B*, *Social & Cultural Geography*, *Geoforum*, *Cities*, *Habitat International*, *Antipode*, *Urban Geography*, and *Urban Studies*. (4) **Real estate economics and housing policy study** included collaborative networks whose nodes were **Li Siming** (HKBU), **Hui Eddie Chi-man**, **Chan Edwin Honwan** (POLYU), **Lai Lawrence Wai-chung**, **Chau Kwong Wing** (HKU). This research, based on urban economics and policy analysis, had analysed urban housing markets and characteristics of people's living space, real estate development and housing security problems, publishing articles in *Environment and Planning A & B*, *Habitat International*, *Urban Studies*, *Urban Geography*, and *Journal of Urban Planning and Development*.

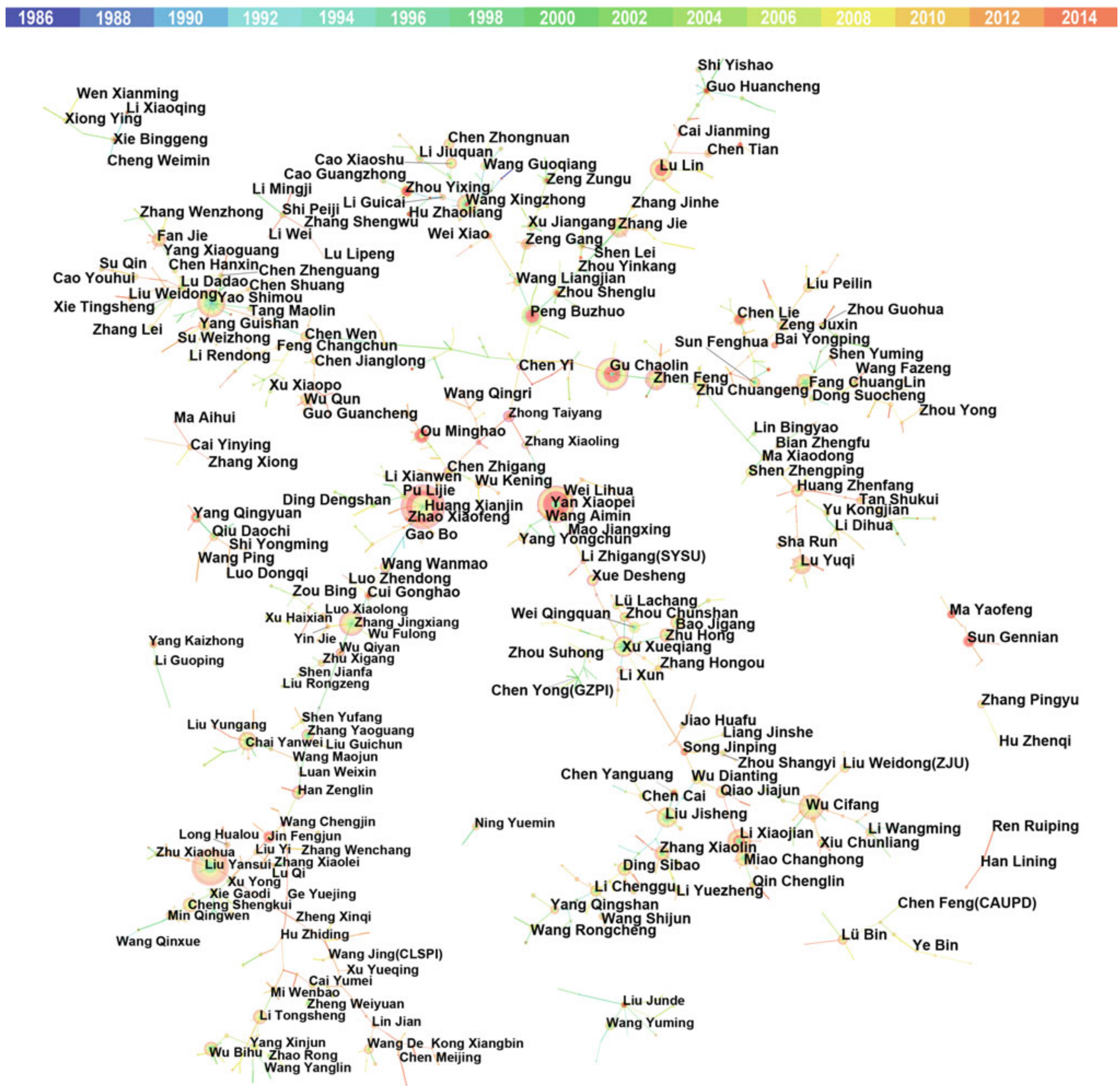


Fig. 5.25 Collaborative network of Chinese authors in CSCD journals of human geography during the period 1986–2015

(5) **Urban transportation and infrastructure study** included collaborative networks whose nodes were with **Loo Becky PY**, **Wong Sze Chun** (HKU), **Wang Donggen** (HKBU), **Lam William HK** (POLYU), **Zhao Pengjun** and **Chai Yanwei** (PKU). This research involved analysis of different types of urban transportation layout, accessibility and travel behaviour as well as relationships between infrastructure construction and urban land use. Articles were published in the *Journal of Transport Geography, Urban Geography, Annals of the Association of American Geographers, Annals of Regional Science, Cities, Urban Studies, Landscape and Urban Planning*, and *Journal of Urban Planning and development*. (6) **Urban quantitative and simulation studies** included collaborative networks whose nodes were **Yeh Anthony Gar-On** (HKU), **Li Xia** and **Liu Xiaoping** (SYSU), and **Leung Yee** (CUHK). This research focused on spatial analysis, dynamic modelling, and artificial intelligence using analogies and simulation models to examine urban spatial patterns and the evolution of urban systems. Articles were published in *Environment and Planning A & B, Urban Studies, Computers Environment and Urban Systems, Cities, Annals of the Association of*

American Geographers, Landscape and Urban Planning, and *Applied Geography*. (7) **Urban landscape development and the study of sustainability** included collaborative networks whose nodes were with **Xiang Weining** (ECNU), **Jim Chiyung** (HKU), **Wang Rusong,** and **Ouyang Zhiyun** (RCEES). This research, based on landscape ecology theories and methods, has analyzed urban expansion, urban land use change and the distribution of and dynamic changes in urban open space using remote sensing images. Articles were published in *Landscape and Urban Planning, Applied Geography, Cities*, and *Habitat International*.

As indicated by the papers published in CSCD-indexed journals, there were other networks. (1) the collaborative network centred on **Xu Xueqiang**, **Yan Xiaopei** (SYSU) which focused on the Pearl River Delta and carried out studies of urbanisation and urban development, regional economic integration, the urban transportation system, urban competitiveness, world cities, urban management and urban planning. (2) The collaborative network of authors conducting studies of urban planning and urban geography has focused on the Yangtze River Delta, Beijing and Shenzhen and conducted studies of urban planning, urban competitiveness, urban-rural development integration, tourism resources development, urban networks, and regional governance. This network was centred on **Cui Gonghao** (NJU), **Gu Chaolin** (TSINGHUA), **Zhen Feng**, and **Zhang Jingxiang** (NJU). (3) The collaborative network of authors conducting studies of urban geography and urban planning centring on **Zhou Yixing**, **Hu Zhaoliang**, and **Chai Yanwei** (PKU), has conducted studies of the degree of urbanisation, urban population, urban form and urban systems, and recently, has examined urban social geography, urban public space, urban commercial space, consumer behaviour consumer space and low-carbon cities. (4) The collaborative network of authors conducting studies of urban regions centring on **Yao Shimou** (NIGLAS) has carried out studies of urban forms, urban functions, urban coordination, urban spatial structure and organization, and resource intensive use and development models in the process of urbanisation. Study regions included Jiangsu, Zhejiang, and Anhui, Shandong. (5) **Mao Hanying** and **Fang Chuanglin** (IGSNRR) have also conducted a large number of studies of urbanisation and regional development.

Economic Geography and Regional Science

Compared with the numerous collaborative networks in the field of urban studies, the number of scholars conducting research in economic geography and regional science was relatively small. However, the economic geography and regional science research network was close-knit with relatively high cooperation among scholars working on different issues. In terms of disciplinary participation, this research involved not just economic geography but also close relations with regional economics and regional science. However, cooperation among economic geography scholars and economics scholars was relatively limited. The main collaborative networks were the following. (1) **Regional development studies**, which included collaborative networks whose nodes were **Lin George CS** (HKU), **Liu Weidong** (IGSNRR), **Wei Yehua Dennis** (University of Utah), and **Yang Chun** (HKBU). This research focused on the characteristics, causes and paths of regional competition and unbalanced development starting from perspectives of factor inputs, economic agglomeration and regional division and searching for the basis of regional governance. The findings of this research were mainly published in *Environment and Planning A, Eurasian Geography and Economics*, *Journal of Economic Geography*, *Urban Studies*, *Regional Studies*, *Urban Geography*, *Habitat International*, *Annals of the Association of American Geographers*, *Geoforum*, and *Economic Geography*. (2) **Industrial geography** included collaborative networks whose nodes were **Yeung Henry Wai Chung** from National University of Singapore (NUS), **He Canfei** (PKU), **Li Xiaojian** (HENU), and **Zeng Gang** (ECNU). This research has focused on analysing the spatial dynamics, causes and mechanisms driving the agglomeration of economic activities and its influence on regional development paying attention to cultural and enterprise aspects. Outputs were mainly published in *Economic Geography*, *Eurasian Geography and Economics*, *Regional Studies*, *Urban Geography*, *Urban Studies*, *Applied Geography*, and *Growth and Change*.

As indicated by the papers published in CSCD-indexed journals, there were other networks. (1) **Lu Dadao**, **Fan Jie**, and **Liu Weidong** (IGSNRR) who focused on critical issues related to human and economic geography, such as territorial space development, the main functional areas and the relocation of manufacturing enterprises that have affected China's regional development. (2) The collaborative network centring on **Li Xiaojian** and **Miao Changhong** (HENU) who have focused on underdeveloped regions in the central plains like Henan. They conducted studies of industrial clusters, rural industry, the financial sector and commercial service sector network structures, farmers, and technological learning and innovation. (3) The collaborative network of the authors conducting studies in regional economics and development, centred on **Lu Yuqi** (NJNU). This group has carried out studies of regional structures, differences, competition, divisions of labour and regional relationships. Tourism economics was also a key study area. (4) The collaborative network of authors conducting studies in transportation geography and regional economics. This centred on **Jin Fengjun** (IGSNRR) and **Han Zenglin** (LNNU). They have carried out studies of transportation structures, spatial agglomeration, transportation networks, and economic and communications belts. These studies examined railway transport, aviation, harbours and modern logistics. The achievements of industrial geography have been numerous with influential work on industrial agglomeration, ecology, innovation and globalization. Related study teams included **Wang Jici** and **He Canfei** (PKU), **Zeng Gang** and **Du Debin** (ECNU), and **Liu Weidong** and **Liu Yi** (IGSNRR).

Rural Geography and Resource Environment

As a research area closely related to the study of people-land relationships, study of rural geography and the resource environment reveals the close interlocking of nature and humanity. In these collaborative networks, it is common to see human geographers cooperate with scholars in fields such as geographical information system, remote sensing, resource environment management, ecology and landscape ecology. Three major network groups have been formed on the basis of different research foci, with scholars in the field of spatial analysis technologies enabling the groups to cooperate with each other. (1) **Land use and regional development** included collaborative networks whose nodes were **Liu Jiyuan, Deng Xiangzhen** (IGSNRR), and **Xie Yichun** (Eastern Michigan University). This research focused on the changing characteristics, drivers and influences of different types of land use, and involved a combination of different GIS technologies and economic analysis. Articles were published mainly in *Land Economics*, *Environment and Development Economics*, *Journal of Urban Economics*, *Landscape and Urban Planning*, and *Journal of Geographical Sciences*. (2) **Resource environment and agricultural policy** included collaborative networks whose nodes were **Huang Jikun**, **Feng Zhiming** (IGSNRR), and **Xu Jintao** (PKU). This research has focused on the sustainable use of, and policy support for, the resource environment, drawing on the tools of economic and policy analysis. Articles were published mainly in *Environment and Development Economics*, *Land Economics*, *World Development*, *Journal of Development Studies*, and *Journal of Geographical Sciences*. (3) **Land use and rural development studies** included collaborative networks whose nodes were **Liu Yansui** (BNU/IGSNRR), **Long Hualou** (IGSNRR), and **Huang Xianjin** (NJU). This research has focused on land and space restructuring in the process of rural transformation and development starting from the features of rural land use and social change. Articles were published mainly in *Applied Geography*, *Journal of Rural Studies*, *Habitat International*, *Land Use Policy*, and *Journal of Geographical Sciences*.

As indicated by the papers published in CSCD-indexed journals, other networks included the collaborative network of authors conducting studies of land management and sustainable land use centring on **Wu Cifang** (ZJU), which have conducted studies into urban spatial expansion, urban land management and the asset management of land resources.

Tourism Development and Management

The tourism development and management study network was obviously independent of other study areas. In terms of cooperation in publishing papers, it took the form of two clearly independent networks, both of which, nevertheless, were involved with main issues associated with the study of tourism development and management. The main collaborative networks included the following. (1) **Tourism information analysis and management** included the collaborative networks whose node was **Law Rob** (POLYU). This research focused on the establishment, management and use of tourism information systems and the analysis of tourism preferences and behaviours, with the research outputs published mainly in *Annals of Tourism Research*, *International Journal of Tourism Research*, and *Asia Pacific Journal of Tourism Research*. (2) **Tourism science theory and methods** included collaborative networks whose nodes were **Wu Bihu** (PKU), **Bao Jigang, Xu Honggang** (SYSU), and **Xiao Honggen** (POLYU). This work examined the theories and methods of tourism science, and sought a comprehensive understanding of the social, economic and environmental dimensions of tourism development and tourism activities, with research findings published mainly in *Annals of Tourism Research*, *International Journal of Tourism Research*, *Asia Pacific Journal of Tourism Research*, and *Tourism Geographies*. (3) **Environmental impacts of tourism and sustainable tourism** included collaborative networks whose nodes were **Ding Peiyi** (Griffith University), and **McKercher Bob** (POLYU). This research focused on the combined effects of tourism development and activities on the environment and on social production. This analysis led to assessment of the demands of and development models for sustainable tourism, with research finding published mainly in the *Journal of Sustainable Tourism*, *Annals of Tourism Research*, *International Journal of Tourism Research*, *Asia Pacific Journal of Tourism Research*, and *Tourism Geographies*. Professor **Ding Peiyi** from Australia has cooperated with **Bao Jigang** and **Xu Honggang** (SYSU).

As indicated by the papers published in CSCD-indexed journals, other networks included (1) the collaborative network centring on **Lu Lin** (ANU) and **Zhang Jie** (NJU), who conducted studies on tourism economics, cultural ecological protection, world heritage, tourism environmental capacity and the life cycle of tourism destinations. (2) The collaborative network centring on **Ma Yaofeng** and **Sun Gennian** (SNNU) which has conducted studies mainly of inbound tourism, border tourism and tourism industry competition strategy.

Transportation Geography and Regional Development

Relatively small in scale, transportation geography study has paid attention to regional development, rooting transport studies in urban and regional studies networks. The main study teams were involved in collaborative networks whose nodes were **Jin Fengjun** and **Wang Jiaoe** (IGSNRR). The research has focused on the characteristics and dynamics of aviation, railway and port systems, and their impact on regional development, publishing findings in the *Journal of Transport Geography*, *Eurasian Geography and Economics*, *Professional Geography*, and *Journal of Geographical Sciences*.

Beyond these five fields, there were several academic collaborative networks of human geography that mainly occurred in CSCD-indexed journals. (1) The network of authors studying Northeast China, which centred on **Chen Cai**, **Ding Sibao** and **Liu Jisheng** (NENU). These authors conducted studies of the Northeast's industrial structure, urbanisation, resource-based cities, old city reconstruction and inland border ports. (2) The network of authors studying resources, which centred on **Cheng Shengkui** (IGSNRR), focused on studies of resource flows, resource development, resource potential assessment, and resource allocation optimization. These resources include land, water, grain, coal, biological energy, agricultural cultural heritage and tourism.

According to statistics of the top 200 Chinese authors who published papers in the SCI/SSCI human geography journals during 1985–2015, there were 1601 papers published. The journals with the largest number of articles were *Habitat International*, *Journal of Geographical Sciences*, and *Landscape and Urban Planning*, each of which published more than 100 papers. Together they accounted for 26.1 % of all papers. Papers published in mainstream journals in different professional fields such as *Environmental and Planning A*, *Urban Studies*, *Cities*, *Environmental and Planning B*, *Eurasian Geography and Economics*, *Asia Pacific Journal of Tourism Research*, *Journal of Transport Geography*, *Urban Geography* also accounted for a large number of papers. Individually each of these journals accounted for about 3–6 % of the total.

About 63 % of Chinese authors publishing papers in mainstream SCI/SSCI-indexed human geography journals and 84 % of Chinese authors publishing papers in CSCD-indexed journals have received funding for NSFC geographical sciences projects. Among the Chinese authors with the SCI/SSCI-indexed publications in the top 100, 18 were also ranked in the top 100 in terms of the CSCD-indexed publications. These authors carried out a total of 410 NSFC-funded geographical sciences projects. As for the top 100 authors in terms of SCI/SSCI-indexed publications, 28 received funding from the Young Scientists Fund (YSF), four from the National Science Fund for Distinguished Young Scholar (DYS Fund), and four from the Excellent Young Scientists Fund (EYS Fund). In general, for these top 100 authors in terms of SCI/SSCI-indexed publications, the funding receiving from General Programme (GP) accounted for 39.2 % of total funding, the funding from the Key Programme (KP) and Major Research Plan (MRP) accounted for 37.5 %. Therefore, research projects such as the General Programme (GP) and the importance-based types such as "Key" and "Major" NSFC programmes have made a great contribution to Chinese human geography research.

Table 5.2 shows the top five institutions in terms of the number of people awarded grants and amount of NSFC human geographical funding won in every 5-year period from 1986 to 2015. The number of people receiving funding refers to the total of those funded by NSFC human geography within an institution in each 5-year period. The same person was only counted once in the 5 year. In the past 30 years, there were 10 institutions entering the top five supported by NSFC, of which eight were universities and two were research institutes. This illustrates the absolute advantage of universities on human geographical research in China. Institute of Geographic Sciences and Natural Resources Research of CAS has always been on the top one position.

Figure 5.26 plots the per capita SCI/SSCI-indexed articles funded by NSFC in the 84 human geography journals for the top five institutions listed in Table 5.2. This indicator is derived by dividing the total number of papers by researchers receiving NSFC human geography funding during the same 5-year period. The proportion of funding refers to the sum of funds received from NSFC in these listed institutions to the total NSFC human geography funds in the five years. The proportion of funding going to the top five institutions has generally decreased over the past 30 years. In 2011–2015, it fell to 30 %, one-half of the proportion in 1986–1990. In this period, there was a substantial increase in the number of human geography research institutes and a convergence in capabilities in human geography. As a result, the absolute advantages of traditional leading human geography institutions in securing NSFC project funding decreased. As a whole, the number of papers per person kept increasing. Before 2005, the number of such publications was less than one but has increased rapidly to 2.1 in 2006–2010 and 2.5 in 2011–2015, 25 times that before, twice that

Table 5.2 Top 5 institutions with NSFC funding for human geography during the period 1986–2015

1986-1990			1991-1995			1996-2000		
Institutions	Number of PIs	Funding (10,000 yuan)	Institutions	Number of PIs	Funding (10,000 yuan)	Institutions	Number of PIs	Funding (10,000 yuan)
Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences	14	74.7	Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences	16	194.5	Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences	16	413.5
Peking University	7	33.5	Peking University	6	45	Sun Yat-sen University	5	186
Nanjing University	5	19.1	Henan University	5	40	Nanjing University	5	159
Northeast Normal University	4	15.5	East China Normal University	6	38.4	Peking University	9	120
Sun Yat-sen University	4	15	Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences	3	28.5	East China Normal University	5	63
Total of top 5	34	157.8	Total of top 5	36	346.4	Total of top 5	40	941.5
Total of non top 5	22	77.7	Total of non top 5	34	244.5	Total of non top 5	39	589
Total of human geography	56	235.5	Total of human geography	70	590.9	Total of human geography	79	1,530.5
Total of geography	294	1,362.3	Total of geography	374	3,840.6	Total of geography	422	9,984.9
2001-2005			2006-2010			2011-2015		
Institutions	Number of PIs	Funding (10,000 yuan)	Institutions	Number of PIs	Funding (10,000 yuan)	Institutions	Number of PIs	Funding (10,000 yuan)
Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences	14	590	Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences	29	1,052.6	Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences	50	3,961.1
Nanjing University	14	434.4	Peking University	26	727.5	Sun Yat-sen University	29	2,770.3
Sun Yat-sen University	12	424	Sun Yat-sen University	18	578.5	Peking University	23	2,240.1
Peking University	15	396.1	Nanjing Normal University	10	309	Nanjing Normal University	19	1,490.3
Northeast Normal University	8	224.7	East China Normal University	11	294	Anhui Normal University	21	1,316.5
Total of top 5	63	2,069.2	Total of top 5	94	2,961.6	Total of top 5	142	11,778.3
Total of non top 5	61	1,578	Total of non top 5	184	5,219.7	Total of non top 5	626	27,432.8
Total of human geography	124	3,647.2	Total of human geography	278	8,181.3	Total of human geography	768	39,211.1
Total of geography	890	33,800.6	Total of geography	2,197	90,823.6	Total of geography	4,821	304,971.3

of other institutions, indicating a greater degree of internationalisation of the top five institutions.

The number of highly cited papers in the field of human geography had increased along with the increase in the number of SCI/SSCI-indexed articles per capita. For the top 50 highly cited SCI/SSCI-indexed articles by Chinese authors (Fig. 5.27), the proportion supported by NSFC funds increased from 10 % in 2000 to 54 % in 2013. The proportion of papers published by researchers from the top ten NSFC-sponsored institutions first increased and then decreased, with an average level of 70 %, and a peak of more than 90 %. It can be concluded that top ten NSFC-sponsored institutions in China have contributed nearly 30 % of high-impact SCI/SSCI-indexed articles (the top 50) by Chinese researchers, and nearly one-third of the top 50 most highly cited SCI/SSCI-indexed articles were sponsored by the NSFC, indicating the considerable importance of NSFC-funded research.

Although Chinese scholars have produced an increasing number of highly cited papers, the number of the highly cited papers has remained limited. Among the top 1000 most highly cited SCI/SSCI-indexed articles, there were only 14 papers by Chinese scholars in 2000–2004 and 36 papers in 2010–2014. Table 5.3 shows the distribution of top 1000 most highly cited SCI/SSCI-indexed articles by country. In 2000–2014, American authors contributed 331 of the top 1000 most highly cited SCI/SSCI-indexed articles, accounting for 33.1 % of the total. In contrast, Chinese authors contributed 11 papers, accounting for only 1.1 % of the total. Over these 15 years, the proportion of papers authored by American scholars decreased by 8.6 %, while the proportion of papers authored by Chinese scholars increased by 2.2 %. Among the papers authored by Chinese scholars, the proportion funded by the NSFC increased from 21.4 % in 2000–2004 to 55.6 % in 2010–2014. The proportion of NSFC-funded articles by scholars from the top 10 institutions decreased from 57.1 % from 2000 to 2004 to 34.6 % from 2005 to 2009, rebounding to 50 % from 2010 to 2014. Of NSFC-funded articles, the share of the top ten institutions increased from 37.5 % in 2000 to 2004 to 77.8 % from 2010 to 2014. The above statistics indicate that the number of internationally recognised research outputs have increased substantially over the past 5 years. Among these outputs, more than 50 % were sponsored by the NSFC. Nearly 80 % of NSFC-sponsored most highly cited papers came from the top ten institutions, which received the largest amount of NSFC funding. These ten institutions accounted for 45 % of all highly cited papers authored by Chinese scholars.

To analyse the relationships between the topics of highly cited papers and the research topics funded by the NSFC, the keywords of the top 1000 most highly cited human geography papers written by Chinese scholars were ranked. The top 10 keywords were identified, and the ratio of the citation of top 10 keywords to the number of papers written by Chinese scholars was calculated (hereafter, "paper-based top 10 keywords"). Next, the keywords used in research projects funded by the NSFC were ranked, and the top ten most frequently used keywords were identified, and the ratio of the citation of top ten keywords to the number of human geography research projects founded by NSFC was

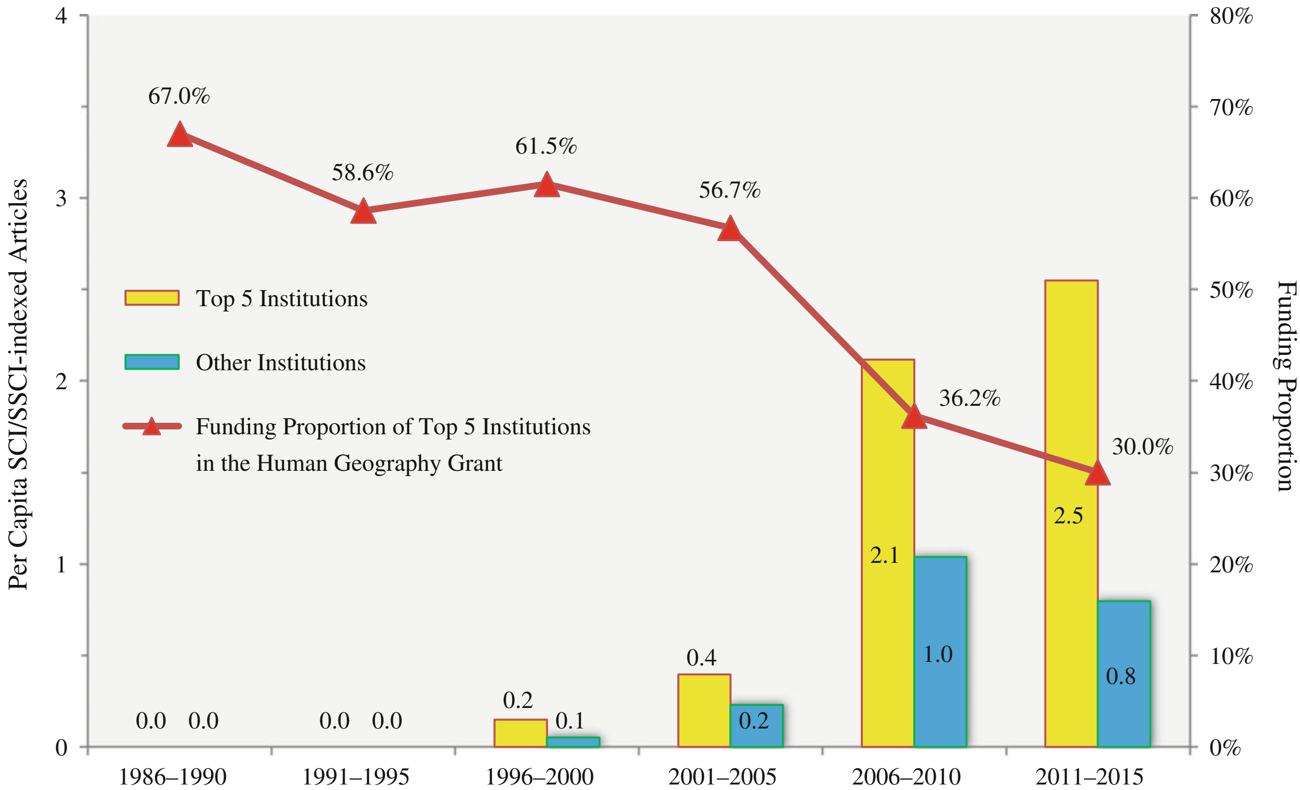


Fig. 5.26 Funding proportion of top 5 NSFC-funded institutions and their per capita SCI/SSCI-indexed articles in human geography during the period 1986–2015. *Note* Co-authors from different institutions were counted separately

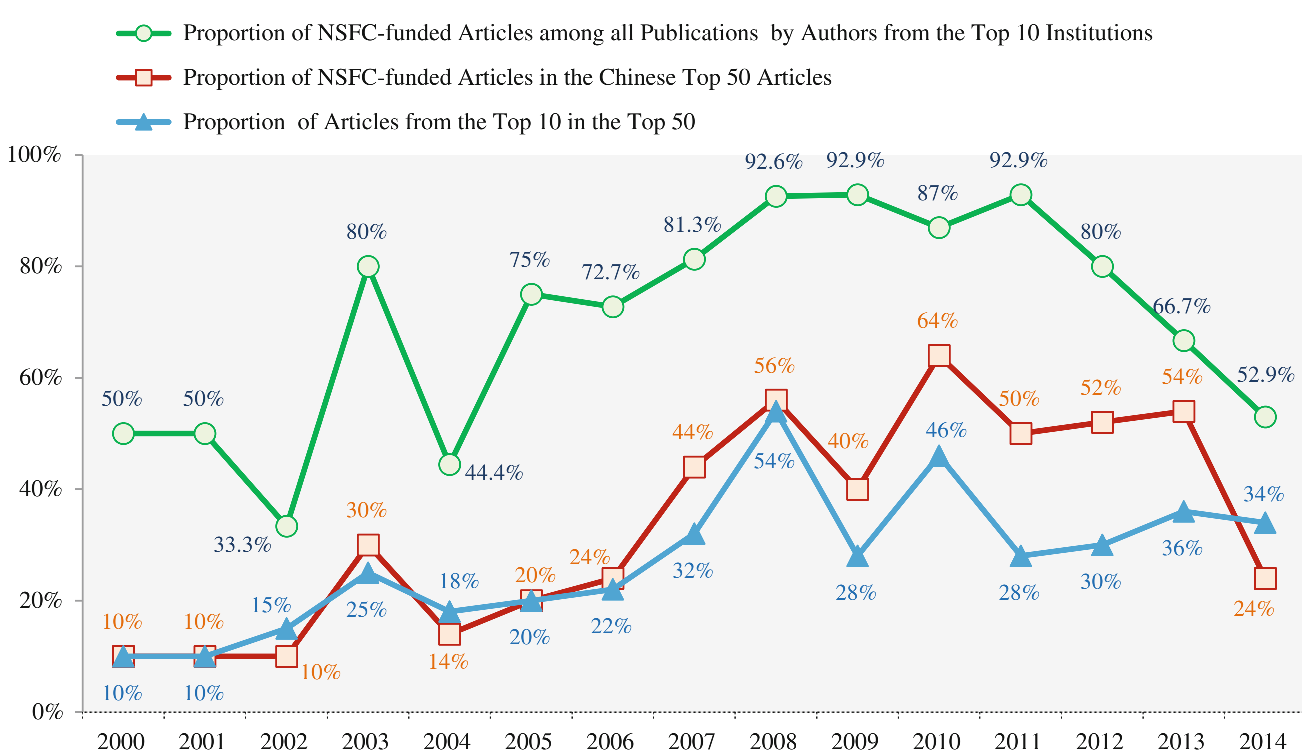


Fig. 5.27 Proportion of NSFC-funded SCI/SSCI-indexed articles in Chinese top 50 citation in human geography during the period 2000–2014. *Note* The Top 10 institutions refer to those with Top 10 NSFC's annual funding for human geography during the period 2000–2014, including Institute of Geographic Sciences and Natural Resources Research of CAS, Sun Yat-sen University, Peking University, Nanjing University, Nanjing Normal University, Anhui Normal University, East China Normal University, Henan University, Nanjing Institute of Geography and Limnology of CAS, Northeast Normal University, Beijing Normal University, Hebei Normal University, and Xinjiang Institute of Ecology and Geography of CAS

Table 5.3 Analysis of top 1000 highly cited SCI/SSCI articles in human geography during the period 2000–2014

Periods	% of articles by American authors	% of articles by Chinese authors	% of articles with NSFC funding by Chinese authors	% of articles from Top 10 institutions with NSFC funding to articles by Chinese authors	% of articles from Top 10 institutions with NSFC funding to articles funded by NSFC
2000-2004	34.5	1.4	21.4	57.1	37.5
2005-2009	29.4	2.6	53.8	34.6	88.9
2010-2014	25.9	3.6	55.6	50.0	77.8
2000-2014	33.1	1.1	36.4	45.5	80.0

Note Top 10 institutions refer to those with top 10 NSFC's annual funding for human geography during the period 2000–2014, including Institute of Geographic Sciences and Natural Resources Research of CAS, Sun Yat-sen University, Peking University, Nanjing University, Nanjing Normal University, Anhui Normal University, East China Normal University, Henan University, Nanjing Institute of Geography and Limnology of CAS, Northeast Normal University, Beijing Normal University, Hebei Normal University, and Xinjiang Institute of Ecology and Geography of CAS

calculated (hereafter, "project-based top 10 keywords"). Comparing the two results (Fig. 5.28), we found that one-half of the paper-based keywords were the same as the project-based keywords, and included *urbanisation*, *land use*, *GIS*, *model*, and *patterns*. This result indicates that the NSFC played an advanced role in this discipline. In particular, *land use* had already taken a place in NSFC-funded projects from 2000 to 2004, while *land use change* did not appear in the highly cited papers until 2005–2009. There were no significant ratio changes in project-based keywords in 2000–2004, 2005–2009, and 2010–2014, while in the paper-based keywords, the use of the keywords *urbanisation* and *land-use change* grew rapidly over the past 5 years. This result indicates that the research projects funded by the NSFC dealt with long-term concerns with some significant research topics and that high-level research results were published after intensive research. In terms of the distribution of the paper-based keywords, Chinese human geography made significant contributions to international research results in the fields of *urbanisation* and *regional development*. Most of these results were based on the application of GIS/RS and modelling. Project-based keywords, which corresponded with paper-based keywords, included *urbanisation*, *land use*, and *model*. This indicates that fundamental human geography research in China has covered both basic theory and cutting-edge issues. Specifically, the concern with *location theory* indicates the attention paid to basic theories, and the keyword *social space* indicates the interest in cutting-edge issues. An analysis of the most highly cited papers using the keywords *urbanisation* and *land use change* shows that these papers discussed not only the issues of urbanisation and land-use changes, but also their dynamics and their impacts on urban spatial and ecological structure. These papers were written by scholars not only from a human geography background, such as **Zhou Yixing** from Peking University, **Gu Chaolin** from Tsinghua University, and **Deng Xiangzheng**, **Long Hualou**, and **Liu Yansui** from Institute of Geographic Sciences and Natural Resources Research of CAS, but also from physical geography, ecology and geographical information science, such as **Li Xia** from Sun Yat-sen University, **Liu Jiyuan** from Institute of Geographic Sciences and Natural Resources Research of CAS, and **Li Yangfan** from Nanjing University/Xiamen University. This indicates that publications in human geography journals were not always written by scholars with a human geography background. As a result, an evaluation of the development of human geography should not confine its attention to scholars with a human geography background. We deduce from the above analysis that research on urbanisation and regional development will have more inter-disciplinary features and a comprehensive geographic perspective, based on the accumulation of research dealing with key ideas such as *model*, *spatial analysis*, and *GIS* which have played a significant role in higher level human geography research in China.

5.4 Summary

Human geography has developed over the past 30 years as a result of dramatic social and economic changes and accompanying revolutions in social thought. Globalization and sustainability are two topics receiving wide attention. The development of human geography in China not only followed international academic trends, but also was driven by the need for national and local development. Therefore, there are some differences between Chinese human geographers and their international colleagues in terms of research

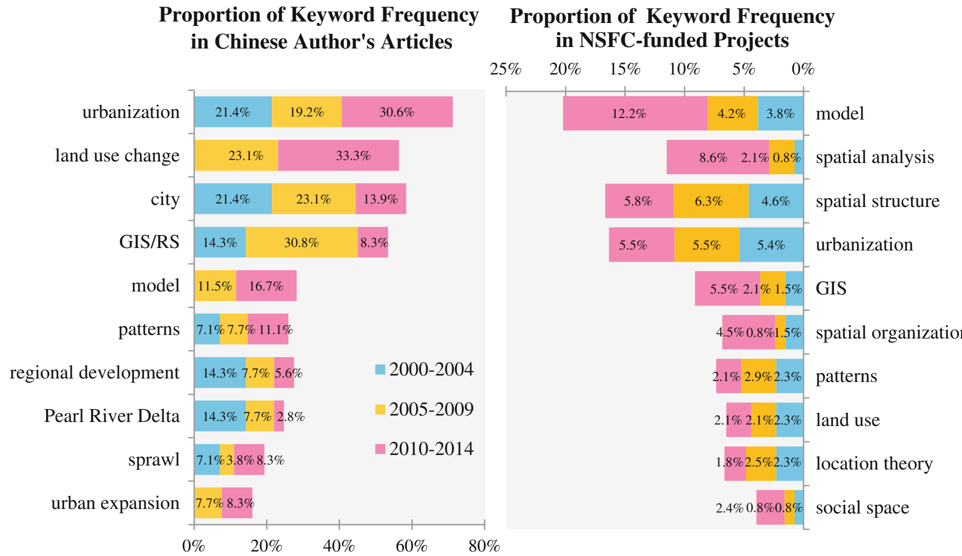


Fig. 5.28 Comparative diagram of prominent keywords in the articles by Chinese authors among the top 1000 highly cited SCI/SSCI-indexed articles with those in NSFC-funded projects in human geography during the period 2000–2014

hotspots, research themes, and research perspectives. Chinese human geographers have conducted a large number of studies into land use and management, urbanisation and urban systems, regional sustainable development, and tourism. They also have paid particular attention to industrial agglomerations, foreign direct investment, international trade, global cities, and other popular international topics. The Pearl River Delta, Yangtze River Delta, Guangzhou, Shanghai, Beijing, and Hong Kong are the most important study areas. From 1986 to 2015, there had been substantial increases in the number of papers published in mainstream SCI/SSCI-indexed human geography journals and in CSCD human geography journals. About one-half of these papers were published over the last decade. Papers published by Chinese scholars in mainstream SCI/SSCI-indexed journals accounted for 5.6 % of the total in the last 5 years. On average, each Chinese author published about 1.5 SCI/SSCI-indexed articles, five times more than 10 years ago. In terms of the average number of citations per paper of the 100 most highly cited papers published in mainstream SCI/SSCI-indexed human geography journals, in the last decade, the UK overtook the US and ranked first, while China ranked between 6 and 9. In terms of the average number of citations per paper for all papers, China lies below the average level for the top 20 countries (regions), a rank that requires further improvement.

The NSFC has played a significant role in Chinese human geography research. Over the last three decades, 84 % of the top 100 authors with the most publication in the CSCD journals and 63 % of the top 100 Chinese authors with the most publications in the SCI/SSCI journals received funding for NSFC geographical sciences projects. Of these authors, 18 were ranked among the top 100 authors with publications in both the SCI/SSCI and CSCD journals. Over the last decade, 44.7 % of papers published in mainstream SCI/SSCI-indexed journals, and 48 % of papers published in CSCD journals received funding for NSFC geographical sciences projects. 48.8 % of the top 50 most highly cited SCI/SSCI-indexed journal papers in 2010–2014 authored by Chinese scholars were funded by the NSFC, about 3.3 times that from 2000 to 2004. The proportion of Chinese authors' papers in the top 1000 most highly cited SCI/SSCI-indexed articles increased by 2.2 % from 2000 to 2004 to 2010 to 2014. Of those 55.6 % were sponsored by the NSFC. The three institutions with the largest amount of NSFC grant funding—the Institute of Geographic Sciences and Natural Resources Research of CAS, Sun Yat-sen University, and Peking University—have advantages in the field of human geography in China, playing a leading role in international collaboration and intellectual exchanges. Over the past 30 years, NSFC Geographical Sciences meeting the need for integrated research on the land surface has led the significant research foci, including the human-environment system and regional sustainability, the elements, patterns, and coordination of regional development, urbanisation and its resource and environmental foundations, rural settlements and rural sustainable development, adaption to climate change, and a low-carbon economy. Such efforts enable human geography not only to focus on practical issues, but also increasingly to emphasise international cutting-edge theoretical research, thereby reforming an empiricism-led academic tradition. The NSFC Geographical Sciences encourages the collection of systematic data, the application of spatial analysis, and visualisation. The emphasis of human geography research has been shifting from the investigation of macro-level spatial patterns to the examination of processes and mechanisms, the mutual relationships between humanity and environment, and policies for regional sustainable development.

Geographical Information Science

6

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and Yongjun Wang

Abstract

Geographical information science is the scientific discipline that studies to capture, process, analysis, transmit, store, and manage the geographical information with fast, mass volume, and high fidelity modern technologies. Geographical information science in NSFC includes remote sensing, geographical information system (GIS), surveying and mapping. The analysis in this chapter is based on 37 SCI/SSCI mainstream journals and 4 CSCD core journals in geographical information science. Geographical information science gets full developments during the past 30 years in the fields of remote sensing platforms and sensors, remote sensing mechanisms and models, image processing, information extraction, terrain surface parameters inversion, geo-positioning, change detection, digital terrain model, etc. Comprehensive applications and supports on researches of the earth system provided by geographical information science are increasingly reinforced. The integrated application and supporting role of geographical information science continue to increase. Trends of geographical information science in China well match the global import, with specific emphases on high-resolution image acquisition, high-accuracy positioning, and land-surface information extraction. The number of publications have increased rapidly in both the SCI/SSCI mainstream journals and the CSCD journals during 1986–2015. SCI/SSCI-indexed articles published by Chinese scholars have reached 21.6 % in the last 5 years. Among the top 100 Chinese authors with the most publications in both the SCI/SSCI mainstream journals and the CSCD journals during the past 30 years, 81 % are supported by NSFC.

Keywords

Geographical information science • Research topics in geographical information science • NSFC-funded projects for geographical information science • Chinese scholars and institutions of geographical information science • Geographical information system • Remote sensing

After 30 years of progressive development, geographical information system (GIS) is currently in an excellent state. **Michael F. Goodchild**, member of United States National Academy of Sciences, proposed the concept of geographical information science to geographical information system academia.[1] He believed that, among the many disciplines of spatial data analysis, this science should focus on the problem of transforming data analysis in remote sensing, photogrammetry, geodesy, and geographical information system. This would cause generated information to have greater geographical meaning, leading to greater acceptance and support of geographical research. In this sense, although

[1]Goodchild (1992).

S. Leng et al., *The Geographical Sciences During 1986–2015*,
Springer Geography, DOI 10.1007/978-981-10-1884-8_6

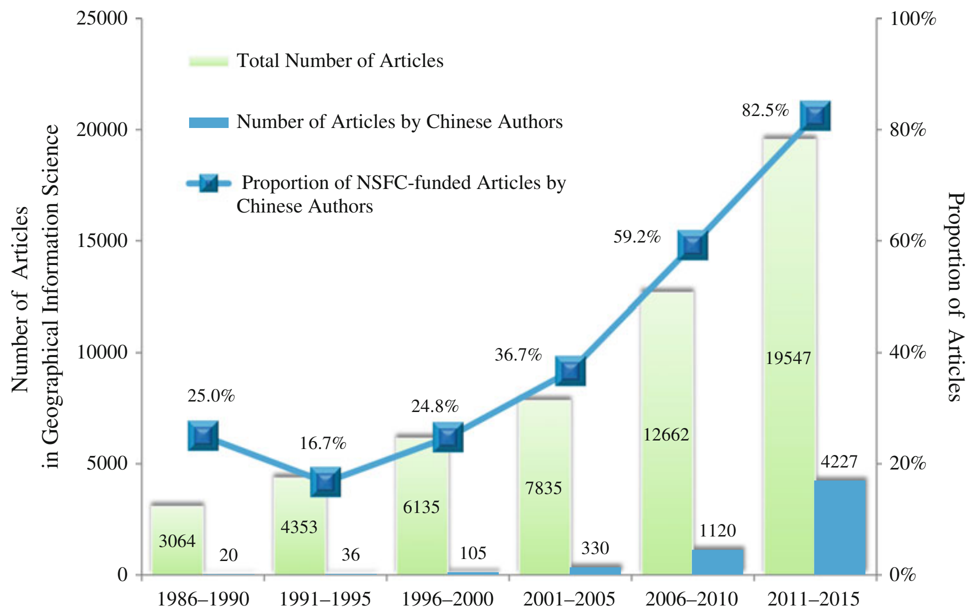


Fig. 6.1 Number of SCI/SSCI-indexed articles and proportion of NSFC-funded articles by Chinese authors in geographical information science during the period 1986–2015

geographical information science originates from *spatial data handling*, it is beyond spatial data analysis and contains a series of basic theoretical and technical problems within geographical information processing, storage, extraction, management, and analysis. This is the case even in the processes of geographical information services. After advancing the concept of geographical information science, many well-known local academics like **Chen Shupeng**[2, 3] **Zhou Chenghu**,[4] **Li Deren**,[5] and others wrote articles to elaborate the concepts of geoinformatics, geographical information science, geospatial information science (geomatics), bringing new understanding of these research fields. Geographical information science, according to the National Natural Science Foundation of China (NSFC), includes remote sensing, geographical information system, surveying and mapping. Therefore, this forms a research chain from data capture and spatial analysis to information representation, and transforms previously abstract research into the real-world geographical applications. Among all fields of NSFC geographical information science, geographical information system (GIS) as an integrated system is at the core, because it powerfully connects earth observation and geographical information visualisation. Because the three aforementioned NSFC research areas correspond well with the core concept of geographical information science and have the common purpose of supporting geography research, they are summarised and analysed together in this section. The analysis in this section is based on 37 SCI/SSCI mainstream journals and four CSCD journals in geographical information science. Twenty-four of the SCI/SSCI journals are comprehensive geographical information science journals and the rest are specialised. Because of the limited number of SCI/SSCI journals on geographical information system (GIS), the result of cluster analysis reflects mainly researches of remote sensing and earth observation. Therefore, to supplement research topics in geographical information system (GIS), a cluster analysis of only keywords of SCI/SSCI journals in geographical information system (GIS) since 1996 was done. Because the Web of Science database contains very few papers from 1985 to 1995, no separate study was done on those papers.

Figure 6.1 shows the number of publications in the 37 SCI/SSCI mainstream journals in geographical information science and the number written by Chinese authors. The total number of papers was 53,596 (some published before 1990 were not included in the Web of Science database), 60.1 % of which were published in the last decade. Chinese authors published 5,838 papers (10.9 % of the total), 91.6 % of which were published in the last decade. During that decade, Chinese authors published 16.6 % of papers globally, and 21.6 % in the last 5 years. Chinese authors supported by NSFC published 4,307 papers in the past 30 years, of which 96.3 % were published in the last decade. In the last 30 years, papers supported by NSFC constituted 73.8 % of all papers by Chinese authors. This proportion before the period of 2001–2005 was less than 36.7 %. This increased to 59.2 % between 2006 and 2010, and was 82.5 % in the last 5 years.

Figure 6.2 shows the total paper number of four Chinese journals in geographical information science and the

[2] Chen (1996).
[3] Chen (2007).
[4] Zhou and Lu (1998).
[5] Li and Li (1998).

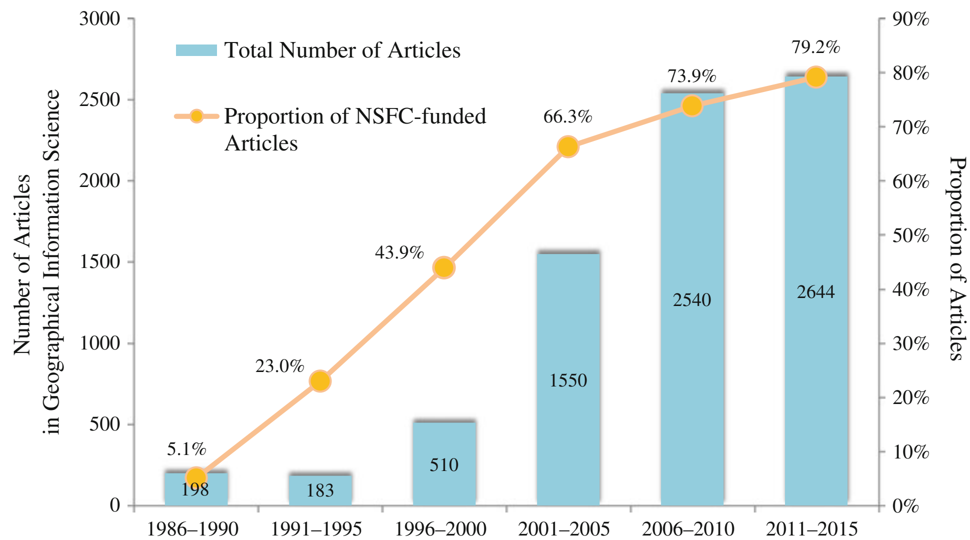


Fig. 6.2 Number of CSCD-indexed articles and proportion of NSFC-funded articles in geographical information science during the period 1986–2015

proportion supported by NSFC over the last 30 years. The four journals are *Acta Geodaetica et Cartographica Sinica*, *Journal of Geo-Information Science*, *Geomatics and Information Science of Wuhan University*, and *Journal of Remote Sensing*. The total number of Chinese papers was 7625, 68 % of which were published in the last decade. The number of papers supported by NSFC was 5273, 75.3 % of which were published in the last decade. Papers supported by NSFC in the last 30 years accounted for 69.2 %; before the period of 2001–2005, the proportion was less than 66.3 %. The proportion increased to 73.9 % between 2006 and 2010, and then reached 79.2 % during the last 5 years. Based on average citations per paper of publications in Chinese journals in geographical information science, those supported by NSFC in the last 30 years had a larger average citation numbers (17.8) every 5 years than unsupported ones (5.4). The data indicates that those supported by NSFC had a greater scientific contribution and thereby attracted substantial attention. The average citations per paper on geographical information science in Chinese journals were less than those on physical geography (23.4) and human geography (21.1), on the other hand average citations per paper of those supported by NSFC were more than those of unsupported ones. This indicates characteristics of the geographical information science development stage, in which the research target foci are more about specialised concrete problems such as technology, models, and algorithms. As a result, research achievements are not universal and restricted in citation number.

Table 6.1 shows average citations per paper of the top 100 cited papers of each country (region), from analysis of data from SCI/SSCI mainstream journals in geographical information science. This table indicates the highest level of geographical information science research achievements of each country (region). In the past 30 years, China was always on the list of top 20 countries (regions) with higher average citations per paper. In 1996–2000, China ranked in the lowest two. From 2001 to 2005, its rank was 10th, and between 2006 and 2010 it was ninth. During 2006–2010, average citations per paper of the top 100 papers in China neared those of Spain and the United Kingdom (UK). However, there still remained a gap with Canada, Italy, Germany, France, and the Netherlands. According to current statistics, average citations per paper of the top 100 papers in China outnumbered those of the aforementioned countries, and the country held second place along with Italy. However, its number equalled only half of the United States of America (USA), which was the leader. Considering the average citations per paper of all papers, the numbers for China in 1986–1990, 1996–2000, and 2006–2010 were 10.2, 14.3, and 9.8, respectively, less than the average of the top 20 countries (regions) (18, 27.5, and 13.9, respectively) in those periods. From this perspective, China was among the lowest ranked—only surpassing Brazil and Chinese Taiwan. This indicates that the study of geographical information science in China needs to be developed further.

Table 6.1 Top 20 countries (regions) of average cites per paper for highly cited SCI/SSCI-indexed articles in geographical information science during the period 1986–2015

Rank	Countries (Regions)	1986–1990	1991–1995	1996–2000	2001–2005	2006–2010	2011–2015
1	USA	219.8	282.1	301.5	273.4	130.3	33.0
2	Italy	16.5	44.3	68.5	83.0	51.5	17.1
3	China	10.2	19.1	15.0	39.1	38.6	17.1
4	France	44.5	85.2	96.9	60.3	49.2	16.6
5	Germany	21.8	25.0	59.0	71.2	56.0	15.9
6	Spain	21.6	38.2	44.4	55.6	39.0	15.1
7	Netherlands	12.6	24.7	50.5	46.9	43.3	12.5
8	Canada	43.6	42.7	70.6	86.8	51.7	11.0
9	UK	45.9	63.4	87.8	87.8	40.5	10.6
10	Australia	34.5	23.8	36.6	49.2	29.2	9.0
11	Japan	16.1	18.3	24.4	35.5	24.4	7.4
12	Switzerland	15.0	13.5	38.5	25.6	24.9	6.6
13	India	16.5	13.4	18.2	23.1	19.1	5.9
14	Belgium	13.9	9.9	25.9	38.0	25.3	5.9
15	Austria	13.9	18.9	38.4	18.5	18.5	4.9
16	Denmark	16.0	12.6	19.7	35.8	16.2	4.7
17	Norway	8.9	9.6	30.9	30.7	17.5	4.2
18	Brazil	27.5	29.8	29.0	16.6	12.6	4.1
19	Taiwan, China	11.0	10.4	14.6	16.5	12.6	4.0
20	Sweden	9.3	17.5	26.3	32.7	11.2	3.5

Note Top 20 countries (regions) were selected based on average cites of the top 100 highly cited articles in each county (region) out of 25 countries (regions) with the largest number of articles from the 37 SCI/SSCI mainstream journals in geographical information science; that is, total cites of the 100 articles were divided by 100, with listing by descending order for the period 2011–2015 in the last column

6.1 General Characteristics of the Research Topics Over the Past 30 Years

This section focuses on the popular topic words of publications in SCI/SSCI mainstream journals and keywords of CSCD core journals in geographical information science from 1986 to 2015. Also analysed is the co-occurrence of major topics (keywords), to elaborate overall characteristics of geographical information science research in the past 30 years.

Figure 6.3 indicates that since 1986, research into remote sensing and earth observation in SCI/SSCI mainstream journals in geographical information science expanded in the following major areas: Remote sensing mechanisms and models, data processing and analysis methods, remote sensing earth surface inversion and applications, and general scientific issues. These are treated individually as follows. (1) **Remote sensing mechanisms and models** include remote sensing topics on *thermal infrared, hyperspectral, radar, multi-temporal*, *LiDAR*, and *calibration*. Remote sensing sensors have attracted the most attention in the last 30 years, including active microwave synthetic aperture radar (SAR), hyperspectral, LiDAR, visible spectral, thermal infrared and passive microwave sensors. Remote sensing sensor series like *Landsat*, *AVHRR*, and *MODIS* have had extensive use. High-resolution remote sensing is becoming increasingly popular. (2) **Data processing and analysis methods** include *image classification*, *image segmentation*, *change detection*, *multi-resolution analysis*, *data accuracy*, *and uncertainty analysis*, *machine learning*, *artificial intelligence* methods in remote sensing, such as *artificial neural networks*, and *support vector machine* (*SVM*). (3) In the field of remote sensing **earth surface retrieval and applications**, information captured by remote sensing mainly contains qualitative classification and quantitative parameter information of the earth surface, and changes of both with time. Major application areas were *ocean colour*, *water quality*, *ecosystems*, *soil systems*, *climate change*, *land-use* and *land-cover change*, *urbanisation*, and *forests*. Topics like *vegetation*, *soil*, *water*, *snow*, and *sea ice* were primary objects of

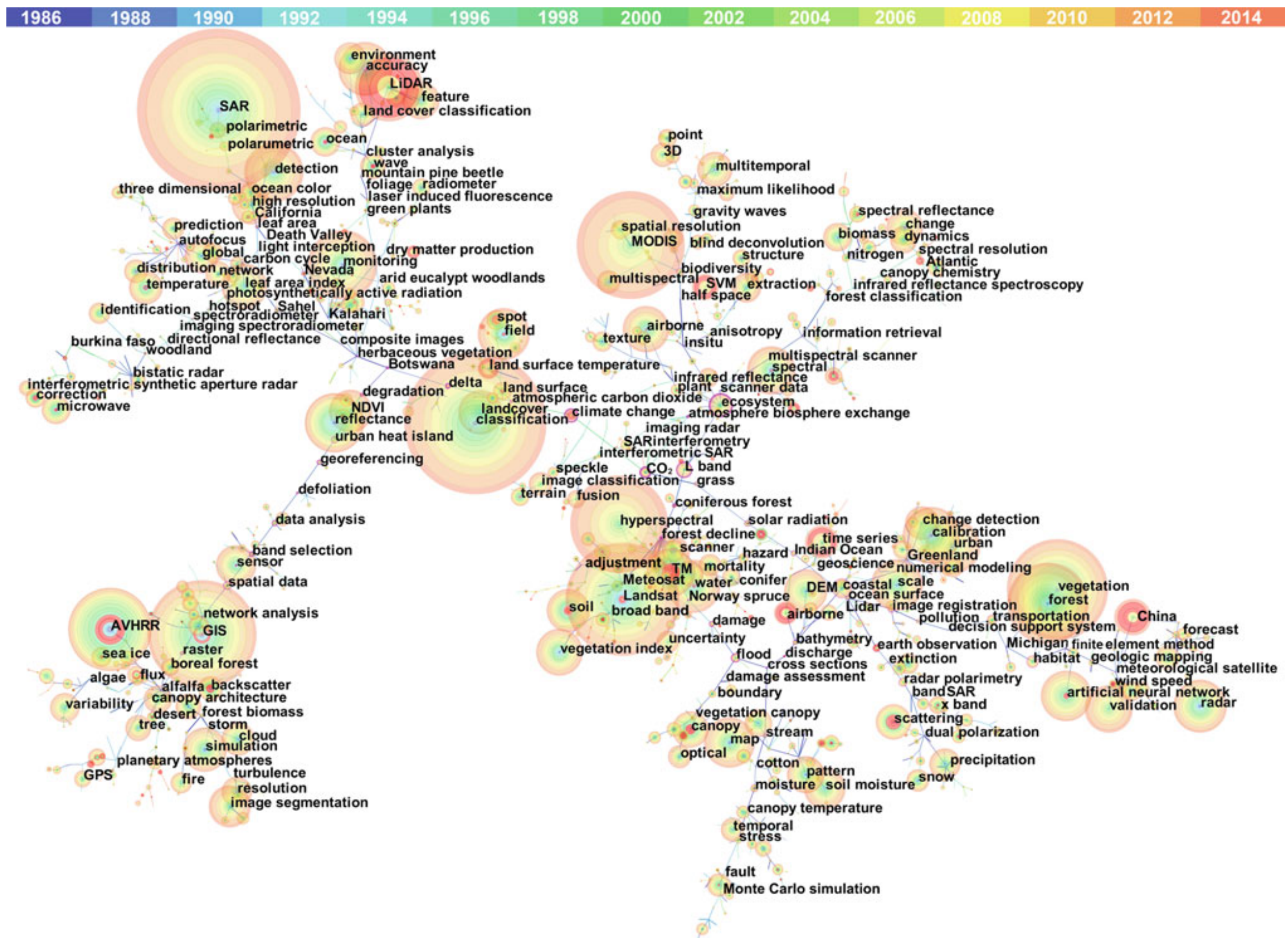


Fig. 6.3 Co-occurrence network of keywords in SCI/SSCI mainstream journals of geographical information science during the period 1986–2015

remote sensing observation, which have remained unchanged for the last 30 years. (4) **General scientific issues** focus on sensor *calibration*, remote sensing product *validation* and *accuracy assessment*, *scale*, *simulation*, *error*, and *uncertainty*.

Research into surveying and mapping mainly includes: (1) research on multiple theories and methods of data measurement, including *photogrammetry*, *lasers*, r*adar, interferometry*, and *polarimetry*; (2) data processing and error analysis including *error analysis*, *data precision*, *data verification*, *quality control*, *data regularisation* and *parameterisation*, and *uncertainty*; and (3) mapping theories including cartography of *thematic maps*, *map perception*, and *digital cartography*.

Figure 6.4 shows overall characteristics of frequently used keywords of publications in the 37 SCI/SSCI mainstream journals in geographical information system (GIS) since 1986. The topics can be summarised as follows. (1) **Connotation and recognition of geographical information**. This involves geographical semantics, geographical ontology, recognition of Cyberspace, space syntax, map recognition, and spatial uncertainty. (2) **Modelling and organisation of geographical information**. This topic contains geo-information capture, multi-sources data integration, data models, data integration and assimilation, data indexing, database, 3D geographical information system, and spatio-temporal geographical information system. (3) **Geographical information analysis and knowledge discovery**. This topic is mainly concentrated on spatial analysis, spatial data knowledge discovery, spatial statistics, spatio-temporal data analysis, and network analysis. (4) **Geographical simulation and geographical computation**. This topic includes research directions such as spatial simulation, spatial decision support, and geographical prediction. It also develops geographical computation methods like cellular automaton, fuzzy modelling, and artificial intelligence algorithms. (5) **Geographical information system architecture and computing model**. The architecture consists of component geographical information system, grid geographical information system, cloud geographical

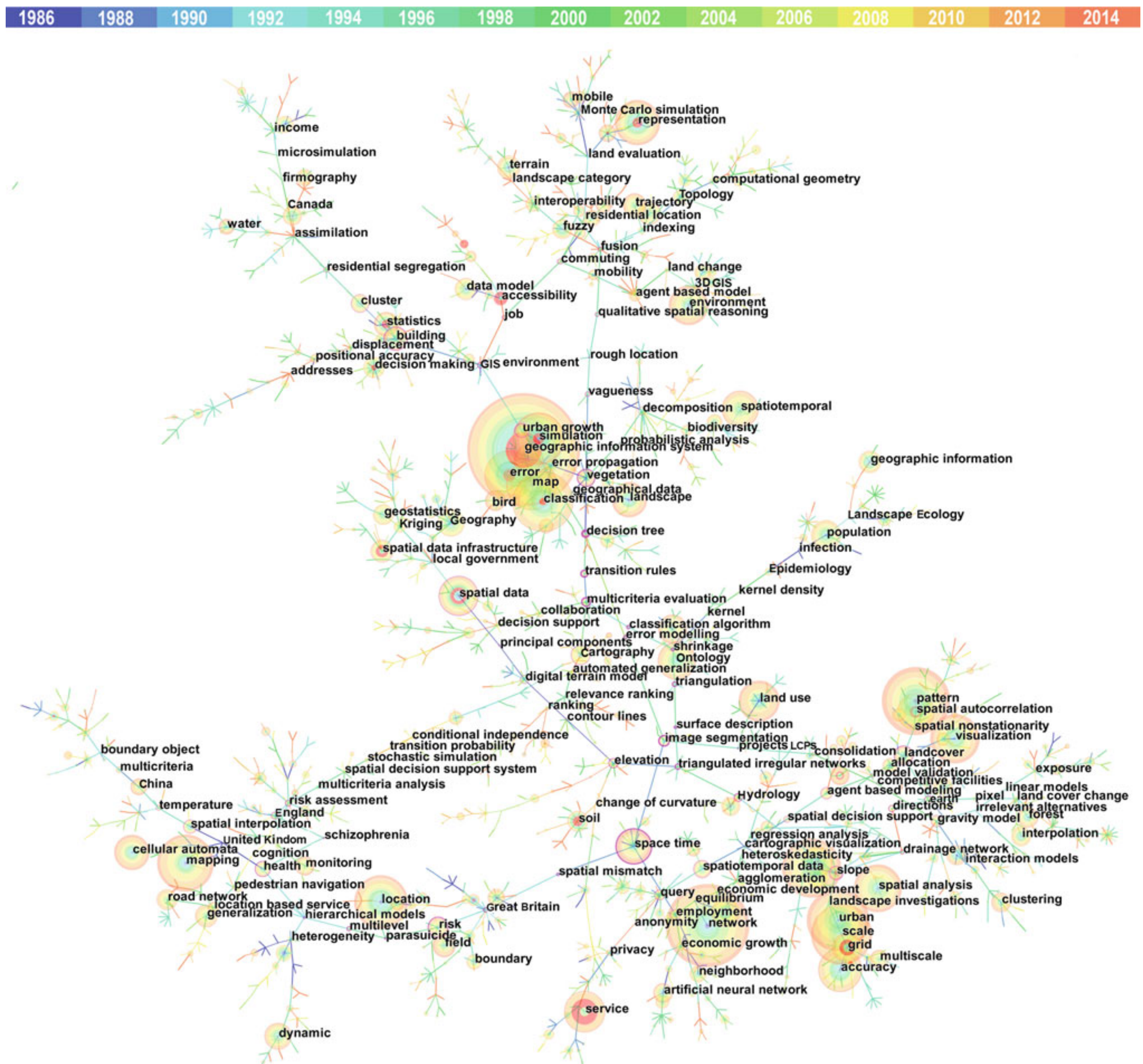


Fig. 6.4 Co-occurrence network of keywords in SCI/SSCI mainstream journals of geographical information system (GIS) during the period 1986–2015

information system, and mobile geographical information system. The computing model contains parallel computing, grid computing, cloud computing, mobile computing, big data, and ubiquitous information processing. (6) **Geographical information representation and visualisation**. This topic includes map representation, virtual reality representation, and geographical information visualizing analysis. (7) **Geographical information system sharing service**. This contains spatial information infrastructure, geographical information system data sharing standard, model, and interoperability. (8) **Geographical information system applications**. This topic is mainly about urban modelling, urban management, land use, public health, disaster monitoring, and emergency management.

Figure 6.5 shows the overall characteristic of frequently used keywords of publications on four Chinese journals in geographical information science since 1986. The development of geographical information science was based on two cores, remote sensing and geographical information system (GIS), and the development network was interconnected as a whole. The network shows the characteristic of local radiation from keywords found in important methods. These indicate that geographical information science is significant for the study of geography. Thus, publications in Chinese

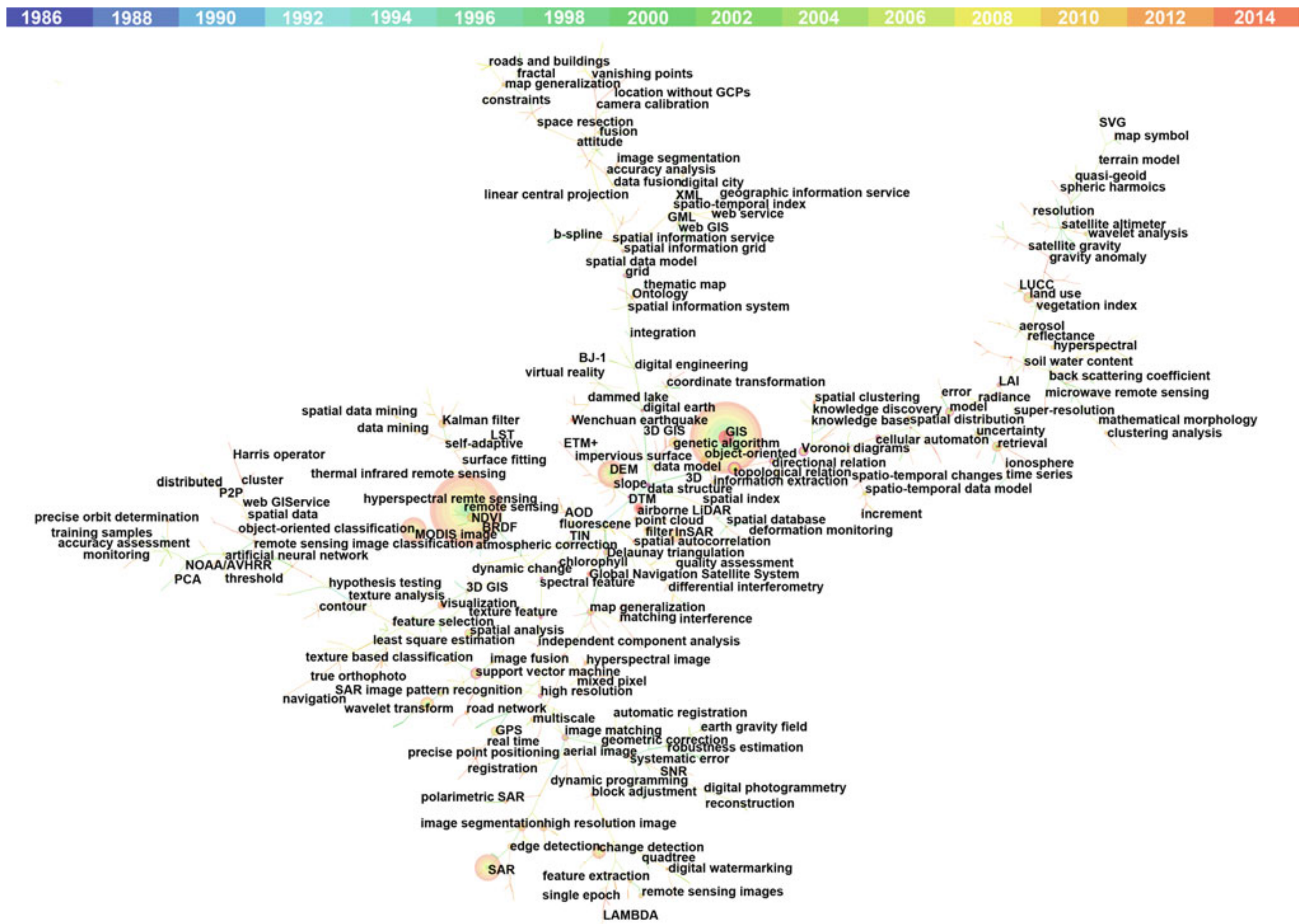


Fig. 6.5 Co-occurrence network of keywords in CSCD journals of geographical information science during the period 1986–2015

journals demonstrate the diverse drivers of the development of that discipline. (1) Research topics motivated by technique advancement include *MODIS*, *hyperspectral*, *SAR*, *interference SAR* in *remote sensing*, plus *digital elevation models* (*DEM*), *topological relationships*, *spatial relationships*, and *spatial databases* in *geographical information system* (*GIS*). (2) Research topics driven by problems comprise *land use*, *leaf area index* (*LAI*), *water*, and the *Wenchuan earthquake*. (3) Research topics driven by methods comprise *data fusion*, *wavelet analysis*, *change detection*, and *data mining*. This category also includes keywords of quantitative remote sensing, such as *atmospheric correction*, *inversion*, and *model simulation*.

The time range of the warm colour central node in the above figure indicates that early popular research topics of Chinese geographical information science papers mainly centred on geographical information system (GIS). The most popular research topics were related to remote sensing, which increased explosively in the last 10–15 years. This demonstrates that remote sensing has become a significant approach in geographical information science. However, among all research topics, most were about specific methods of remote sensing and geographical information system (GIS), and studies driven by geographical applications were relatively scarce.

From cluster results, we conclude as follows. (1) Early research topics in geographical information science included **topological relationships**, **object-based**, **spatial relationships**, and **spatial indexes**. With the advancement of geographical information system technology and spatial analysis capabilities, *DEM*, *map generalisation*, *virtual reality*, *spatial clustering*, *visualisation*, *3D geographical information system*, and *digital earth* became the popular research topics in remote sensing communities of China. (2) Studies of ***MODIS imagery*** have become a research focus in those communities. *Normalized Difference Vegetation Index* (*NDVI*), *bidirectional reflectance distribution function* (*BRDF*), *atmospheric correction*, and *land surface temperature* have become very common keywords. *Hyperspectral*, *thermal infrared*, and *multi-angle remote sensing* are also becoming common topics. (3) Since 1995, after the launches of high-resolution **radar** satellites, polarimetric and interferometric SAR satellites, *SAR* and *InSAR* have become important research foci in the remote sensing field. Radar-related image processing techniques such as *speckle noise*, *edge detection*, and *image segmentation* are extensively studied. With the advancement of laser ranging techniques, *LiDAR* and *LiDAR point cloud* processing technology have become popular topics in urban building and vegetation cover measurement. (4) The rapid accumulation of high-resolution remote sensing imagery has led to the explosive growth of remote sensing **image processing** technologies. *Image matching*, *feature matching*, *image fusion*, *spatial data mining*, and *SNR* have become research foci. From the point *view* of remote sensing mapping, keywords such as *map generalisation* of high resolution satellites, *exterior orientation elements*, *data fusion*, *image segmentation*, *bundle adjustment*, and *geometric features* have received much attention. (5) **Global change** research has led to thriving application-oriented research, such as that on the *Tibetan Plateau*, *land use, Land-use and Land-cover Change* (*LUCC*), *LAI*, *soil moisture*, and *evapotranspiration*. This research has also popularised quantitative remote sensing research such as *model simulation*, *inversion*, *uncertainty*, and *error*.

6.2 Change of Research Topics in Various Periods

This section divides the period of 1986–2015 into time intervals of every 5 (or 10) years, to analyse the characteristics of international research topics based on publications on SCI/SSCI mainstream journals, and the characteristics of Chinese research topics based on publications of CSCD Chinese journals. Meanwhile, differences of Chinese and international research topics are also analysed by comparing the keywords of SCI/SSCI-indexed articles written by researchers in China or aboard.

6.2.1 Period of 1986–1995

Figure 6.6 shows the research topic evolution of publications in geographical information science SCI/SSCI mainstream journals during 1986–1995. It is believed that this was the fundamental research stage in the fields of remote sensing theory and earth observation during this period. Research during this period included remote sensing mechanisms of surface features like *vegetation*, *soil, water*, *ice*, and *snow* using visible and near infrared remote sensing,

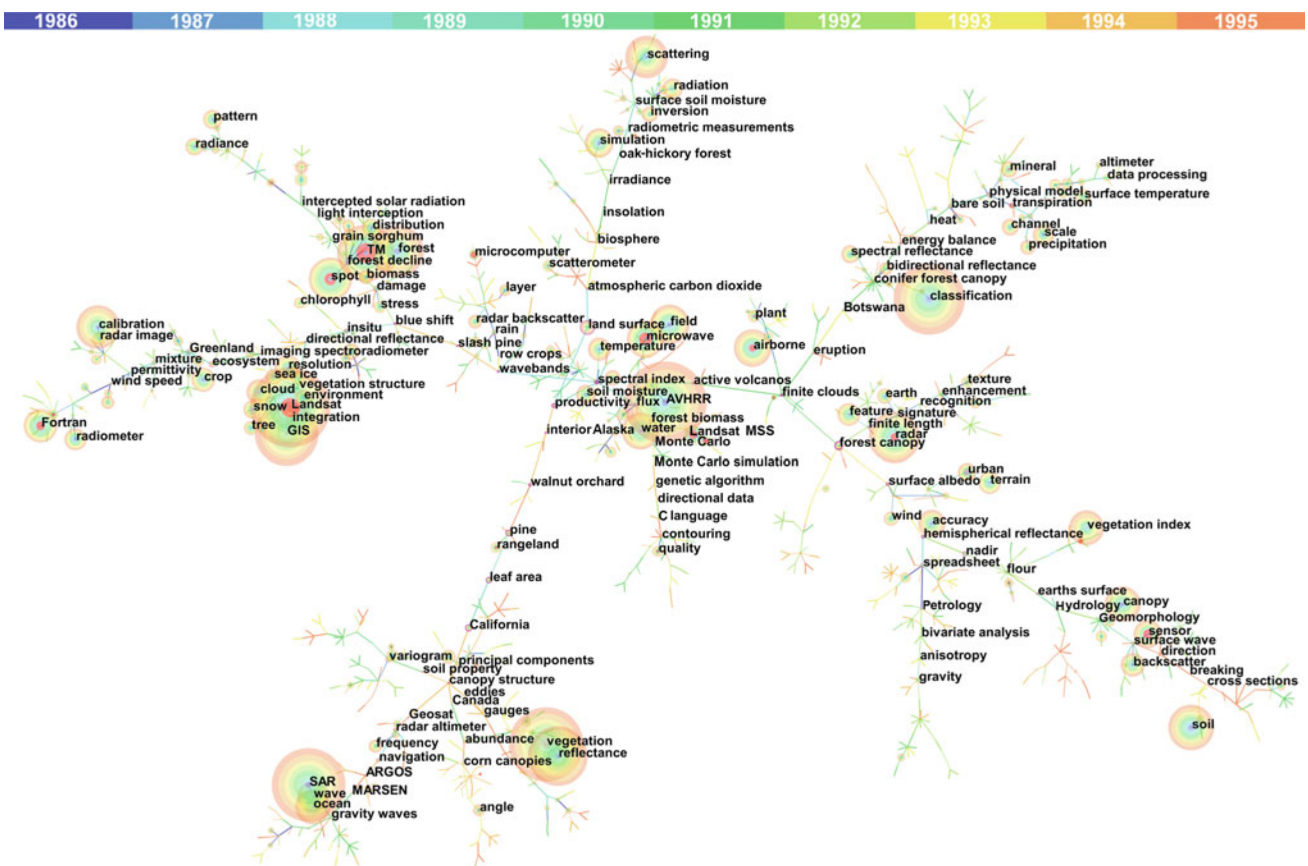


Fig. 6.6 Co-occurrence network of keywords in SCI/SSCI mainstream journals of geographical information science during the period 1986–1995

visible and thermal infrared remote sensing, active microwave remote sensing, and passive microwave remote sensing. This mainly advanced research on remote sensing forward models. Furthermore, topics like satellite remote sensing *sensors* (*Landsat*, *AVHRR*, *radar*, *microwave remote sensing*, and *infrared remote sensing*), remote sensing mechanisms such as bidirectional reflectance, radiative transfer, directional reflectance, and analysis methods *(image classification*, *multi-resolution analysis*) also started to develop. Spectral characteristics and spectrum libraries were researched and established for various elements and objects such as *vegetation*, *soil*, and *water*. In the field of surveying and cartography, methods such as *thematic mapping*, *data precision*, and *mutual verification*, *data regularisation* came into application, and *data standards* sprang up.

Figure 6.7 shows research topic evolution of publications in Chinese journals in geographical information science from 1986 to 1995, the formative years of this discipline. In general, keywords centred on geographical information system (GIS) and related methods departed from traditional mapping, geodesy, and photogrammetry, and became independent research foci. Foci of geographical information science research in this period were mainly as follows. (1) Key theories and technologies of geographical information system (GIS) included keywords such as *data model*, *data structure*, and *object-oriented methods*. (2) Mapping included keywords such as *map generalisation*, *map algebra*, and *map database*. (3) Image analysis and processing included keywords such as *image matching*, *fractal analysis*, *deformation model*, *spline estimation*, and *monitoring network design.* They dramatically increased in the field of measurement. (4) Data quality and precision included keywords such as *quality analysis*, *ill-conditioned phenomena*, *original data errors*, *accuracy estimation*, and *observation scheme*. (5) Keywords such as *vertical crustal movement*, *mainland China*, and *geodynamics characteristics* have consistently attracted research attention.

Figure 6.8 shows a comparison of keywords used by Chinese authors and others in SCI/SSCI mainstream journals during 1986–1995. The frequency of keywords was low because the total number of journals and papers was relatively small. The maximum was 40. The highest frequency

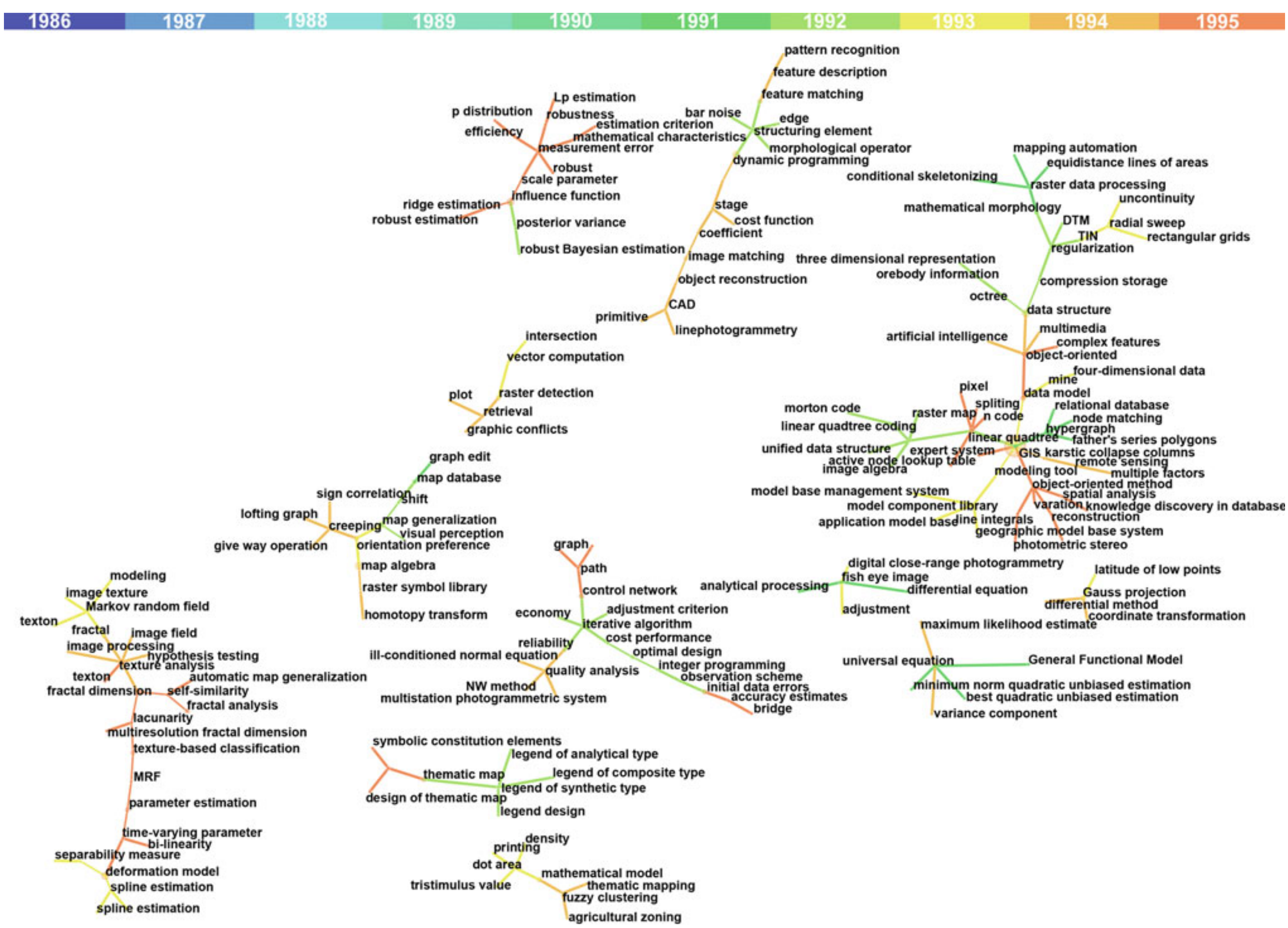


Fig. 6.7 Co-occurrence network of keywords in CSCD journals of geographical information science during the period 1986–1995

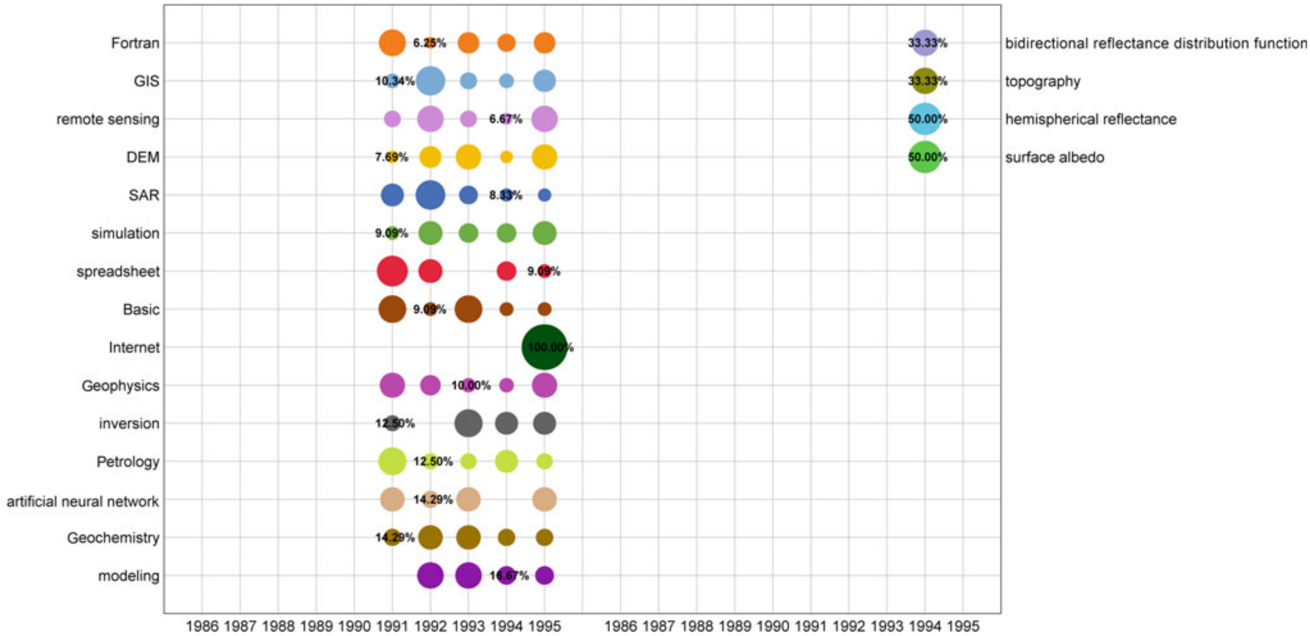


Fig. 6.8 Comparative diagram of prominent keywords by Chinese authors and others in SCI/SSCI mainstream journals of geographical information science during the period 1986–1995. *Note* Right panel shows keywords used by Chinese authors and left panel shows those used by the authors from other countries (regions). Size of circles represents the proportion of keyword frequency in a single year to its total frequency in 1986–1995. Each keyword has the same colour. Keywords are listed in descending order according to their total frequencies in the above period

of the top 15 keywords used by Chinese authors was only one. During the decade, the frequency of the top 15 keywords used by foreign authors was more than six. The corresponding research foci were data processing and programming languages (*Fortran*, *Basic*, *spreadsheets*, *inversion*), models (*DEM*, *simulation*, *artificial neural network*, *modelling*), data source (*SAR*), *quantitative inversion*, disciplines (*GIS*, *remote sensing*, *Geophysics*, *Petrology*, *Geochemistry*), and the Internet. This shows that geographical information system (GIS) and remote sensing were two major fields of international geographical information science. Keywords except *DEM*, *inversion*, *artificial neural network*, and *SAR* did not closely reflect characteristics of geographical information science research. The frequency of keywords such as *DEM*, *remote sensing*, and *simulation* grew rapidly. However, the top 15 high frequency keywords used by Chinese authors were all different from those of foreign authors. The latter revealed that the research foci of Chinese authors were basic issues of remote sensing radiative transfer (*bidirectional reflectance distribution function*, *topography*, *hemispherical reflectance*, and *surface albedo*).

6.2.2 Period of 1996–2000

Figure 6.9 shows keyword characteristics of publications in SCI/SSCI mainstream journals in geographical information science from 1996 to 2000. Earth observation data accumulated continuously and remote sensing theory and methods greatly progressed. There was much research in the fields of *land surface temperature* retrieval and *biomass* retrieval, *land cover*, and *atmosphere* and *ocean colour remote sensing*. *Multispectral* remote sensing methods and all types of artificial intelligence/machine learning methods (such as *neural networks*) began to be introduced. Sensor *calibration* and data *accuracy assessment* became research foci. Spectrum and *texture* information have received substantial attention in the field of remote sensing image classification. Regarding surveying, mapping and cartography, research based on satellite imagery and all types of sensors has become a research focus. *Error* theory, data *sensitivity*, and parametric studies have also been undertaken. Map-focused cartographic theory has gradually developed into a system.

Figure 6.10 shows prevalent keywords of publications in SCI/SSCI mainstream journals in the geographical information system (GIS) area of geographical information science from 1996 to 2000. This was the initial period of research on geographical information system (GIS) theory and methods. Research emphases were mainly in spatial data *representation* and *modelling*. Geographical information system spatial analysis and geographical statistical analysis, such as spatial data analysis models, spatial statistics, and data mining, developed rapidly. There was much research in

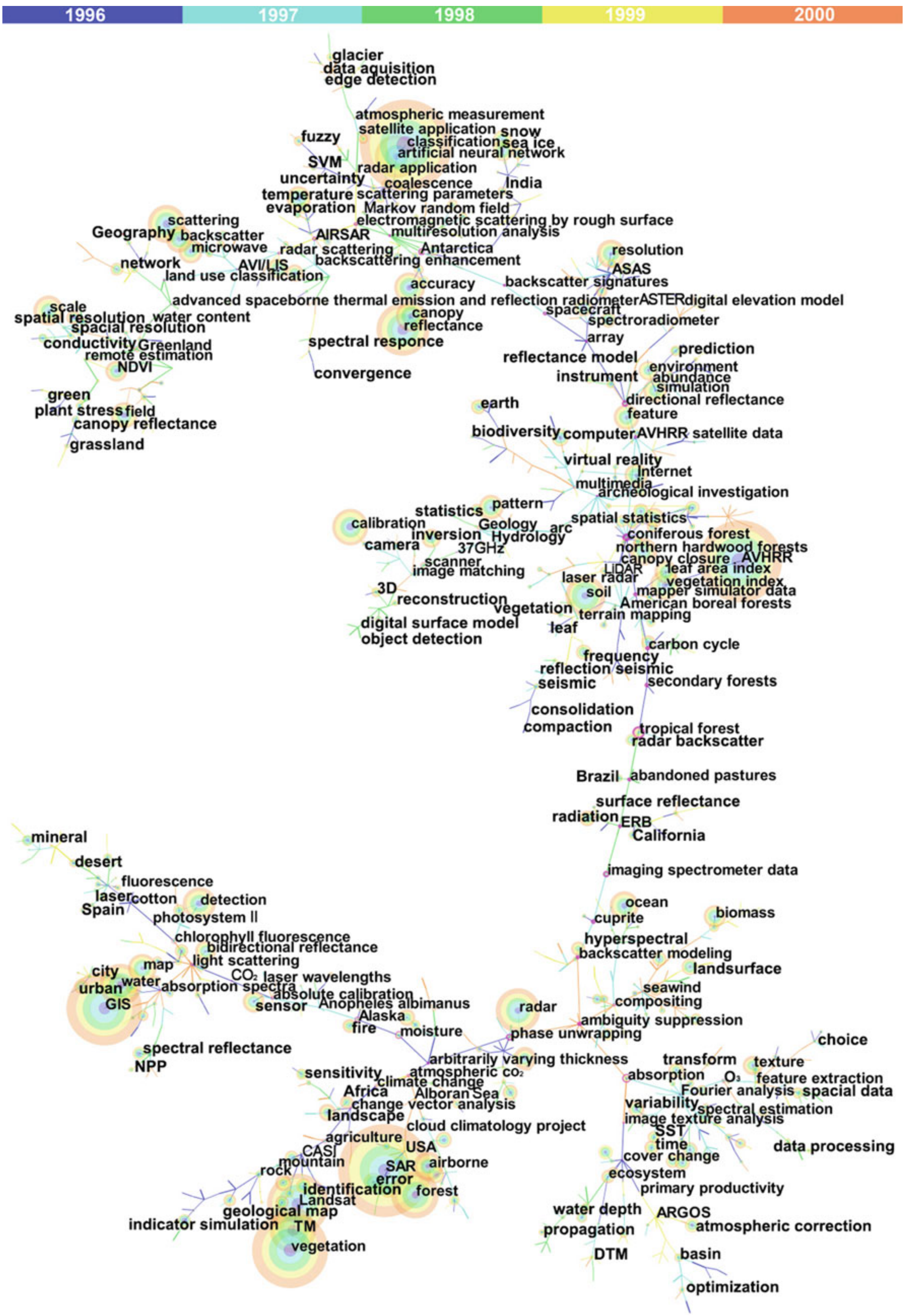


Fig. 6.9 Co-occurrence network of keywords in SCI/SSCI mainstream journals of geographical information science during the period 1996–2000

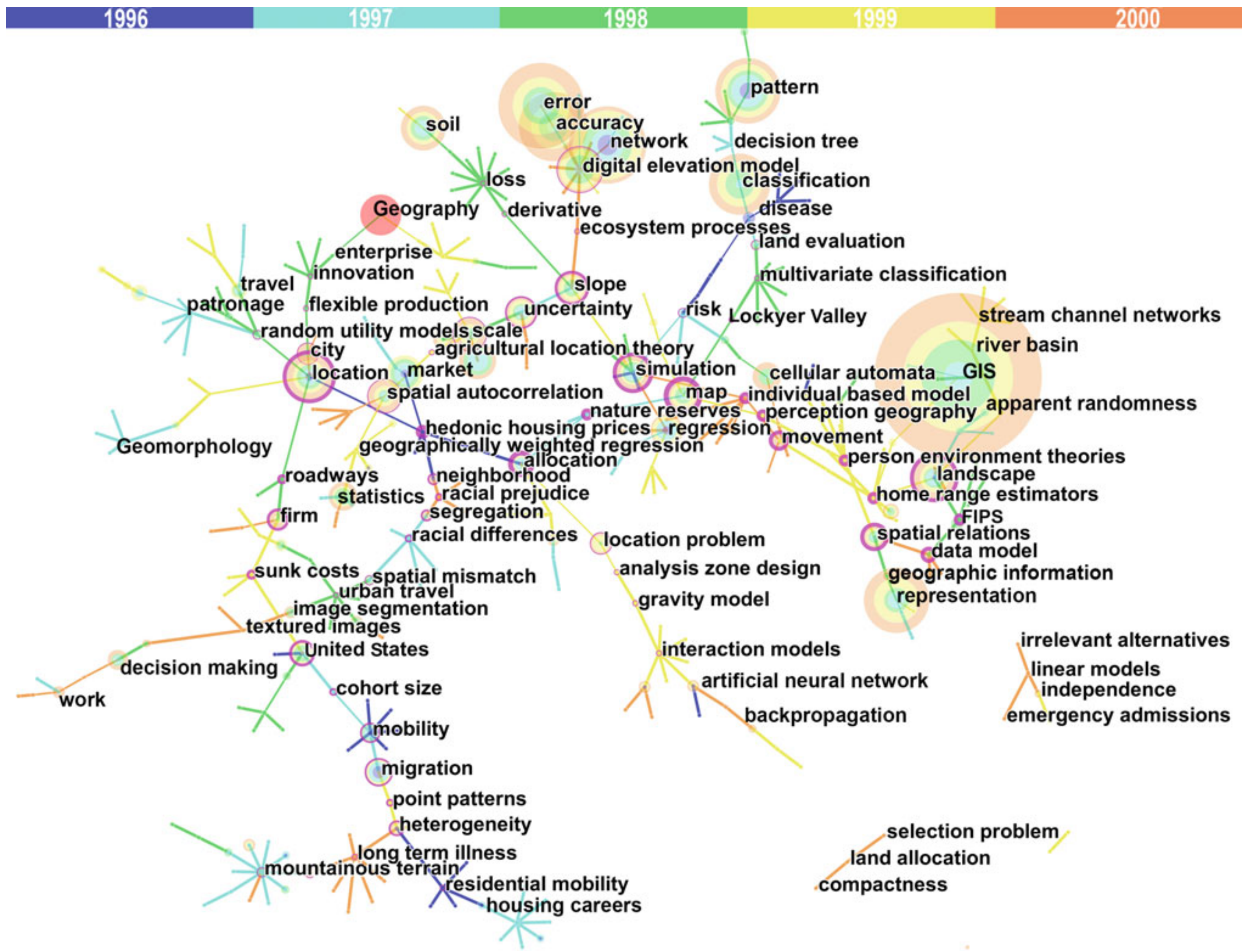


Fig. 6.10 Co-occurrence network of keywords in SCI/SSCI mainstream journals of geographical information system (GIS) during the period 1996–2000

the areas of databases, component-based geographical information system, and object-oriented geographical information system design methods. Multi-source data fusion and integration, geographical information interoperability, and *network* geographical information system studies began to increase. Geographical *mapping*, *spatial relationships*, spatial data *heterogeneity*, and *uncertainty* also attracted research attention.

Figure 6.11 illustrates research foci as reflected by Chinese CSCD journals in geographical information science from 1996 to 2000. The overall pattern changed greatly compared with that of the previous 10 years. Along with rapid development of satellite remote sensing technologies such as high-resolution optical imagery and SAR, remote sensing technology quickly emerged as a popular topic, according to keywords of geographical information system (GIS). Some recurring research interests were as follows. (1) Based on data models and structure, **geographical information system (GIS)** developed in a networked and distributed direction. Great improvement in geographical information system application and analysis capability was reflected by keywords such as *3D geographical information system*, *spatial decision support systems*, *3D city models*, and *digital earth*. Keywords such as *national spatial data infrastructure*, *national information infrastructure* and *digital earth* indicate tremendous attention to digital construction of geographical information system at a national level. (2) For **remote sensing theory and methods**, issues concerning *inversion*, *calibration*, *vegetation index*, *atmospheric radiation*, *hyperspectral* and *multi-angle remote sensing* became popular topics. (3) In remote sensing applications, research mainly focused on global change and biosphere program applications. *LAI* and *land use* were also common keywords in this area. (4) For **sensors**, optical methods of *NOAA/AVHRR*, *microwave remote sensing* and the *backscattering coefficient* of radar remote sensing were closely integrated. *DEM* and *InSAR* became core keywords. New types of sensors emerged such as *GPS*, *inertial navigation systems*, and

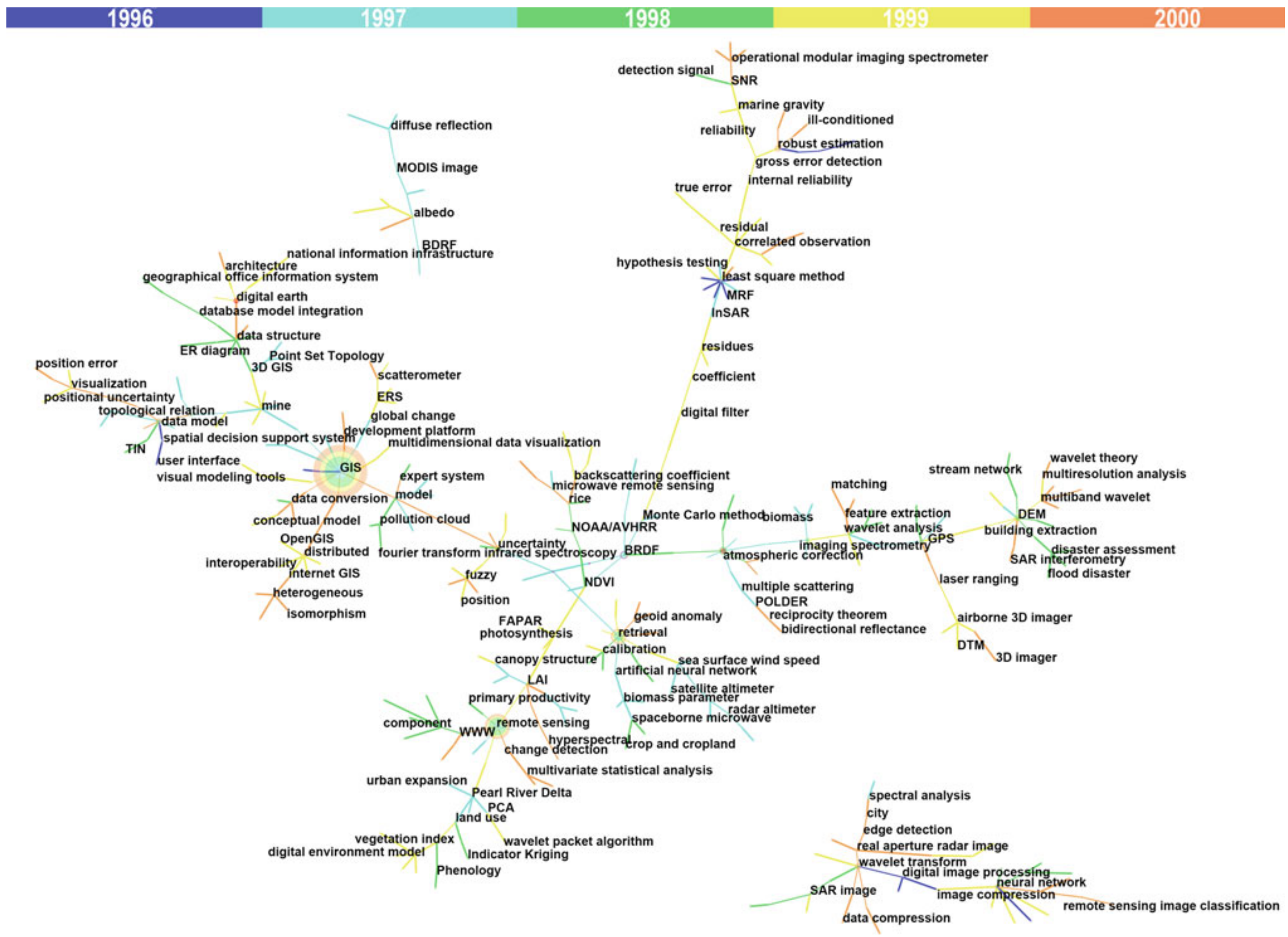


Fig. 6.11 Co-occurrence network of keywords in CSCD journals of geographical information science during the period 1996–2000

laser ranging. (5) Regarding traditional **surveying and mapping** technologies, *robust estimation* and *uncertainty problems* become research foci. The appearance of high resolution optical and radar imagery promoted the study of various image processing technologies. Meanwhile, *remote sensing image classification methods*, especially *neural networks*, were pervasive research topics.

Figure 6.12 compares popular keywords in SCI/SSCI journals used by Chinese authors and others during the period 1996–2000 (the diagram description see the note of Fig. 6.8). The number of journals and papers published with these keywords increased dramatically. The total keyword frequency increased greatly. For example, *remote sensing*, the keyword with highest frequency, appeared more than 140 times. Frequencies of the top 15 keywords used by Chinese authors grew as well. Frequencies of the top 15 keywords used by foreign authors all exceeded 20 during the period. Compared with 1986–1995, research characteristics reflected by high-frequency keywords included were as follows. Remote sensor *calibration*, image *classification*, and *radar* image were prominent subjects in the dominant research. Great advancements were made in models (*artificial neural network*, *DEM*, and *modelling*). There was a decline of research on general computer languages (*Fortran*), and *sea ice* and geographical information *visualisation* research appeared. Considering the growth rate of keywords themselves, *interferometry*, image *classification*, and *calibration* increased very rapidly. Among the top 15 high-frequency keywords in publications from Chinese authors, *remote sensing* was the only one matching high-frequency keywords used by foreign authors. Frequencies of *polarimetric SAR* and *microwave* were similar to the keywords used by international authors. The remaining keywords were seldom used by international authors, illustrating the significant difference in research between Chinese scholars and researchers in other countries.

6.2.3 Period of 2001–2005

Figure 6.13 shows characteristics of keywords of publications in SCI/SSCI mainstream journals of geographical

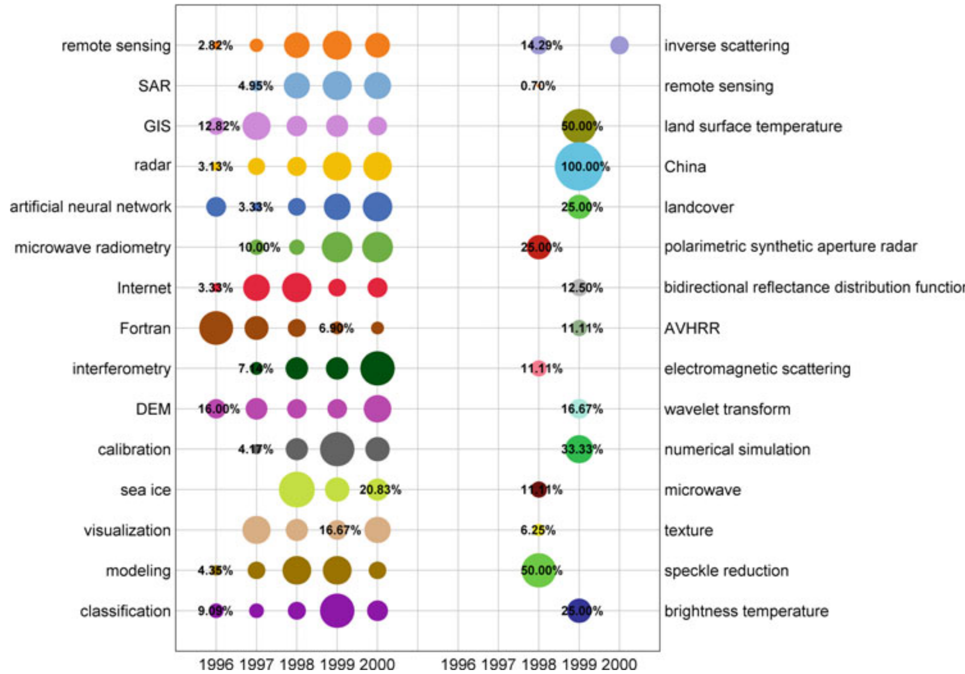


Fig. 6.12 Comparative diagram of prominent keywords by Chinese authors and others in SCI/SSCI mainstream journals of geographical information science during the period 1996–2000

information science from 2001 to 2005. In this period, geographical information science theory, methods, and technology developed rapidly. Forest, vegetation, water bodies, ecosystems, laser, radar, microwave, and infrared remote sensing all grew into independent and specific topics. Remote sensing applications, including fire disaster, urban simulation, *forest* monitoring, *land use*, *soil moisture*, plant productivity (*net primary production* and *biomass*), *sea wind* fields, and comprehensive remote sensing research on *coastal* zones, became research foci. Research intensified in the fields of multispectral, high-resolution and multi-temporal remote sensing, production and inspection of remote sensing products, data correction, and uncertainty analysis. Research into new remote sensing data processing methods increased gradually, including various methods of *regression*, *optimisation*, *classification*, and *segmentation*. Studies on the dynamics and simulation of geographical processes became increasingly detailed. In surveying and cartography, the integrated system of surveying and mapping began to form, with the integration of polarisation, interferometry, lasers, aerial photogrammetry, radars, multiple sensors, high precision, large areas, and multi-sensor integrated continuous measurements becoming the principal features. Studies had increased in the areas of data error, sensitivity, uncertainty, parameterisation and regularisation of data, and surveying algorithms. Map cognition and representation theory, digital maps, virtual reality, and other technologies began to mature, and were widely used in many fields.

Figure 6.14 shows keyword characteristics of publications in SCI/SSCI mainstream journals in the geographical information system (GIS) part of geographical information science from 2001 to 2005. This was a breakthrough period of studies on the theory, method, and technology of geographical information system (GIS). The spatial cognition system of geographical information, centred on geography ontology and spatial syntax, strengthened continuously. Acquisition, geocoding, retrieval, sharing of geographical information, and spatial database technology developed rapidly. Mapping methods concentrated on electronic maps and comparison of maps gradually increased. Spatial statistics became an important study direction. Model verification, error theory, data verification, and assessment progressed appreciably, and they were widely used in spatial econometrics, regional development, and economic decision-making. Research into geographical information system analysis methods such as spatial interpolation, semantic similarity, association rules, cellular automata simulation, path planning, and time-space analysis greatly increased. 3D geographical information system and digital cities become study foci, and applications of geographical information system increased in the fields of multi-constrained comprehensive evaluation, decision support, city planning, forest landscapes, disaster management, and emergency response.

Figure 6.15 portrays research foci reflected by Chinese CSCD journals in geographical information science from 2001 to 2005, revealing a greater change of overall pattern compared with the previous 5 years. Given the abundance of high spatial resolution data, hyperspectral data, InSAR, active microwave data, and MODIS data suitable for global change research, new research foci of remote sensing continually emerged. (1) *Spatial databases*, *spatial data*

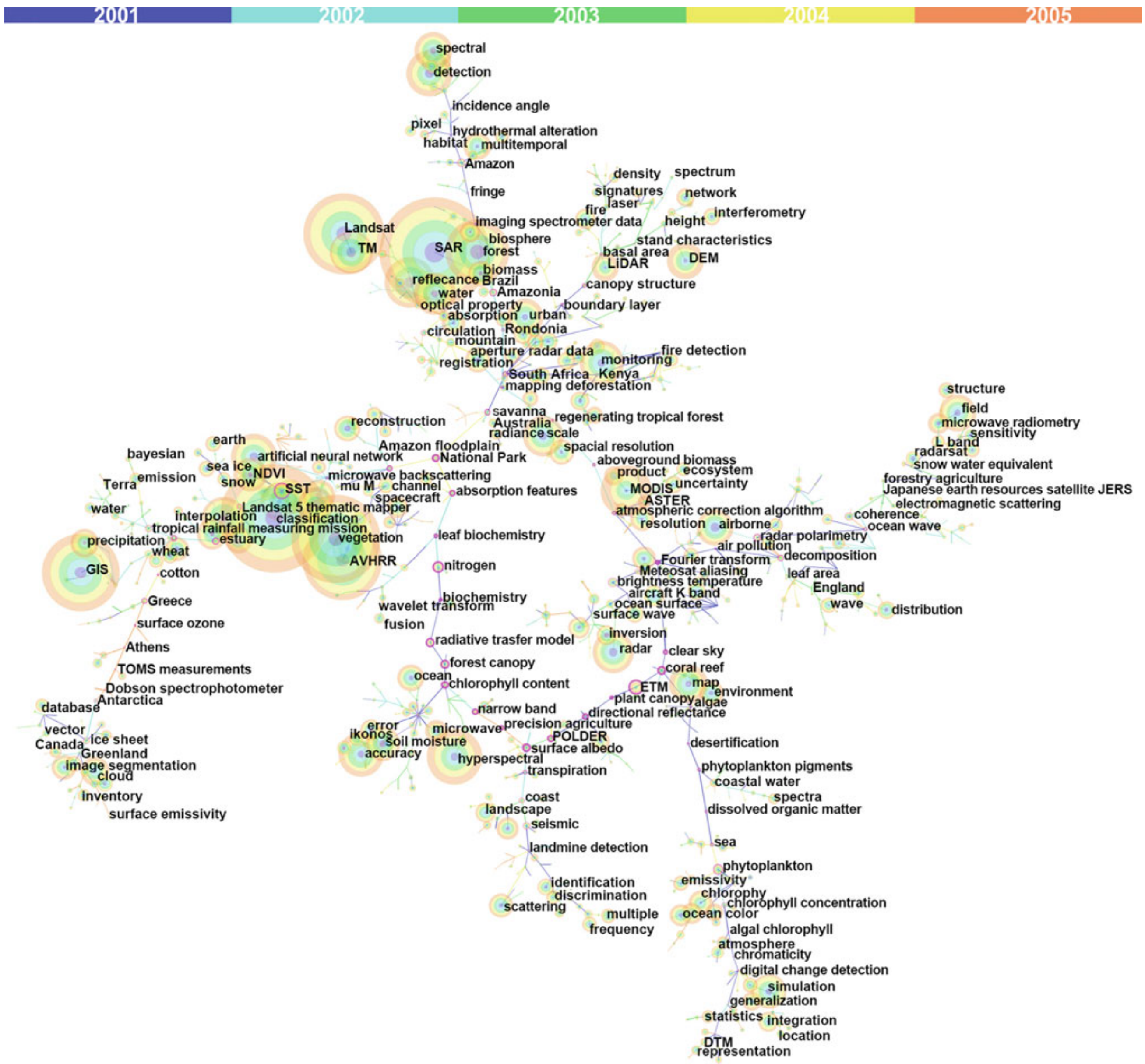


Fig. 6.13 Co-occurrence network of keywords in SCI/SSCI mainstream journals of geographical information science during the period 2001–2005

models, *digital earth*, *digital maps*, *virtual reality*, and *3D geographical information system* became prevalent topics. (2) *Land use*, *land use/land cover* and all types of related research methods became prominent keywords in remote sensing. (3) *SAR*, *InSAR*, and *DEM* related research developed explosively. (4) With the launch of hyperspectral imaging spectrometer Hyperion, *hyperspectral remote sensing* became a core keyword. Related inversion methods, such as *genetic algorithm*, *neural network*, *back propagation neural network*, and *simulated annealing*, grew dramatically. Research on microwave remote sensing for *rice* remained popular. (5) *GPS* became a core keyword. With the integration of high-resolution data and high precision positioning information, dynamic change, deformation monitoring, and cartographic generalisation became research concentrations. (6) Traditional surveying and mapping research focused on *uncertainty*, *variance component estimation*, *earth gravitational field*, and *spatial reasoning*.

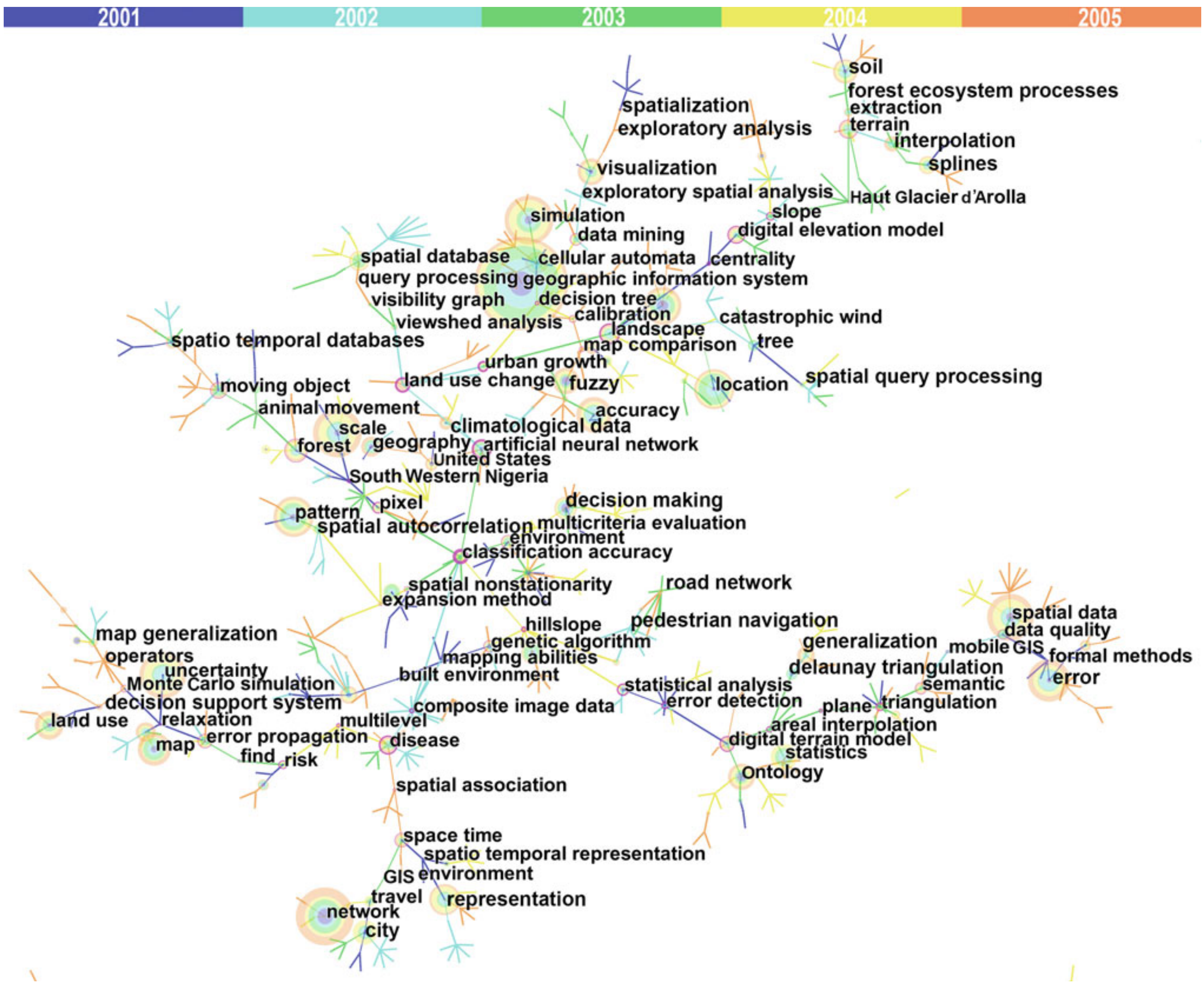


Fig. 6.14 Co-occurrence network of keywords in SCI/SSCI mainstream journals of geographical information system (GIS) during the period 2001–2005

Figure 6.16 compares popular keywords in SCI/SSCI journals used by Chinese authors and others during the period 2001–2005 (the diagram description see the note of Fig. 6.8). There was a significant increase in related journals and publications together with total keyword frequency. The keyword *remote sensing* had the highest frequency, more than 320. Frequencies of the top 15 keywords used by Chinese authors also increased. Frequencies of the top 15 keywords used by foreign authors were all greater than 48 during the period. Research characteristics reflected by the high-frequency keywords were as follows. *Radar* remote sensing still constituted for the largest part. Rapid development in *hyperspectral* and *microwave* remote sensing was achieved. Much research dealt with optical remote sensing data (*MODIS* and *Landsat*), image *classification*, and remote sensor *calibration*. Substantial research focused on remote sensing *radiative transfer*, *soil moisture* and vegetation parameter inversion (*leaf area index*, *LAI*), artificial *neural networks*, and *DEM*. In this view, *MODIS*, *radiative transfer* and *LAI* showed rapid growth in keywords. Among the top 15 high-frequency keywords in publications from Chinese researchers, there were four consistent with those of foreign researchers (*remote sensing*, *geographical information system* (*GIS*), *SAR*, *artificial neural network*). However, these keywords were already widely used by foreign scholars 5–10 years ago, demonstrating a lag of this duration by Chinese scholars in tracking popular international research topics. The high-frequency keywords used by Chinese scholars, such as *modelling*, *ground penetrating radar*, *genetic algorithm* and *simulated annealing*, were all used by international researchers more than 10 times. The frequencies of *Voronoi diagram*, *error propagation*, *data* or *technology integration*, *data structure*, *land use*, and *ocean colour remote sensing* were all less than 10, and more than

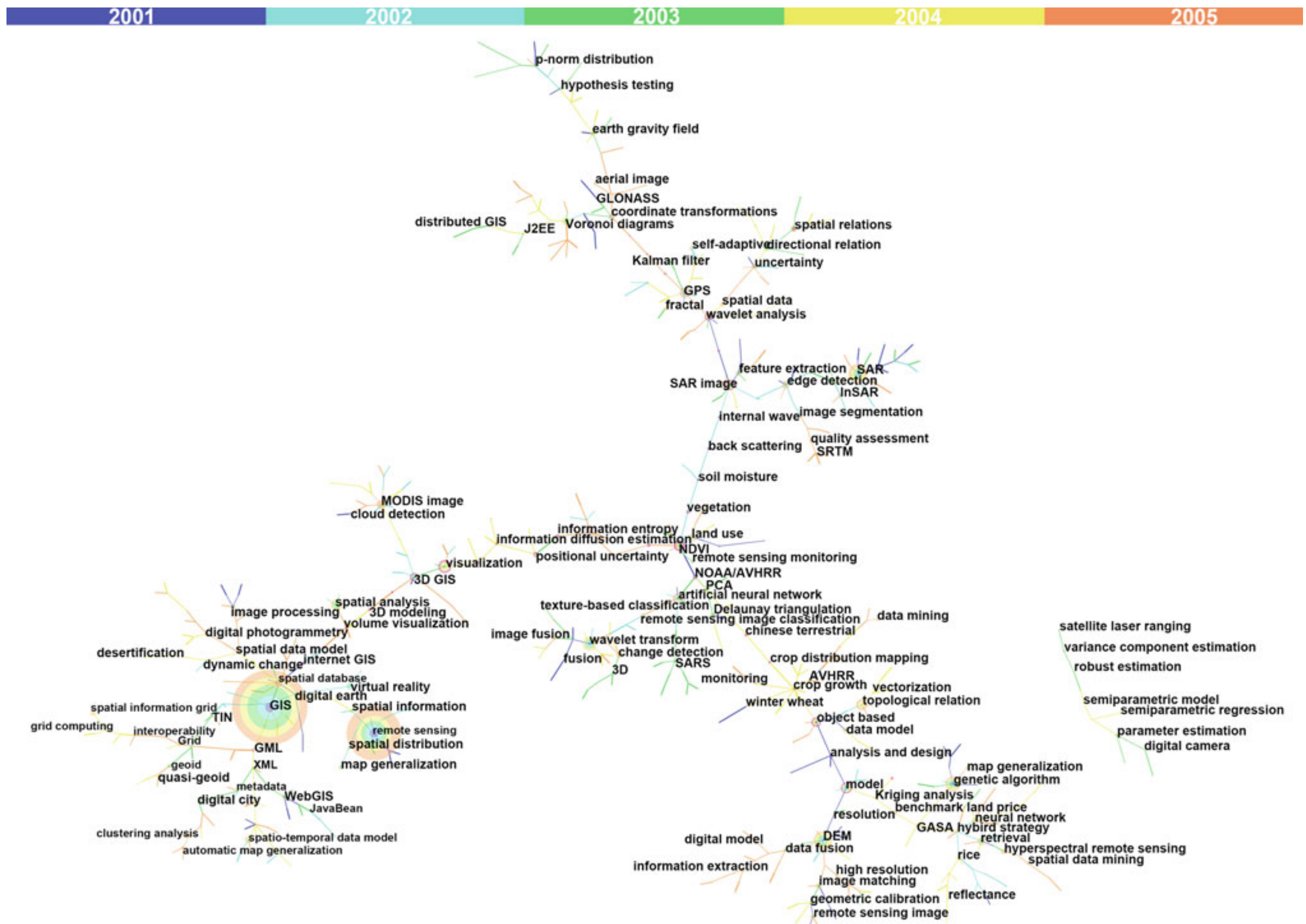
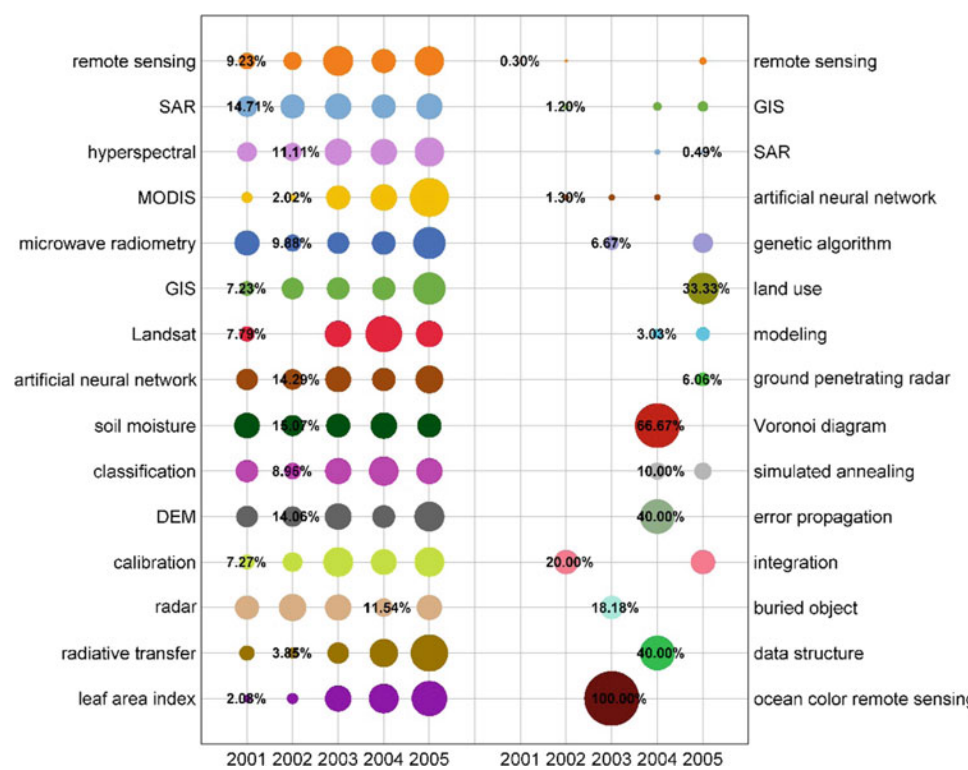


Fig. 6.15 Co-occurrence network of keywords in CSCD journals of geographical information science during the period 2001–2005

Fig. 6.16 Comparative diagram of prominent keywords by Chinese authors and others in SCI/SSCI mainstream journals of geographical information science during the period 2001–2005



30 % of those were contributed by Chinese authors. This shows that the above subjects were not international research foci in the period. It also shows that Chinese scholars chose some distinctive research directions, such as *land use* and *water* (*ocean*) *colour remote sensing*, which fit the requirements of China's resource and environment research. Use of the *Voronoi diagram* and *error propagation* study became directions representative of Chinese geographical information system research.

6.2.4 Period of 2006–2010

Figure 6.17 shows keyword characteristics of publications in SCI/SSCI mainstream journals in geographical information science from 2006 to 2010. This indicates that the theory, method, and technology of geographical information science made great progress in this period, with increased integration of various research directions. In the field of remote sensing, multiscale, multi-resolution, high spatial resolution and hyperspectral remote sensing become mainstream topics. Productive algorithms of remote sensing satellites represented by MODIS were mature. Quantitative land surface parameter inversion products covered a global scale. Land-use and land-cover products began to be used in a wider range of earth system research on global change and surface ecological environment change. Various remote sensing applications showed explosive growth, and comprehensive remote sensing research such as *feature extraction*, *change detection*, *multi-temporal remote sensing*, *monitoring*, and *data fusion* gradually improved. There was a development of synergetic use of multiple sensors (e.g., synergy of *laser scanner* data and high-resolution imagery for extraction of vegetation canopy parameters), *assimilation* of remote sensing data and geographical models, and long-time-series remote sensing information extraction such as *phenology*. These were widely used in many fields, such as global change, ecosystems, oceans, rivers, lakes, and snow. Interaction and fusion of surveying, remote sensing, and geographical information system (GIS) gradually advanced.

Figure 6.18 shows characteristic keywords of publications in SCI/SSCI mainstream journals in the geographical information system (GIS) part of geographical information science from 2006 to 2010. This reveals a rapid development stage of theory, method and technology in geographical information system (GIS). As a whole, 3D geographical information system developed swiftly. There were many topics, such as spatiotemporal data capture and observation, spatial data

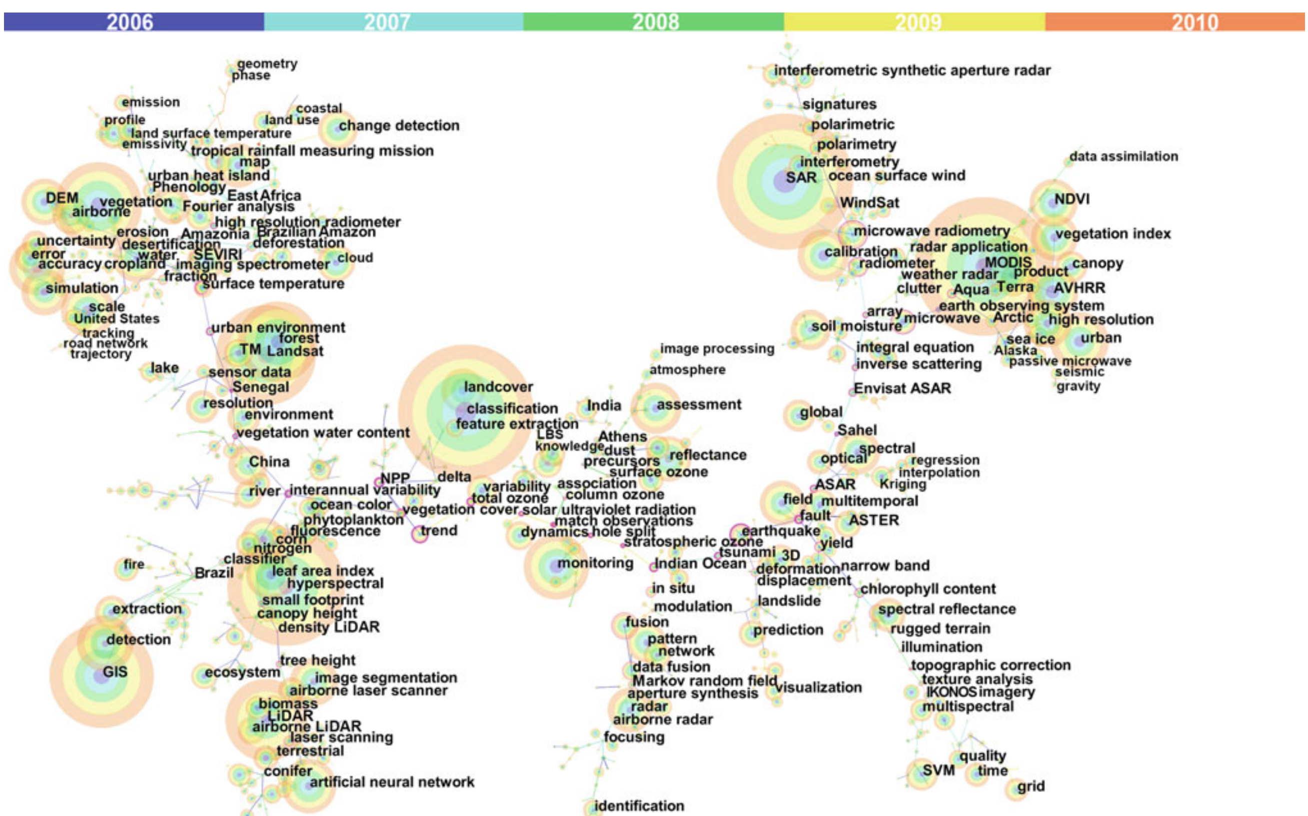


Fig. 6.17 Co-occurrence network of keywords in SCI/SSCI mainstream journals of geographical information science during the period 2006–2010

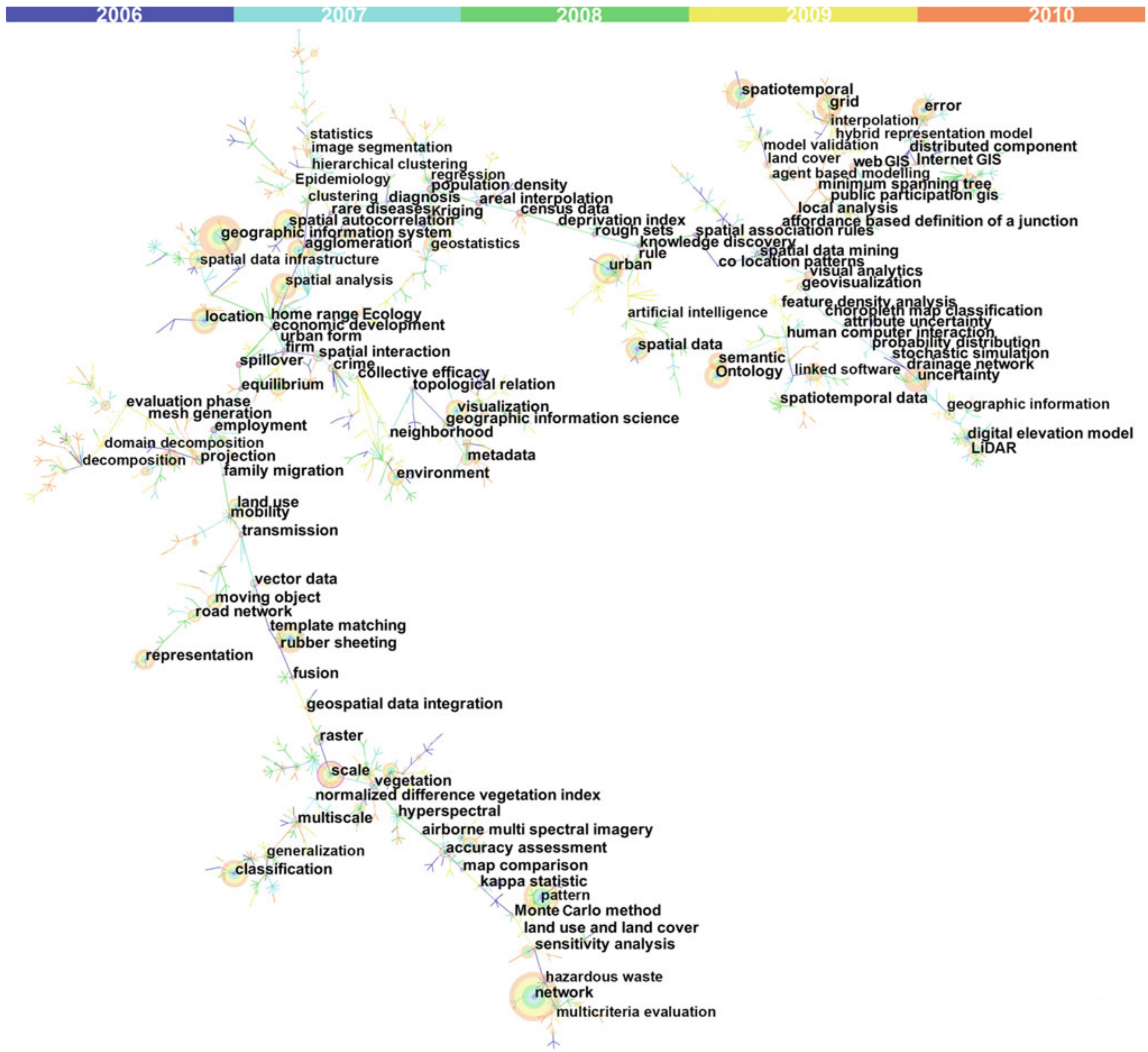


Fig. 6.18 Co-occurrence network of keywords in SCI/SSCI mainstream journals of geographical information system (GIS) during the period 2006–2010

processing and visualisation, visualisation of geographical analysis, data accuracy verification, exploratory spatial data analysis, spatial data modelling, data engines, spatial relationships, and semantic integration became research foci. New types of spatial data mining and knowledge discovery methods were continually emerging and were widely used in the fields of earth system science, global change, public health, resources, ecology, sustainable environmental development, and macroscopic decision-making. Geographical information system (GIS) architecture and service research received increasing attention. Modern geographical information system (GIS) technologies grew remarkably, including Internet geographical information system, grid and parallel computing. Diversity and professionalization of geographical information system software grew substantially. Great progress was made in the fields of data error, sensitivity, uncertainty, parameterisation, regularisation, and surveying algorithms. Technologies such as digital earth, spatiotemporal geographical information system, map cognition and representation theory, volunteer-based geographical information mapping, digital mapping, social media, visual reality, and augmented reality were widely used.

Figure 6.19 shows dominant research in Chinese CSCD journals in geographical information science from 2006 to 2010. There was not much change in the overall pattern compared with the last 5 years. The concentration on remote sensing and geographical information system (GIS) remained considerable. (1) Development of geographical information system (GIS) had a network-based trend and, as such, supportive technologies such as *WebGIS*, *spatial index*, and *spatial database* grew dramatically. Rapid progress of geographical information system analysis methods was demonstrated by keywords like *data mining*, *cellular automation*, *particle swarm optimisation*, and *spatial cognition*. (2) Popular research topics in remote sensing included *high-resolution remote sensing*, *hyperspectral remote sensing*, *hyperspectral imagery*, *mixed pixel,* and *remote sensing monitoring*. (3) In remote sensing application, *land use*, *water quality remote sensing*, *aerosol optical depth*, *urban heat island*, *change detection*, *data updating*, and the *Wenchuan earthquake* become major keywords. (4) For sensors, *Beijing-1*, *MODIS*, *interferometric synthetic aperture radar*, and *radar data processing algorithms* became core keywords. (5) Much attention was given to positioning technology, such as *airborne laser radar*, *aerial images*, *precise point positioning*, and *Positioning and Orientation System* (*POS*) *systems.*

Figure 6.20 compares popular keywords in SCI/SSCI journals used by Chinese authors and others during the period 2005–2010 (the diagram description see the note of Fig. 6.8).

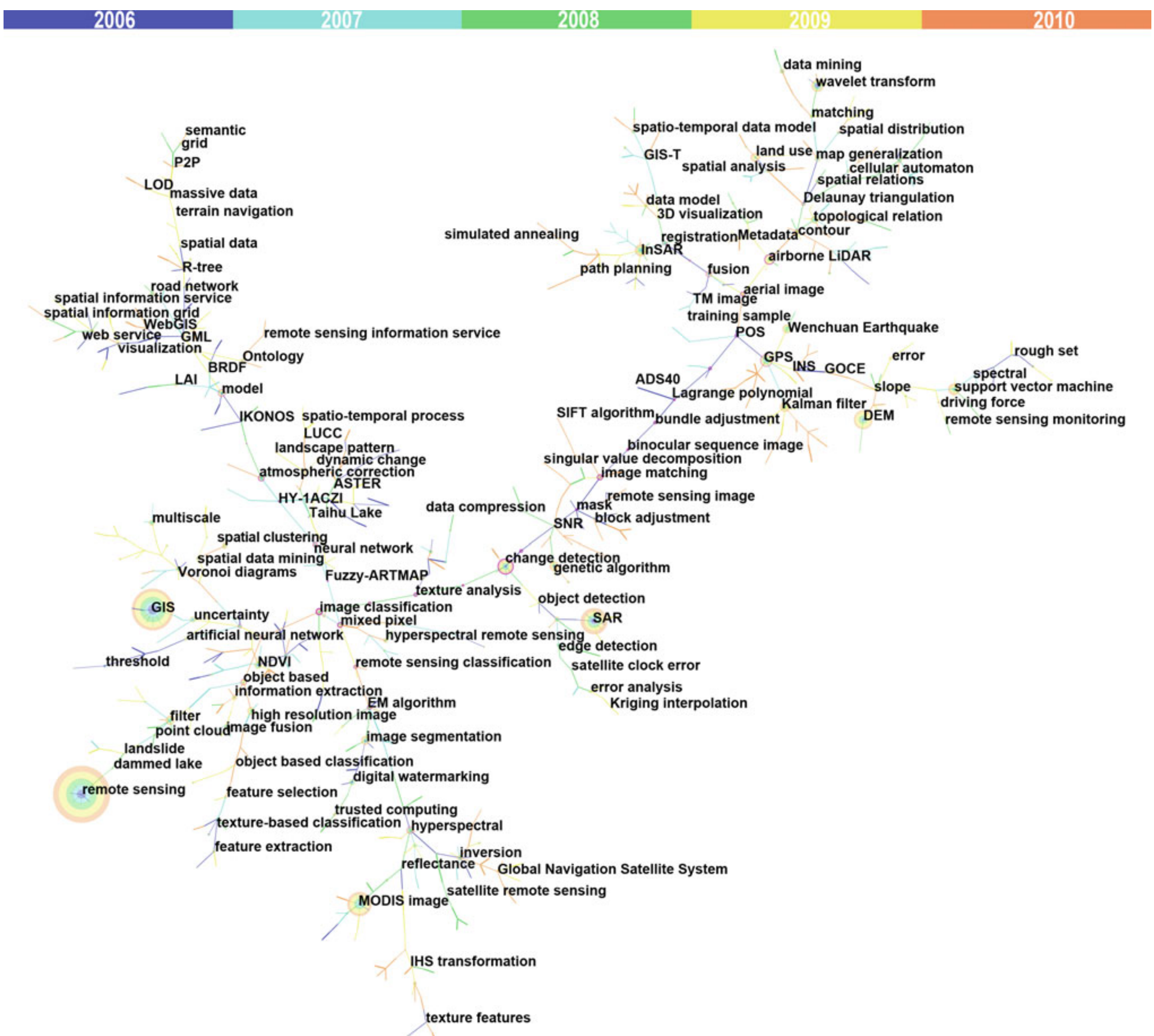


Fig. 6.19 Co-occurrence network of keywords in CSCD journals of geographical information science during the period 2006–2010

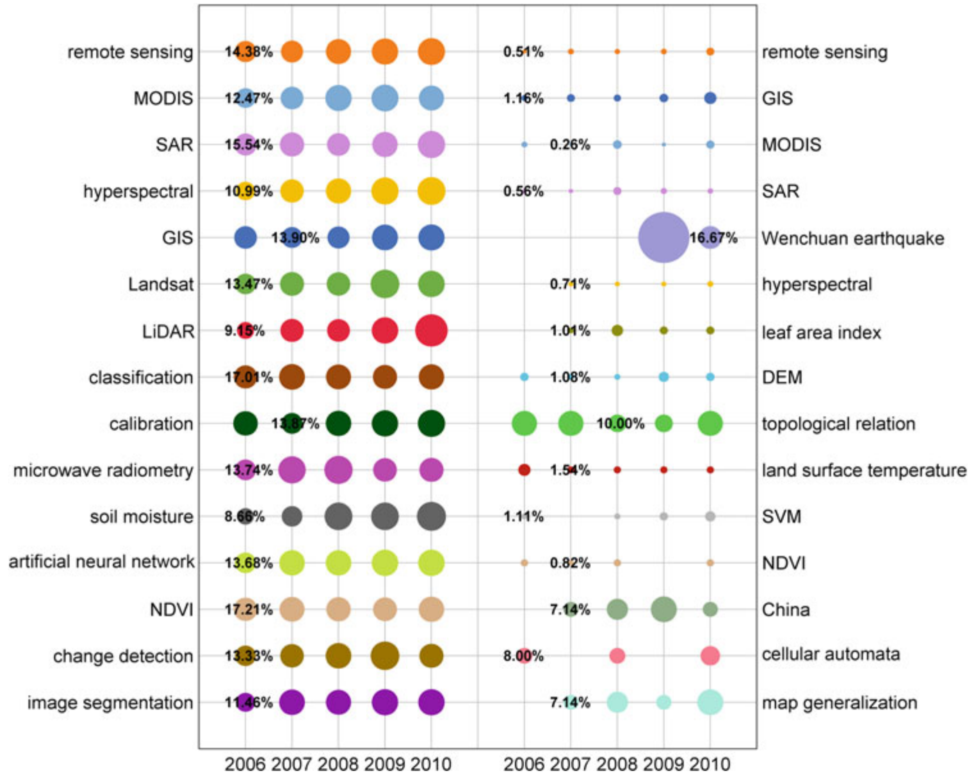


Fig. 6.20 Comparative diagram of prominent keywords by Chinese authors and others in SCI/SSCI mainstream journals of geographical information science during the period 2006–2010

The journals and papers published in this area increased rapidly, total keyword frequency increased, and the most frequent keyword (*remote sensing*) doubled in number over the past 5 years, increasing to more than 780 uses. Frequencies of the top 15 keywords used by Chinese authors all increased to seven. Frequencies of the top 15 keywords used by foreign authors were all more than 90, among which remote sensing remained the most frequent. There was no specific keyword pointing to geographical information system research except *GIS* itself. Research on MODIS data clearly increased, and *MODIS* became the second most frequent keyword. Research into Landsat data increased by a factor of 2.5 compared with the previous period. Although the rate of increase for radar (*SAR*), *hyperspectral* and *microwave* remote sensing slowed, they remained important research directions. Research on *LiDAR* developed rapidly, becoming the seventh most used keyword. High-frequency keywords such as remote sensing image *classification*, remote sensor *calibration*, *artificial neural networks*, and *soil moisture* appeared in the previous period and continued to be included in the top 15 frequent keywords in 2006–2010. *Change detection*, *image segmentation* and *NDVI* became new prominent keywords in this period. Considering the growth rate of keywords themselves during the 5 years, *LiDAR*, *soil moisture* and *hyperspectral* increased quickly. Among the top 15 high-frequency keywords of publications from Chinese authors, there were six consistent with foreign authors, i.e., *remote sensing*, *geographical information system* (*GIS*), *MODIS*, *SAR*, *hyperspectral*, and *NDVI*. This clearly demonstrates that research on geographical information science in China kept pace with the international development trend. Among the remaining top 15 high-frequency keywords used by Chinese authors, the *Wenchuan earthquake* represented a unique characteristic of geographical information science service in rapid disaster relief and mitigation. *Topological relationships* and *map generalisation* were extensively researched by Chinese geographical information science scholars, while foreign peers contributed less than 50 % to the total in this field, so Chinese authors had more advantages there. *Cellular automaton* and *SVM* were also included in the top 15 keywords, showing that Chinese geographical information science investigators focused on model algorithms, similar to the finding that *genetic algorithm* and *simulated annealing* were included in the high-frequency keywords of Chinese authors during 2001–2005. This demonstrates that Chinese scholars maintained strong interest in new methods. *DEM* always ranked in the list of top 15 high-frequency keywords of foreign authors during 1986–2005, except during 2006–2010. However, *DEM* appeared in the list of high-frequency keywords of Chinese authors in that period, revealing that Chinese scholars caught up with the dominant international research fields.

6.2.5 Period of 2011–2015

Figure 6.21 shows characteristic keywords of publications in SCI/SSCI mainstream journals in geographical information science from 2011 to 2015. This indicates explosive growth and wide application in geographical information science during this period, and expansion of interchange and integration of different research directions. (1) In remote sensing, multiscale, multi-resolution, high-resolution, multispectral, and hyperspectral remote sensing became mainstream. All types of remote sensing applications grew explosively. Comprehensive research in remote sensing became increasingly prominent, represented by *image segmentation*, *feature extraction*, *classification*, *change detection*, *time series*, *remote sensing monitoring*, and *data fusion*. Test and verification of remote sensing data drew

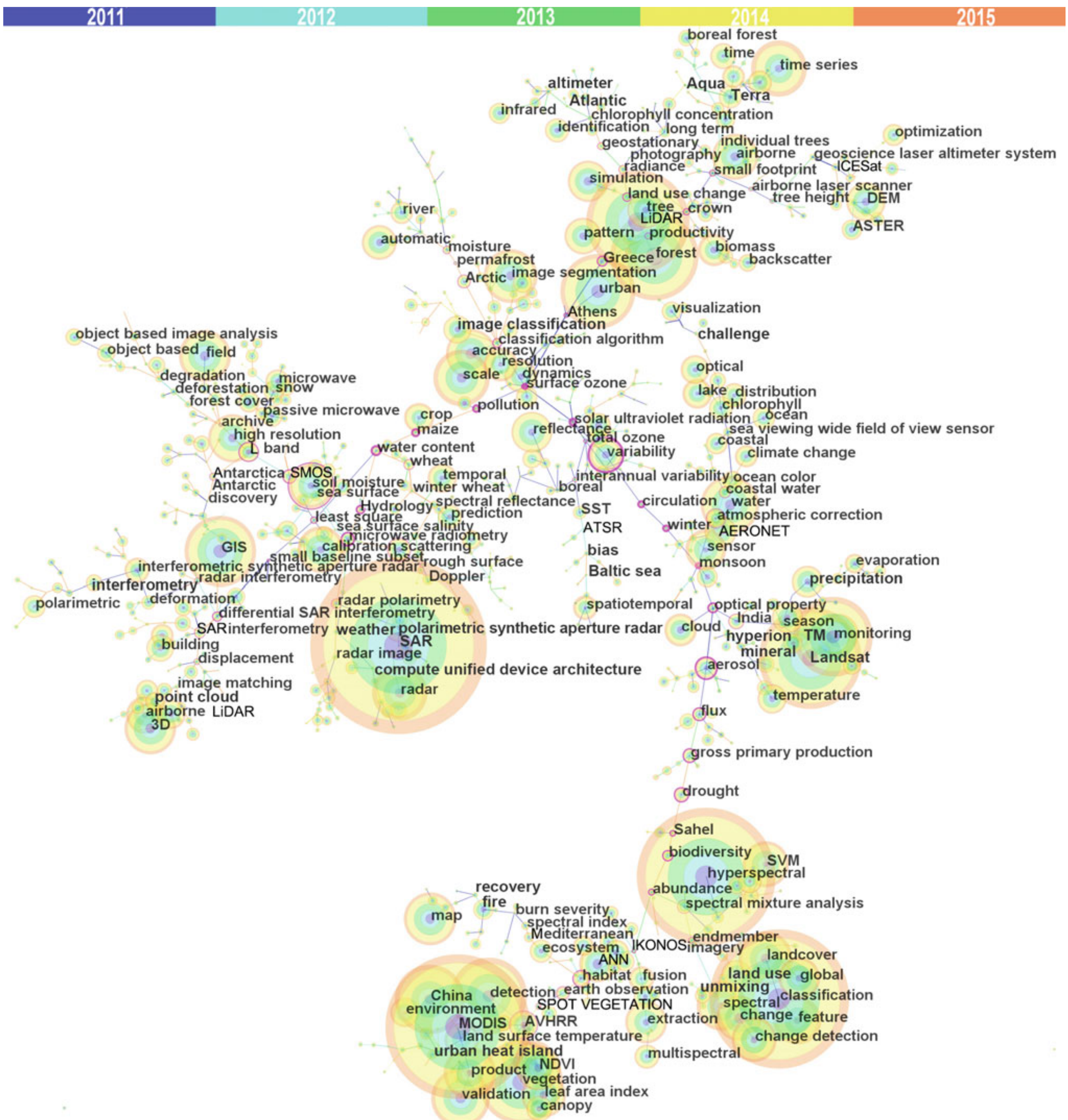


Fig. 6.21 Co-occurrence network of keywords in SCI/SSCI mainstream journals of geographical information science during the period 2011–2015

more attention. The application fields of remote sensing kept expanding and increased in popularity, with continued strengthening in *climate change*, *ecosystems*, *surface ozone*, *oceans*, *rivers*, and *lakes*. Remote sensing technology itself saw continuous development. For imaging radar, with the launch of full-polarisation SAR systems, e.g., ALOS, TerraSAR-X, and Radarsat-2, *polarimetric SAR* research developed very quickly during the period. These have been applied in parameter inversion of *soil moisture* and forest as well as in ground feature classification. The emergence of *LiDAR* made it possible to extract more forest parameters (*NDVI*, *vegetation*, *tree crown*, *productivity*, and *biomass*). Aimed at higher spectral, spatial and temporal resolution remote sensing data, *object-based image analysis*, *land-use change monitoring*, and *land-surface temperature* have become research foci. Evolution of the above research subjects were largely synchronised with development of the Earth Observation System (EOS) plan of NASA, which is moving into a more detailed earth observation stage. (2) Regarding surveying and cartography, research increased in fields such as data quality, error estimation, optimisation, data accuracy, and variability. Laser mapping and aerial photogrammetry technologies gradually matured. *Urban*, *3D*, *DEM*, *mapping*, and other applications grew dramatically. In addition, research on long time-series continuous surveying and related survey products greatly increased.

Figure 6.22 shows characteristic keywords of publications in SCI/SSCI mainstream journals in the geographical information system (GIS) area of geographical information science during 2011–2015. This indicates that geographical information system (GIS) attained robust development and popular application in this period. Interchange and fusion of different research directions increased. Cloud computing, cyber geographical information system, wireless sensor

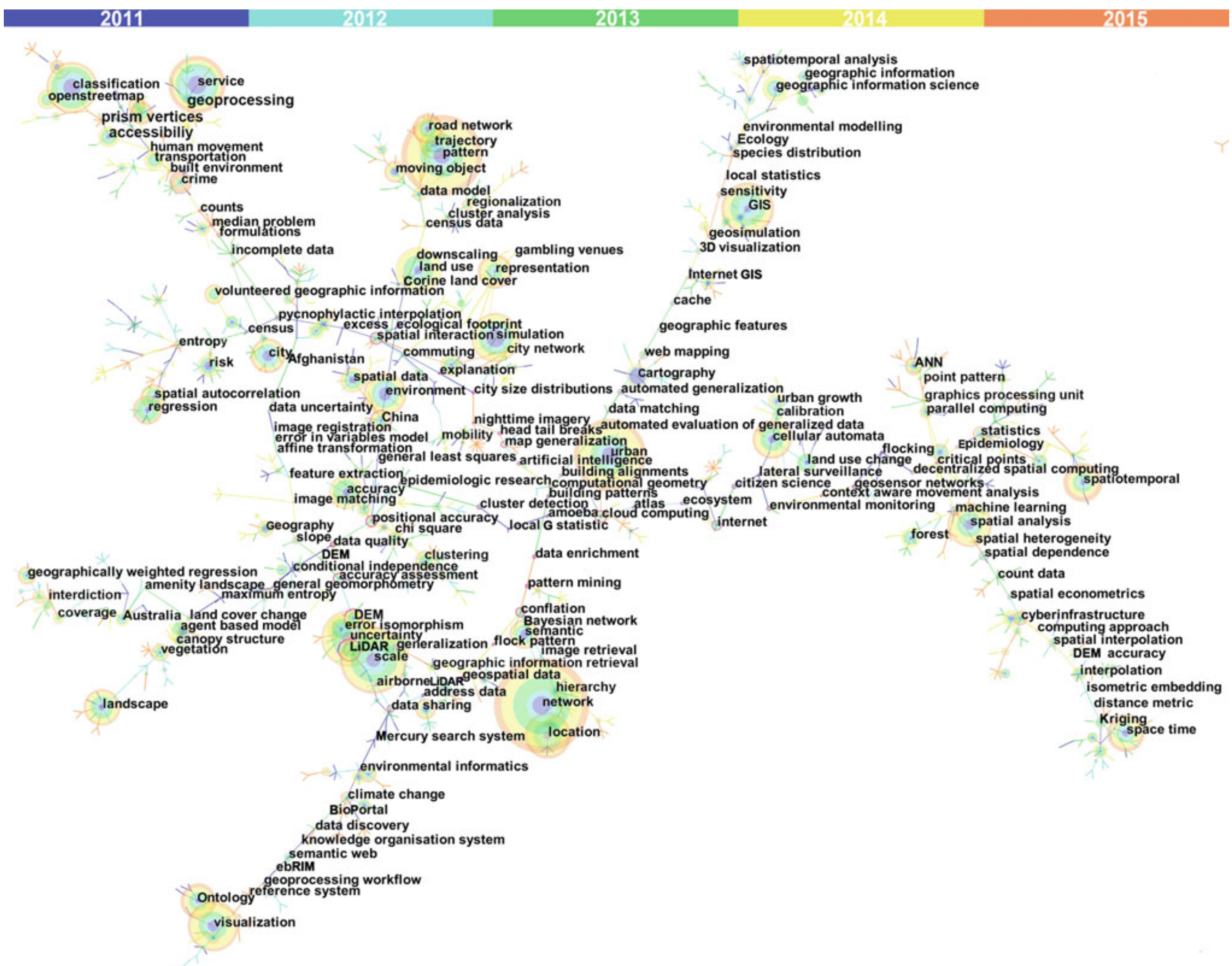


Fig. 6.22 Co-occurrence network of keywords in SCI/SSCI mainstream journals of geographical information system (GIS) during the period 2011–2015

networks, and ubiquitous information processing marked the transformation of geographical information system development. Geographical information system software had a clear trend toward open-source and standardisation. The technology of *road networks*, *visualisation*, *parallel computing*, *environmental modelling*, *cluster analysis*, *web mapping*, and *classification* developed rapidly. Centred on *artificial neural networks*, *cellular automata* and *agent simulation*, *geographical intelligence computing*, *simulation*, and *optimisation*, and *building pattern*, *pattern mining*, *machine learning*, and *automated generalisation* were gradually optimised. These were effectively used in urban computing, regional planning, and path optimisation. With the popularisation of *LiDAR*, related scale analysis, *DEM* construction, and data *uncertainty* analysis were used in environmental monitoring. Geographical information system applications gradually transformed from natural processes to comprehensive observation and analysis of human social processes, e.g., with gradual appearance in urban governance, behaviour *trajectories* and *moving objects*, and environmental and regional development. Applications in the fields of societal networks, urban governance, and transport planning by *open street map* were evidenced by *VGI*, *OSM* and *spatiotemporal analysis*. These applications have great research potential in terms of service. Therefore, attention to social geographical information system clearly increased.

Figure 6.23 shows research foci as reflected by publications in Chinese CSCD journals in geographical information science during 2011–2015. The main characteristics are as follows. (1) Keywords of spatial analysis, such as *spatial relationship*, *multiscale segmentation*, and *3D geographical information system* (*GIS*) indicate that the analysis capability and application fields of geographical information system all expanded greatly. The increasing frequency of keywords *hyperspectral remote sensing*, *GPS*, *precise point positioning*, *spatial database*, and *spatial index* showed the amalgamation of geographical information system, remote sensing, and positioning technology research. Clustering of keywords in spatial mapping, such as *map generalisation*, *feature matching*, *Delaunay triangulation*, *quadtree*, and *triangulated irregular network*, indicated that spatial map representation still had substantial research value.

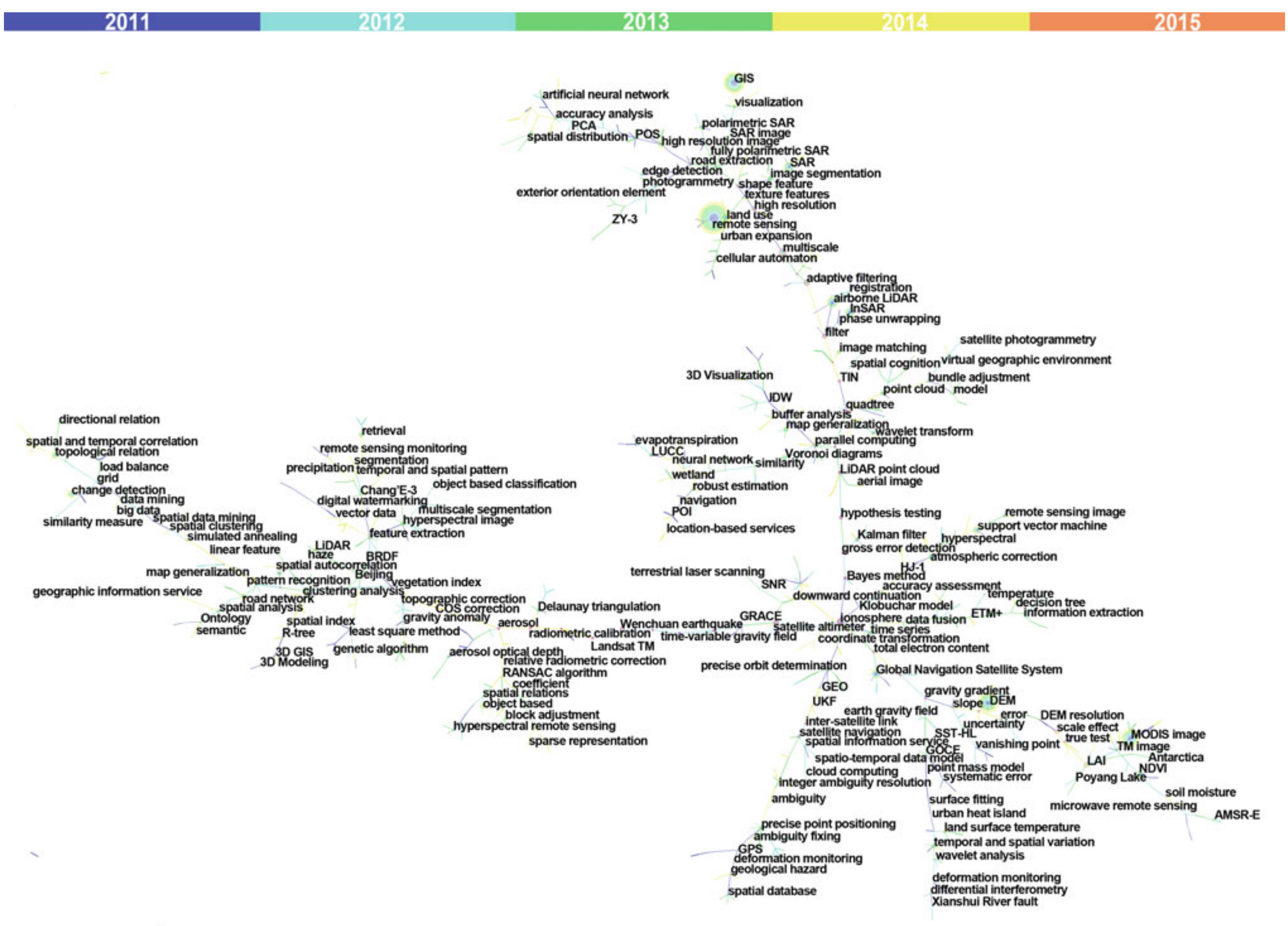


Fig. 6.23 Co-occurrence network of keywords in CSCD journals of geographical information science during the period 2011–2015

(2) *Hyperspectral images*, *land-use/land-cover change*, *remote sensing monitoring*, *BRDF*, *mixed pixels*, and *DEM* were keywords in core research. (3) *MODIS imagery* remained the core keyword of remote sensing. Keywords *aerosol* and *haze* increased rapidly, reflecting the requirement of remote sensing for monitoring air pollution in northern China. (4) Technologies of high-resolution detection unaffected by clouds, such as *InSAR*, *SAR*, *fully polarimetric SAR*, and *radar image processing* continued as important research foci. (5) *Global navigation satellite system* became an important keyword, benefitting from the availability of the Beidou navigation service. (6) *TianHui-1*, *Chang'e-1*, *rational function model*, *positioning without ground control points*, *bundle adjustment*, *satellite navigation*, *orbit determination*, *ionosphere*, *satellite altimetry*, and *Gravity Recovery and Climate Experiment (GRACE)* were all popular keywords in the period.

Figure 6.24 compares popular keywords in SCI/SSCI journals used by Chinese authors and others during the period 2011–2015 (the diagram description see the note of Fig. 6.8). The highest frequency keyword remained *remote sensing*. Frequencies of the top 15 keywords of Chinese authors increased to at least 23, while those of foreign authors exceeded 106. Overall, there was little difference in the distribution of the top 15 keywords between the period and 2006–2010, which mostly had research topics in the field of remote sensing. The difference was in the substitution of *microwave radiometry* by *SVM* and of *artificial neural network* by *DEM*. *SVM* was one of the most frequent keywords of Chinese authors during 2006–2010, but only contributed 7.8 % to global research. The proportion of Chinese authors increased to 21.3 % during 2011–2015, showing the perceptiveness and rapid development of Chinese scholars. *DEM*, *topological relationship*, *Wenchuan earthquake*, *map generalisation*, and *cellular automata* were all high-frequency keywords of Chinese scholars during 2006–2010. However, they were superseded by *classification*, *image segmentation*, *change detection*, *Landsat*, and *soil moisture* from 2011 to 2015. Three of the top 15 frequent keywords used by Chinese authors were different from those used by foreign authors (*land surface temperature*, *leaf area index*, and *China*). Among them, *leaf area index* (*LAI*) was a frequently used keyword by foreign authors during 2001–2005. The proportion of this keyword by Chinese authors accounted for 27.6 % of the total up to the present. Chinese authors contributed 71.9 % of the total frequency of the keyword *China*, 20 % more than in 2006–2010. *Land surface temperature* became a frequent keyword of Chinese scholars in 2006, with their contribution rising from 10.8 % during 2016–2010 to 32.3 % now. Since 2001, *soil moisture* research has been a focus of foreign authors, and has also become a common topic of Chinese authors. The above findings indicate that in addition to tracking international research, Chinese geographical information science still

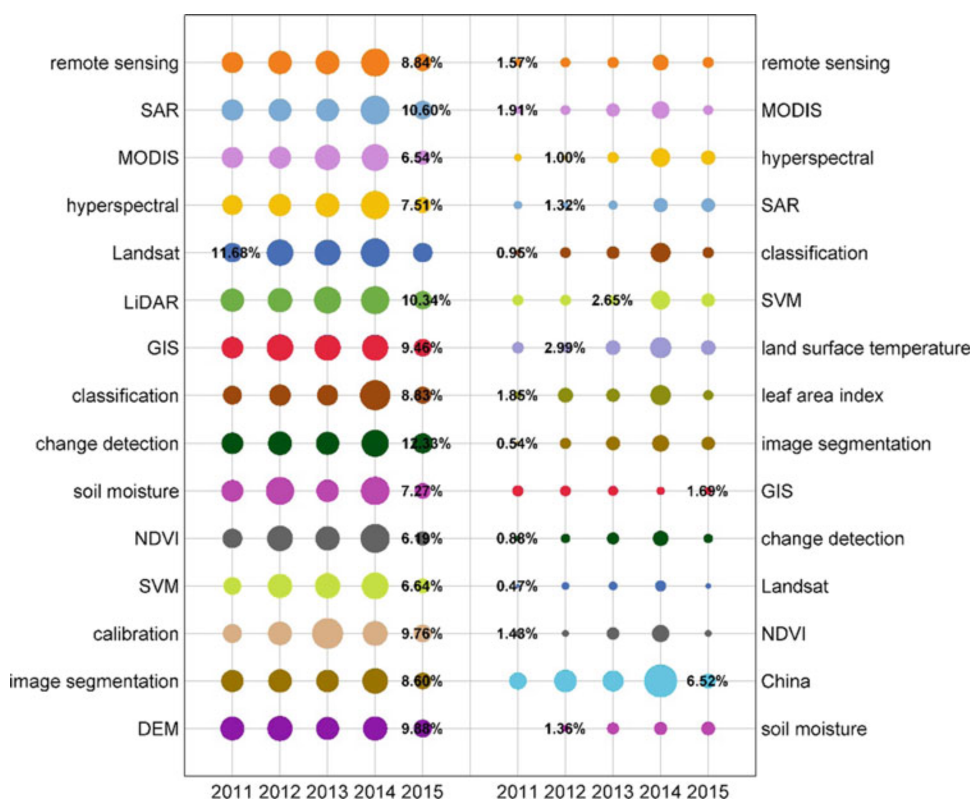


Fig. 6.24 Comparative diagram of prominent keywords by Chinese authors and others in SCI/SSCI mainstream journals of geographical information science during the period 2011–2015

followed certain research directions. However, *LiDAR*, which has been a focus of international researchers since 2006, was not a research priority among Chinese scholars.

6.2.6 Analysis of Driving Factors for Disciplinary Development over the Past 30 Years

The development of geographical information science in the last 30 years has had obvious periodic characteristics, and the impetus for disciplinary development is attributed to growing demand and technical progress.

Research into global change since 1986 and the International Geosphere-Biosphere Programme (IGBP) in 1986 directly promoted the development of earth observation of land use and land cover and vegetation status information in remote sensing. Moreover, because of global change research and the launch of the U.S. EOS MODIS in 1999, research on remote sensing quantitative inversion of land surface parameters greatly increased. Therefore, major land-surface parameter inversion, such as land-surface temperature, leaf area index (LAI) and evapotranspiration became frequent keywords over the last 20 years. In November 2000, the U.S. launched the EO-1 (Earth Observing-1) satellite, which carried the first spaceborne imaging spectrometer (Hyperion) for civilian use. This promoted hyperspectral research on land-surface parameters. The demands of disaster relief and hazard assessment of the 2008 Wenchuan earthquake impelled comprehensive emergency remote sensing with definite objectives, such as SAR, airborne remote sensing, and high-resolution optical remote sensing that can be used to detect terrain deformation and target change. The major haze pollution event in Beijing and east-central China in January 2013 promoted rapid development of monitoring and research of haze and aerosols based on MODIS data.

Satellite remote sensing is an important technology of surface data acquisition for earth surface system research. The influence of weather conditions on optical remote sensing has promoted the development of radar technology. For example, the European Space Agency (ESA) launched European Remote Sensing Satellite-1 (ERS-1) carrying an advanced InSAR in 1991, which provided abundant InSAR data. After the launch of Radarsat by Canada in November 1995, InSAR technology developed from pure theoretical research toward actual applications in agriculture and geology. The ESA system contains five imaging modes. Distance and azimuth resolution can reach 25 m × 28 m with 100-km width imaging. When image width is 300 km, the resolution can reach 50 m × 50 m. As an extension of ERS-1, ENVISAT, one of the series of ESA earth observation satellites, was launched in March 2002. This included four modified equipment components from ERS-1/2 (the largest of which is Advanced Synthetic Aperture Radar) that can generate high-quality images of ocean, coast, polar ice caps, and land. SAR and InSAR technology greatly expanded the application areas of remote sensing, promoting the geological usage of remote sensing technologies. In particular, the American Shuttle Radar Topography Mission acquired InSAR data covering 80 % of the Earth surface from an orbit of 200 km above the earth, and generated global 30-m, high-resolution terrain data and three dimensional image maps. The generation of terrain data and its wide use in geography was a major factor in direct promotion of DEM development. China launched TianHui-1 and TianHui-2 in 2010 and 2012, respectively, and ZY-3 in 2012. These further promoted the technology and application of digital elevation, three-dimensional geographical information management and analysis. Geographical information system has an ability for spatial data management and analysis, and it was a core area in the decade after 1986. With the wide use of high-resolution satellite data and DEMs, strong integration of geographical information system, remote sensing and DEM technology impelled comprehensive application and development of geographical information science.

The research foci of Chinese papers were consistent with the research demands of global change and the development trend of remote sensing in both China and abroad. Regarding drivers of global change, research affecting China was mostly in land use/land cover, vegetation remote sensing, and flood and earthquake disasters. At a global scale, quantitative remote sensing monitoring and inversion have always been important themes in earth observation technology of remote sensing. Many keywords focused on the treatment of high-resolution remote sensing and SAR imagery appeared in geographical information science, which clearly reflects a high prioritisation in China of the technology of surface information in both cloudy and cloud-free conditions. This was to meet the demands of land-surface change detection caused by land resources, agriculture, the water environment, and earthquakes. Frequent appearance of keywords such as high-resolution imagery and precision position technology, and the launch of TianHui-1 and ZY-3, clearly reflected the great demand for high-resolution digital maps in the country.

6.3 Disciplinary Development and Research Teams in China

Development trend analysis in this section focuses on the change in number of projects applications and funded by NSFC in geographical information science, the change in proportions of application and supported projects in geographical information science branches, and characteristics of them chosen by researchers in NSFC-funded projects. The

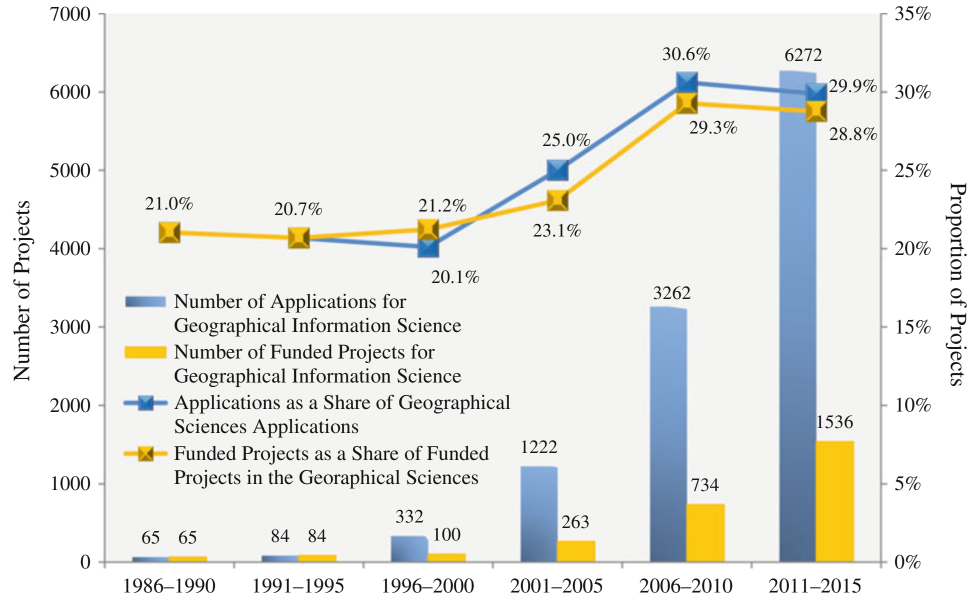


Fig. 6.25 Proportions of NSFC projects for geographical information science during the period 1986–2015. *Note* Non-funded proposals from 1986 to 1997 were not recorded in NSFC database. Therefore, number of applications and NSFC-funded projects are identical from 1986 to 1995, as shown in the figure

conditions of teams in research institutions in China are analysed by (1) the number of institutions with research in geographical information science, (2) the number of publications in SCI/SSCI journals per researcher in these institutions, (3) the collaborative network of Chinese authors with publications in SCI/SSCI or CSCD journals, and (4) institutions with which the highly cited SCI/SSCI-indexed articles were affiliated and situation of NSFC-funded projects in these institutions.

6.3.1 Numbers and Proportions of NSFC Applications and Funded Projects for Geographical Information Science

The proportion of NSFC-funded projects in geographical information science within geographical sciences has increased over the past 30 years. This proportion was nearly 30 % during 2010–2015, clearly indicating that geographical information science has become an important part of geographical sciences and teams of fundamental research are growing. Further, the proportion of projects in geographical information science applying to and supported by NSFC kept growing with a similar proportion, showing that NSFC has adequately considered the development demand of geographical information science in making funding plans (Fig. 6.25).

Based on the application for General Programmes (GP), Young Scientists Fund (YSF) and the Fund for Less Developed Regions (LDR Fund) in geographical information science from 1986 to 2015, we analysed the proportion of project applications in each branch of geographical information science (Fig. 6.26). The objectives of developing geographical information science are to advance the ability to capture land surface data, analysis, simulation, and representation by figures. Research on remote sensing and

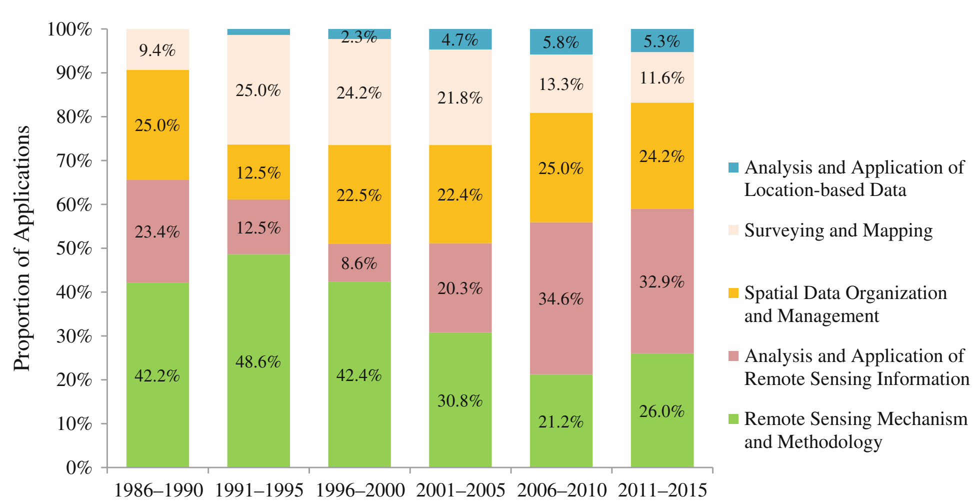


Fig. 6.26 Proportions of NSFC applications of branches of geographical information science during the period 1986–2015. *Note* Non-funded proposals from 1986 to 1997 were not recorded in the NSFC database. Therefore, the proportion of applications shown in the figure is the proportion of funded projects during the period

surveying mainly targets data capture. By contrast, geographical information system (GIS) and mapping mainly aim at analysis, simulation and figure representation. Figure 6.26 shows that research in remote sensing accounted for 50–60 % of total applications in geographical information science over the past 30 years. Geographical information system (GIS) studies represented by spatial data organisation and management had a steady proportion of 25 %. Research into surveying and mapping decreased gradually, and that into analysis and applications of spatial positioning data appeared. Considering the fundamental nature and applicability of research on remote sensing, the proportion of research in remote sensing information analysis and application clearly grew in the last decade. This benefitted from improvement in the ability of earth observation data capture. The abundance of remote sensing data provided various possibilities for information extraction and analysis in environmental, ecological, disaster, and resource remote sensing. The application code of remote sensing information analysis and application was moved from the category of remote sensing into that of geographical information system (GIS) by NSFC in 2008, promoting the use of remote sensing information in analysis and modelling of geographic information. This adjustment followed the co-development trend of remote sensing and geographical information system (GIS). A decrease in mapping applications corresponded to the overall development trend of this discipline, because researches on mapping and geographical information system (GIS) are inseparable. The proportion of analysis and application of spatial positioning data continued to increase, indicating that Global Navigation Satellite System (GNSS) greatly increased the measurement accuracy of moving objects. GNSS provides a high-quality data source for mobile geographical information system and location-based services.

6.3.2 Objects of Studies in NSFC-Funded Projects

Remote sensing provides abundant spatial data sources for research of the earth surface. Because of the difference of land surface components, the requisite remote sensing data types are also different. Therefore, continued provision of data types aimed at specific demands in land surface research is a key aspect of remote sensing service. We reviewed 2375 projects (representing 85.5 % of the 2,778 projects funded by NFSC in geographical information science) in 40 research directions funded by NFSC in geographical information science research by retrieving remote sensing data types from keywords, titles, and abstracts. We found that nearly 40 % clearly described those data types. Analysis showed that the types of remote sensing data used in the projects funded by NSFC in geographical information science changed constantly (Fig. 6.27). (1) **Active microwave remote sensing** was the data type with the largest retrieval number, at 233 projects, 134 of which were funded in the last 5 years. Projects with this data type were distributed in 35 research directions, the top five of which were remote sensing mechanism, remote sensing of hazards, agricultural remote sensing, urban remote sensing, and soil parameter retrieval and assimilation. (2) The retrieval number of **hyperspectral remote sensing** was 179, of which 134 were funded in the last 5 years. The rate of increase of this data type surpassed

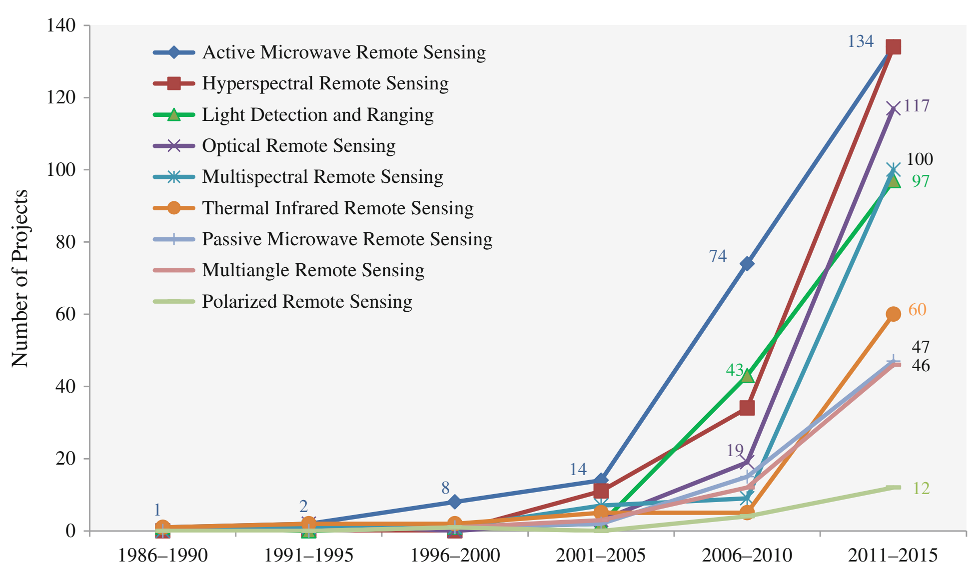


Fig. 6.27 Number of NSFC-funded projects with different types of remote sensing data in geographical information science during the period 1986–2015

that of active microwave remote sensing. Projects with this data type appeared in 24 research directions, the top five of which were remote sensing image classification, agriculture remote sensing, vegetation parameter retrieval and assimilation, remote sensing mechanisms, and ecological remote sensing. (3) The retrieval number of light detection and ranging (**LiDAR**) was 144, which increased rapidly in the last 10 years; 97 of those were funded in the past 5 years. Projects of this data type had 28 research directions, the top five of which were forestry remote sensing, laser measurement, urban remote sensing, remote sensing mechanisms, and vegetation parameter retrieval and assimilation. (4) The retrieval number of **optical remote sensing** was 141. Its growth rate was similar to that of hyperspectral in the last decade, there were 117 funded in the past 5 years. Projects using this data type referred to 28 research directions, the top five of which were agricultural remote sensing, vegetation remote sensing, remote sensing image classification, water parameter retrieval and assimilation, vegetation parameter retrieval and assimilation, and remote sensing mechanism. (5) The retrieval number of **multispectral remote sensing** was 118, 100 of which were funded in the past 5 years. Projects with this data type had 25 research directions, among which agricultural remote sensing, atmospheric parameter retrieval and assimilation, and vegetation parameter retrieval and assimilation were mainstream. Urban, remote sensing, ecological remote sensing, remote sensing of hazards, hydrological remote sensing, and remote sensing of global change also appeared at certain times. (6) The retrieval number of **thermal infrared remote sensing** was 75, which grew fast. Up to 60 were funded in the past 5 years. Projects with this data type related to 21 research directions, which were mainly in radiation and energy balance parameter retrieval and assimilation. An agricultural remote sensing, atmospheric parameter retrieval and assimilation, remote sensing modelling, and urban remote sensing appeared at certain times. (7) The retrieval number of **passive microwave remote sensing** projects was 65, of which 47 were funded in the past 5 years. Projects with this data type had 18 research directions, which were mainly in snow-ice parameter retrieval and assimilation, soil parameter retrieval and assimilation, remote sensing mechanism, and theory and methodology of quantitative remote sensing inversion and assimilation. (8) The retrieval number of **multi-angle remote sensing** was 62, of which 46 were funded in the past 5 years. This had a similar growth rate as passive microwave remote sensing. Projects with this data type related to 15 research directions, which were mainly in remote sensing mechanism, remote sensing modelling, and feature measurement and analysis. (9) The retrieval number of **polarized remote sensing** was 17, the smallest of all data types. Almost all projects of this data type were funded in the past 10 years and were mainly in feature measurement and analysis.

6.3.3 Research Teams

The analysis targets of the research teams mainly included the following: Number of institutions applying for NSFC funding for projects in geographical information science; number of institutions publishing papers in SCI/SSCI or CSCD journals; authors and their collaborative networks, average number of papers from institutions supported by NSFC geographical information science; general situation of the highly cited papers in SCI/SSCI journals published by Chinese authors (top 50 Chinese papers and top 1000 international papers); and the top 10 institutions receiving the most NSFC funds. To distinguish Chinese authors with the same name, Chinese and English abbreviations of the institutions to which the authors belonged were added

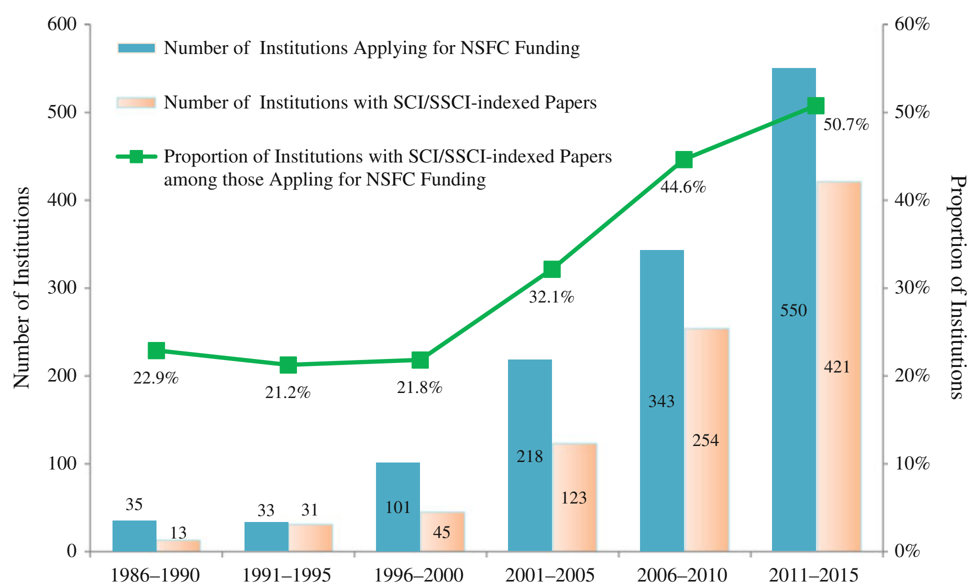


Fig. 6.28 Number of Chinese research institutions on geographical information science during the period 1986–2015

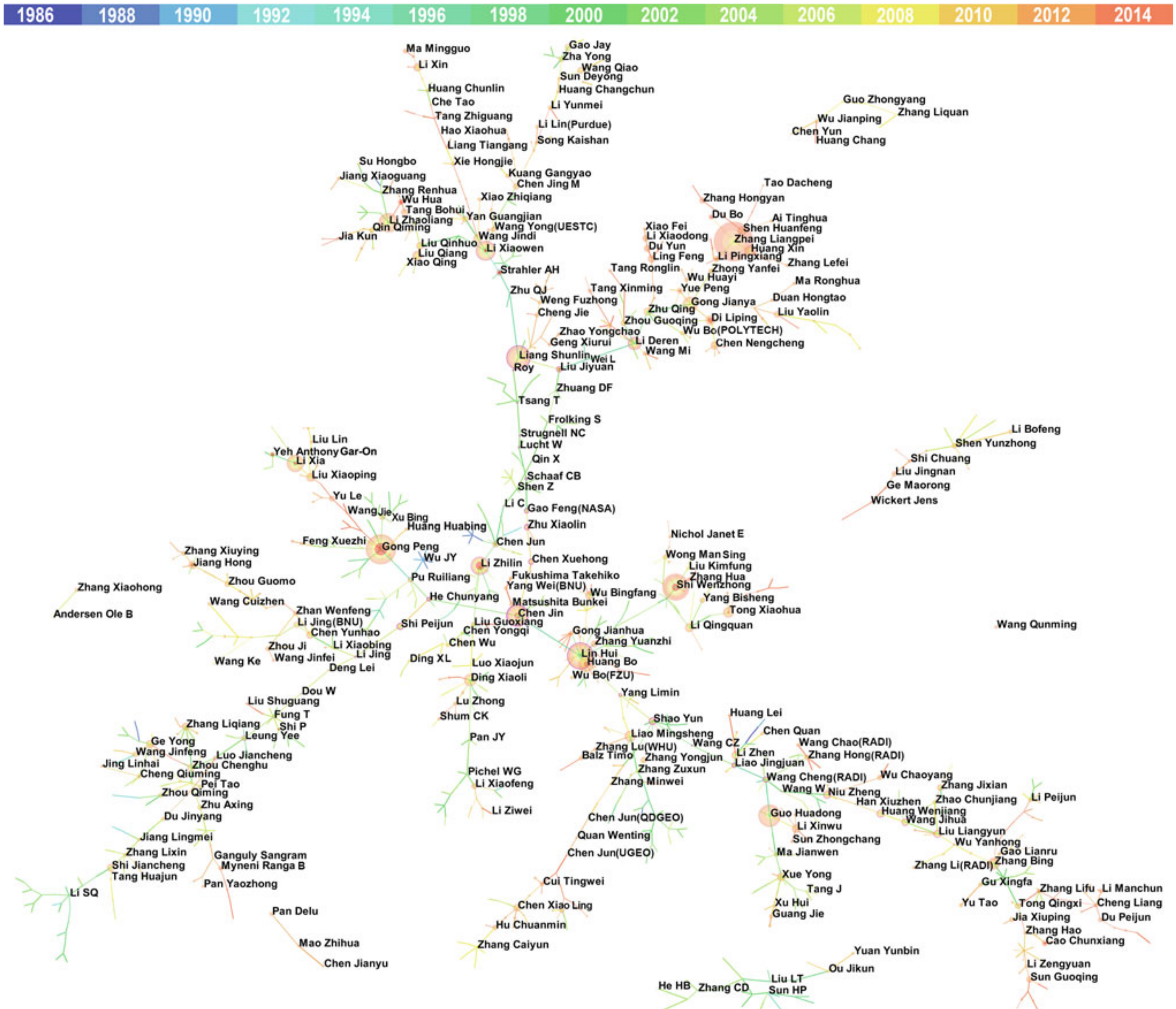


Fig. 6.29 Collaborative network of Chinese authors in SCI/SSCI mainstream journals of geographical information science during the period 1986–2015

behind the author name in the collaborative network of Chinese authors (in SCI/SSCI and CSCD journals, Figs. 6.29 and 6.30). Abbreviations and full names of institutions are listed in Appendix D.

Figure 6.28 shows the number of institutions applying for NSFC geographical information science funding and institutions (all Chinese authors) with publications in SCI/SSCI mainstream journals by 5-year interval from 1986 to 2015. The green line in this figure shows the proportion of institutions with publications to all institutions applying for NSFC funds. This indicates that both the number of institutions applying for NSFC funds and those with publications in SCI/SSCI mainstream journals increased at a similar rate. This demonstrates the growth of interest in fundamental research of Chinese institutions in geographical information science. However, the number of applying institutions was always larger than that of institutions with SCI/SSCI-indexed papers, which indicating that a part of institutions in geographical information science did not follow international research trends. The percentage of institutions with SCI/SSCI publications versus all institutions applying for NSFC funds in geographical information science was about 20 % before 2000. However, this exceeded 50 % in the past 5 years, indicating the improvement of fundamental research in geographical information science. Nevertheless, this is a strong technically based discipline, and therefore, the number of SCI/SSCI papers cannot be used as a unique index to measure research ability in this discipline. Moreover, many researchers hold the view that it is more important to improve data accuracy toward

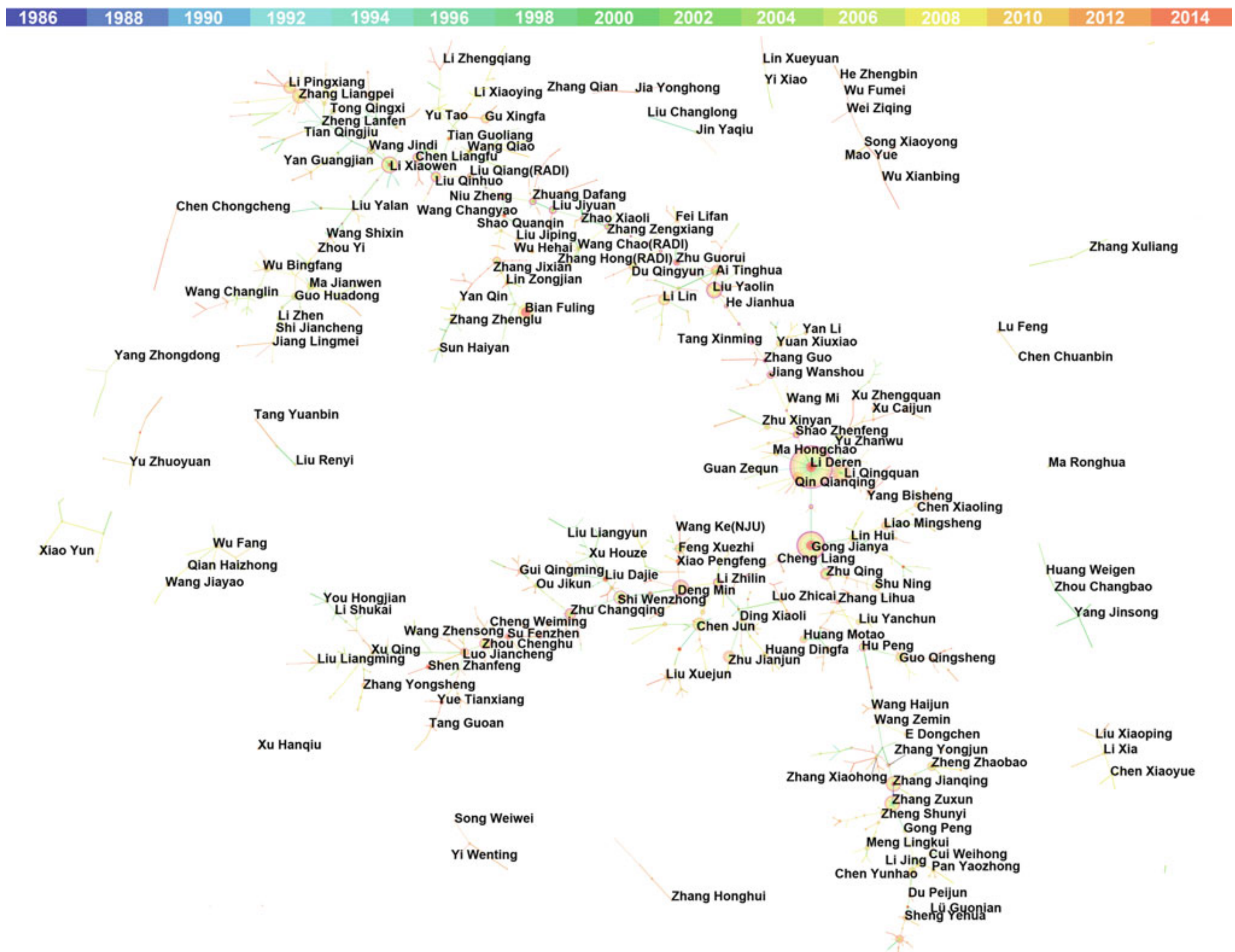


Fig. 6.30 Collaborative network of Chinese authors in CSCD journals of geographical information science during the period 1986–2015

producing high-quality products than to publish SCI/SSCI-indexed articles; as such, they may lack enough motivation to write and publish such papers.

Figures 6.29 and 6.30 show the collaborative network of Chinese researchers with publications in SCI/SSCI mainstream journals and Chinese CSCD journals in geographical information science during 1986–2015 (abbreviations of the institutions are listed in Appendix D). These indicate a clear geographical information science research network in China during the past 30 years. Preponderant research institutions and leading scholars were at the core nodes with high network centrality, shown as large nodes. However, because of the interchange and integration trend of remote sensing, geographical information system (GIS), surveying and cartography, various research institutions cooperated with each other and enhanced their research abilities in every direction of the discipline. Judging from characteristics of the collaborative network in SCI/SSCI and CSCD mainstream journals, teamwork and cooperation were very important. Research teams with long-term cooperation formed based on the core competence of academicians of the Chinese Academy of Science (CAS) and the Chinese Academy of Engineering (CAE), National Science Fund for Distinguished Young Scholar (DYS Fund), the Yangtze River Scholars and other rapidly developing young scholars. Competitive institutions, such as Wuhan University, Beijing Normal University, Institute of Remote Sensing and Digital Earth of CAS, and Institute of Geographic Sciences and Natural Resources Research of CAS. These all had core nodes of high network centrality, consistent with their traditional prominent positions in geographical information science. Most overseas Chinese scholars had core competences in the collaborative network and made important contributions to the rapid development of research capabilities in geographical information science, by being hired by the Thousand Talents Plan or cooperating with domestic professional scholars. The collaborative networks of authors in Figs. 6.29 and 6.30 are analysed in the following section.

Quantitative Remote Sensing

The collaborative network focused on quantitative remote sensing includes the following. (1) A network of **geometric optical remote sensing** research, with the nodel author of **Li Xiaowen** (BNU), focused on radiative transfer theory and quantitative inversion of land cover and forestry remote sensing. Important academic colleagues and contributors to this research were **Xue Yong** (London Met University), **Liu Jiyuan** (IGSNRR), **Wang Jindi**, **Yan Guangjian** (BNU), **Sun Guoqing** (University of Maryland), **Li Zengyuan** (IFRIT), and **Chen Liangfu**, **Liu Qinhuo** and **Liu Qiang** (RADI). Papers from this network were mainly published in journals such as *International Journal of Remote Sensing*, *Photogrammetric Engineering and Remote Sensing*, *Remote Sensing of Environment*, *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *IEEE Transactions on Geoscience and Remote Sensing*, and *IEEE Geoscience and Remote Sensing Letters*. (2) A network of **hyperspectral remote sensing**, with the nodel author of **Tong Qingxi** (RADI) and **Zhang Liangpei** (WHU), focused on image processing and quantification, soil moisture inversion, and ground feature recognition and classification. They worked with **Gu Xingfa**, **Zhang Lifu**, **Zhang Bing**, **Liu Liangyun**, **Zheng Lanfen** (RADI), **Li Pingxiang**, **Zhongyanfei**, **Huang Xin**, **Shen Huanfeng**, and **Zhang Hongyan** (WHU). Papers from this network were mainly published in *IEEE Transactions on Geoscience and Remote Sensing*, *Remote Sensing of Environment*, *International Journal of Remote Sensing*, *ISPRS Journal of Photogrammetry and Remote Sensing*, *Photogrammetric Engineering and Remote Sensing*, *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, and *IEEE Geoscience and Remote Sensing Letters*. (3) A network of **multiscale ground surface remote sensing** and environmental change formed around **Gong Peng** from the University of California, Berkeley (UC Berkeley) and/or Tsinghua University (TSINGHUA), and **Li Zhaoliang** (IGSNRR) and **Shi Jiancheng** from the University of California, Santa Barbara (UCSB) and RADI, respectively. This network focused on global surface environment change and public health, scale effects and transformation, land and water environmental remote sensing, quantitative inversion and data assimilation. Key authors were **Yu Le** (TSINGHUA), **Liu Qinhuo**, **Du Jinyang** (RADI), **Yan Guangjian**, **Jiang Lingmei** (BNU), **Tang Bohui** (IGSNRR), **Qin Qiming** (PKU). Papers were mainly in *IEEE Transactions on Geoscience and Remote Sensing*, *Remote Sensing of Environment*, *International Journal of Remote Sensing*, *ISPRS Journal of Photogrammetry and Remote Sensing*, *Photogrammetric Engineering and Remote Sensing*, *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *IEEE Geoscience and Remote Sensing Letters*, *International Journal of Applied Earth Observation and Geoinformation*, *Journal of Applied Remote Sensing*, *Canadian Journal of Remote Sensing*, and *Remote Sensing*.

Aerial and Space Photogrammetry

An academic collaborative network focused on aerial and space photogrammetry included the following. (1) A network centred around **Li Deren** (WHU) focused on **remote sensing image processing** and information extraction and aeronautic earth observation. This network included **Zhou Guoqing** (GUT), **Fang Tao** (SJTU), **Gong Jianya**, **Wu Huayi**, **Ma Hongchao**, **Wang Mi, Pan Jun** (WHU), and **Li Qingquan** (SZU). Papers were primarily published in *Canadian Journal of Remote Sensing*, *GIScience & Remote Sensing*, *IEEE Geoscience and Remote Sensing Letters*, *IEEE Transactions on Geoscience and Remote Sensing*, *International Journal of Geographical Information Science*, *ISPRS International Journal of Remote Sensing*, *Photogrammetric Engineering and Remote Sensing*, *Photogrammetric Record*, *International Journal of Digital Earth*, and *Journal of Applied Remote Sensing*. (2) A network centred around **Zhang Zuxun** (WHU) focused on **imaging models of remote sensors**, aerial and space sensor orientation, image matching, combined processing of multisource datasets, SAR/InSAR processing, and topographic surveying and mapping. Key scholars in this network included **Zhang Jianqing**, **Zhang Yongjun**, **Liao Mingsheng**, **Zhang Lu** and **Hu Xiangyun**(WHU), and **Zhang Li** (CASM). Academic papers from this network were mainly published in *IEEE Transactions on Geoscience and Remote Sensing*, *ISPRS Journal of Photogrammetry and Remote Sensing*, *Photogrammetric Engineering and Remote Sensing*, *GIScience & Remote Sensing*, *IEEE Geoscience and Remote Sensing Letters*, *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *Photogrammetric Record*, *Journal of Applied Remote Sensing*, and *Remote Sensing Letters*. (3) A network centred around **Guo Huadong** (RADI) concentrated on **topographic observation**, **geological hazards**, **multiscale remote sensing, and global environmental change**. Important authors in this network included **Xue Yong**, **Li Xinwu**, **Sun Zhongchang**, and **Ma Jianwen** (RADI). Papers from this network were largely published in *International Journal of Remote Sensing*, *International Journal of Digital Earth*, *Journal of Applied Remote Sensing*, *Canadian Journal of Remote Sensing*, *Photogrammetric Engineering and Remote Sensing*, *Computers & Geosciences*, *IEEE Journal of Selected Topics in Applied Earth Observations and Remote*

Sensing, *Remote Sensing*, *Remote Sensing of Environment*, and *Remote Sensing Letters.*

Remote Sensing Information Analysis and Application

An academic collaborative network focused on remote sensing information analysis and application included the following. (1) This network with the nodal author of **Liang Shunlin** (University of Maryland/BNU) and **Liu Jiyuan** (IGSNRR) focused on quantitative remote sensing, feature extraction and classification, ground surface parameter inversion, four dimensional assimilated data products, global change, land utilisation modelling, and land information systems. Key researchers were **Li Xiaowen**, **Xiao Zhiqiang**, **Cheng Jie** (BNU), **Li Ainong** (IMHE), **Zhang Zengxiang**, **Wang Changyao and Niu Zheng** (RADI), and **Zhuang Dafang** (IGSNRR). Papers were mainly published in *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *IEEE Geoscience and Remote Sensing Letters*, *IEEE Transactions on Geoscience and Remote Sensing*, *ISPRS Journal of Photogrammetry and Remote Sensing*, *Journal of Applied Remote Sensing*, *Photogrammetric Engineering and Remote Sensing*, *Remote Sensing of Environment*, *Remote Sensing*, *International Journal of Applied Earth Observation and Geoinformation*, and *International Journal of Remote Sensing.* (2) With the nodal author of **Liu Yaolin** (WHU), a network focused on land utilisation modelling, land information systems, digital landscape models, digital mapping models, digital maps, and map generalisation. Important authors were **Ai Tinghua**, **Wu Guofeng**, and **Shen Huanfeng** (WHU). Papers were mainly published in *International Journal of Remote Sensing*, *ISPRS Journal of Photogrammetry and Remote Sensing*, *Remote Sensing, GIScience & Remote Sensing*, *International Journal of Digital Earth*, and *International Journal of Applied Earth Observation and Geoinformation.* (3) A network with the nodal author of **Chen Jin** (BNU) spotlighted quality optimisation of remote sensing data, ecological remote sensing models, and intelligent extraction of land cover thematic information. Key researchers included **Gong Peng** (UC Berkeley and/or TSINGHUA), **Shi Peijun**, and **Yang Wei** (BNU). Papers were principally published in *IEEE Geoscience and Remote Sensing Letters*, *Remote Sensing Letters*, *Remote Sensing*, *Remote Sensing of Environment*, *IEEE Transactions on Geoscience and Remote Sensing*, *International Journal of Applied Earth Observation and Geoinformation*, *International Journal of Remote Sensing*, *ISPRS Journal of Photogrammetry and Remote Sensing*, *International Journal of Geographical Information Science*, *Photogrammetric Engineering and Remote Sensing*, *Canadian Journal of Remote Sensing*, *Computers & Geosciences,* and *Computers, Environment and Urban Systems*.

Integration of Remote Sensing and Geographical Information System

Another academic collaborative network focused on the integration of remote sensing and geographical information system embraced the following. (1) The network with the nodal author of **Gong Jianya** (WHU) concentrated on remote sensing image processing, web geographical information systems, intelligent sensors networks, spatial data standards, and spatial information services. Important researchers included **Di Liping** (George Mason University), **Lin Hui** (CUHK), **Wu Huayi**, **Chen Nengcheng**, and **Yue Peng** (WHU), and **Zhu Qing** (SWJTU). Papers were mainly published in *IEEE Transactions on Geoscience and Remote Sensing*, *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *Remote Sensing Letters*, *Canadian Journal of Remote Sensing*, *International Journal of Remote Sensing*, *ISPRS Journal of Photogrammetry and Remote Sensing*, *International Journal of Geographical Information Science*, *Photogrammetric Engineering and Remote Sensing*, *International Journal of Digital Earth*, and *International Journal of Applied Earth Observation and Geoinformation.* (2) With the nodal author of **Shi Wenzhong** (POLYU) and **Lin Hui** (CUHK), a network focused on spatial data mining, spatial and temporal information extraction, remote sensing image processing, 3D reconstruction, spatial data accuracy assessment, error models, and uncertainty. Authors related to **Shi Wenzhong** included **Li Qingquan** (SZU), **Tong Xiaohua**, **Liu Chun**, **Liu Dajie** (TONGJI), **Yang Bisheng**, and **Huang Bo** (WHU). Authors related to **Lin Hui** were **Zhang Yuanzhi** (CUHK) and **Gong Jianhua** (RADI). Papers were mainly published in *Remote Sensing of Environment*, *Remote Sensing*, *Computers & Geosciences*, *IEEE Transactions on Geoscience and Remote Sensing*, *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *Remote Sensing Letters*, *International Journal of Remote Sensing*, *ISPRS Journal of Photogrammetry and Remote Sensing*, *International Journal of Geographical Information Science*, *Photogrammetric Engineering and Remote Sensing*, *International Journal of Digital Earth*, and *International Journal of Applied Earth Observation and Geoinformation.* (3) With the nodal author of **Chen Jun** (NGCC) and **Li Zhilin** (POLYU/SWJTU), another network focused on topological relationships, digital terrain analysis, DEMs, map generalisation, spatial data mining, map cognition, and location sensor networks. Important researchers were **Jiang Jie** and **Zhao Renliang** (NGCC), **Zhao Xuesheng** (CUMTB), **Du Daosheng** (WHU), **Deng Min** (CSU), **Liu Guoxiang**, **Cen Minyi** (SWJTU), **Ding Xiaoli** (POLYU), **Zhou Qiming** (HKBU), and **Liu Wenbao** (SDUST). Papers were mainly published in *International Journal of Remote Sensing*, *ISPRS Journal* *of Photogrammetry and Remote Sensing*, *International Journal of Geographical Information Science*, *Computers & Geosciences*, *Photogrammetric Engineering and Remote Sensing*, *IEEE Transactions on Geoscience and Remote Sensing*, *IEEE Geoscience and Remote Sensing Letters*, *Photogrammetric Record*, and *Remote Sensing Letters*.

Geographical Information System and Geographical Analysis and Application of Remote Sensing Imagery

An academic collaborative network dedicated to geographical information system and geographical analysis and application of remote sensing imagery included the following. (1) The network, centred around **Zhou Chenghu** (IGSNRR), focused on geographical spatiotemporal data analysis, intelligent geographical calculation, map cognition, geographical information visualisation, geographical analysis and application of remote sensing imagery, and thematic geographical information systems. Major researchers in this network included **Pei Tao**, **Ma Ting**, **Su Fenzhen**, **Du Yunyan**, **Yang Xiaomei,** and **Cheng Weiming** (IGSNRR), **Luo Jiancheng** and **Shen Zhanfeng** (RADI), as well as **Ren Liucheng** (RADI/KJZH). Papers were mainly published in *Remote Sensing of Environment*, *Computers & Geosciences*, *IEEE Geoscience and Remote Sensing Letters*, *International Journal of Applied Earth Observation and Geoinformation*, *International Journal of Geographical Information Science*, *International Journal of Remote Sensing*, *Photogrammetric Engineering and Remote Sensing*, and *Remote Sensing Letters*. (2) With the nodal author of **Li Xia** (SYSU), one network focused on geographical information science, cellular automation, remote sensing image geographical application, geographical simulation, spatial intelligence, and optimal decisions. Important researchers included **Yeh Anthony Gar-On** (HKU), and **Liu Xiaoping** and **Liu Lin** (SYSU). Articles mainly appeared in *IEEE Transactions on Geoscience and Remote Sensing*, *International Journal of Geographical Information Science*, *Computers & Geosciences*, *Computers Environment and Urban Systems*, *Remote Sensing of Environment*, *GIScience & Remote Sensing*, *International Journal of Remote Sensing*, and *Photogrammetric Engineering and Remote Sensing*.

Error Theory and GPS Application

Concentrating on studies of error theory and GPS application, another network, with the nodal author of **Liu Jingnan** (WHU) and **Shen Yunzhong** (TONGJI) focused on error propagation theory, reference station systems, precise orbit determination of satellites, wide area differential GNSS networks and the Beidou satellite navigation system. Important researchers were **Shi Chuang** (WHU), **Ge Maorong** (German Research Center for Geosciences), and **Li Bofeng** (TONGJI). Papers were mainly published in *Journal of Geodesy*, *Earth Science Informatics*, *GPS Solutions*, *IEEE Transactions on Geoscience and Remote Sensing*, *IEEE Geoscience and Remote Sensing Letters*, *International Journal of Remote Sensing*, *International Journal of Geographical Information Science*, and *Journal of Surveying Engineering (ASCE)*. This research group was mainly supported by Geophysics and partly by Geographical Sciences within NSFC.

Geographical Information System and Cartography

The academic collaborative network of geographical information system and cartography solely within Chinese CSCD journals (Fig. 6.30) included the following. (1) The network centred around **Lü Guonian** (NJNU) and investigated remote sensing image simulation, geometric algebra, spatiotemporal data models, spatial data visualisation, and map generalisation. Important researchers included **Sheng Yehua** and **Yuan Linwang** (NJNU). (2) Centred around **Zhu Changqing** (NJNU), a network focused on geographical information services, water marking of digital maps, geographical security of spatial data, digital terrain analysis, and digital raster maps.

According to statistics of the top 200 Chinese authors who published papers in the SCI/SSCI mainstream journals in geographical information science during 1985–2015, a total of 3766 papers were published. The number of publications in *International Journal of Remote Sensing* and *IEEE Transactions on Geoscience and Remote Sensing* was 1299, accounting for 34 % of the total, far ahead of the rest. Fifty-two percent of the publications (1964 papers) were published in international mainstream journals such as *IEEE Geoscience and Remote Sensing Letters*, *Remote Sensing of Environment*, *Photogrammetric Engineering and Remote Sensing*, *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *International Journal of Geographical Information Science*, *Journal of Applied Remote Sensing*, *ISPRS Journal of Photogrammetry and Remote Sensing*, *Remote Sensing*, *International Journal of Applied Earth Observation and Geoinformation*, and *Computers & Geosciences*. The remaining 14 % (503) of the papers appeared in *International Journal of Digital Earth*, *Canadian Journal of Remote Sensing*, *Journal of Geodesy*, *Remote Sensing Letters*, *GPS Solutions*, and *Photogrammetric Record*.

In the collaborative network of Chinese authors publishing in SCI/SSCI mainstream journals and CSCD journals, 81 % of authors of both those journals were supported by NSFC in geographical information science. Thirty authors rank in the top 100 authors with the most publications in both SCI/SSCI and CSCD journals. They were granted 375 projects funded by NSFC. The sum of funds

Table 6.2 Top 5 institutions with NSFC funding for geographical information science during the period 1986–2015

1986–1990			1991–1995			1996–2000		
Institutions	Number of PIs	Funding (10,000 yuan)	Institutions	Number of PIs	Funding (10,000 yuan)	Institutions	Number of PIs	Funding (10,000 yuan)
Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences	9	48.2	Wuhan University	13	184	Wuhan University	19	469
Peking University	6	32.7	Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences	12	168	Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences	11	246
Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences	5	31	Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences	8	73.5	Fudan University	1	100
Nanjing University	3	24.5	Peking University	5	46	Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences	7	97
Wuhan University	7	24.3	The First Institute of Oceanography, State Oceanic Administration	1	24	National Geomatics Center of China	1	93
Total of top 5	30	160.7	Total of top 5	39	495.5	Total of top 5	39	1,005
Total of non top 5	32	144.1	Total of non top 5	38	290.7	Total of non top 5	51	763.5
Total of geographical information science	62	304.8	Total of geographical information science	77	786.2	Total of geographical information science	90	1,768.5
Total of geography	294	1,362.3	Total of geography	374	3,840.6	Total of geography	422	9,984.9
2001–2005			2006–2010			2011–2015		
Institutions	Number of PIs	Funding (10,000 yuan)	Institutions	Number of PIs	Funding (10,000 yuan)	Institutions	Number of PIs	Funding (10,000 yuan)
Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences	24	992.3	Wuhan University	80	3,965	Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences	204	11,387.2
Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences	26	794.5	Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences	84	2,777.1	Wuhan University	130	9,438.5
Wuhan University	28	763.2	Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences	46	1,798.5	Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences	52	6,450.3
Beijing Normal University	15	477.3	Beijing Normal University	36	1,621.2	Beijing Normal University	46	4,100.6
National Geomatics Center of China	6	332.5	Nanjing Normal University	23	991	Nanjing Normal University	41	3,609.8
Total of top 5	99	3,359.8	Total of top 5	269	11,152.8	Total of top 5	473	34,986.3
Total of non top 5	121	3,684.7	Total of non top 5	398	11,174.5	Total of non top 5	957	47,156.6
Total of geographical information science	220	7,044.5	Total of geographical information science	667	22,327.3	Total of geographical information science	1,430	82,142.9
Total of geography	890	33,800.6	Total of geography	2,197	90,823.6	Total of geography	4,821	304,971.3

supporting the Key Programme (KP), Major Programme (MP) and Major Research Plan (MRP) makes up 33.3 % of the total funds, and this proportion for the General Programme (GP) is 32.3 %. Of the top 100 authors with the most publications in SCI/SSCI journals, 34 were supported by the Young Scientists Fund (YSF), and 10 by the National Science Fund for Distinguished Young Scholar (DYS Fund). Three groups lead by **Gong Jianya**, **Zhou Chenghu** and **Shi Peijun** were supported by the Science Fund for Creative Research Groups (CRG Fund). Of the top 100 authors with the most publications in CSCD journals, 70 were granted different types of projects funded by NSFC, and 68.9 % of the total funds were granted as the General Programme (GP). The Key Programme (KP), Major Programme (MP) and Major Research Plan (MRP) granted to them account for 22.3 %. These statistics indicate that talent-originated and research projects with large amounts of funding from NSFC have made important contributions to the output of international-level results. General Programme (GP) has had an even greater effect on Chinese research achievements.

Table 6.2 shows the name, number of PIs and funds for the top five institutions supported by NSFC every 5 years during 1986–2015. The number of PIs shows the number of people supported in 5-year increments; each person was counted only once in the five years. During these 30 years, 10 institutions entered the top five ranks of the funding amount from NSFC, of which six were colleges and universities and others were scientific research institutions. Wuhan University, the Institute of Remote Sensing and Digital Earth of CAS, and the Institute of Geographic Sciences and Natural Resources Research of CAS, maintained their top five ranks, demonstrating their competitive advantages in the study of geographical information science.

Publication per capita of the institutions in Fig. 6.31 was calculated by dividing the total papers supported by NSFC in the 37 SCI/SSCI mainstream journals over 5 years by the total number of people supported. The funding proportion is the sum of funds received from NSFC in these listed institutions to total NSFC geographical information science funds in each five year bin. This shows that the proportion decreased generally but only 10 % in 2011–2015 as compared to that of 1986–1990. However, per capita publication in geographical information science increased overall, especially in the last 5 years. The per capita publication of the top five institutions increased to 3.6 in 2011–2015, double that of 2006–2010. Meanwhile, per capita publications of the other institutions were 2.1, also double that of 2006–2010. Considering each period, per capita publication of the top five institutions exceeded that of the remainder, indicating that the international trend of those institutions was more significant to the development of overall research capabilities in geographical information science in China.

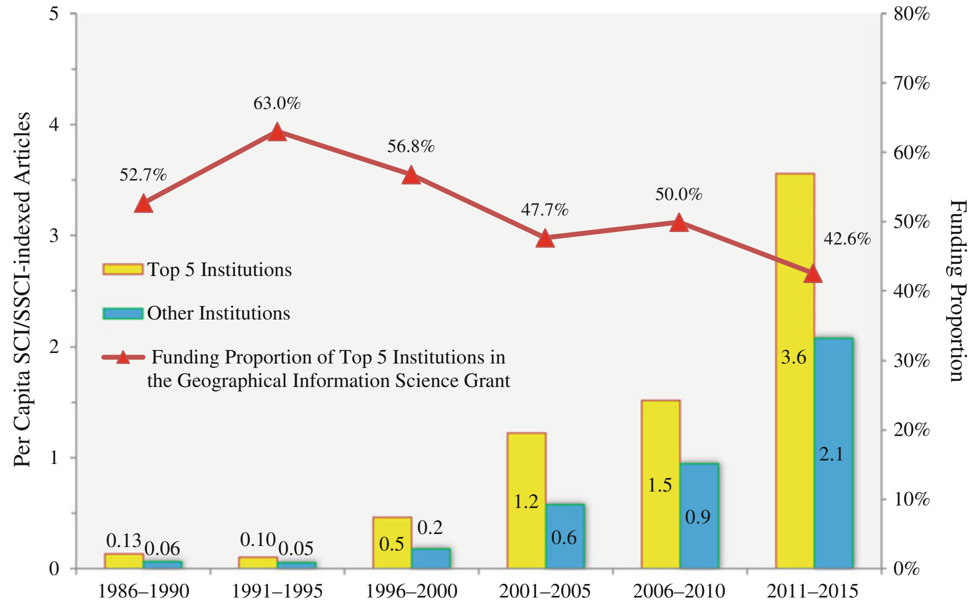


Fig. 6.31 Funding proportion of top 5 NSFC-funded institutions and their per capita SCI/SSCI-indexed articles in geographical information science during the period 1986–2015. *Note* Co-authors from different institutions were counted separately

Along with the increase of per capita publications, the number of highly cited papers published in SCI/SSCI journals of geographical information science grew rapidly. Figure 6.32 shows that the proportion of NSFC funded papers to the top 50 highly cited papers by Chinese authors increased significantly, e.g., from 30 % in 2000 to 82 % in 2014. The proportion of articles by the top 10 institutions to the top 50 highly cited articles fluctuated slightly across

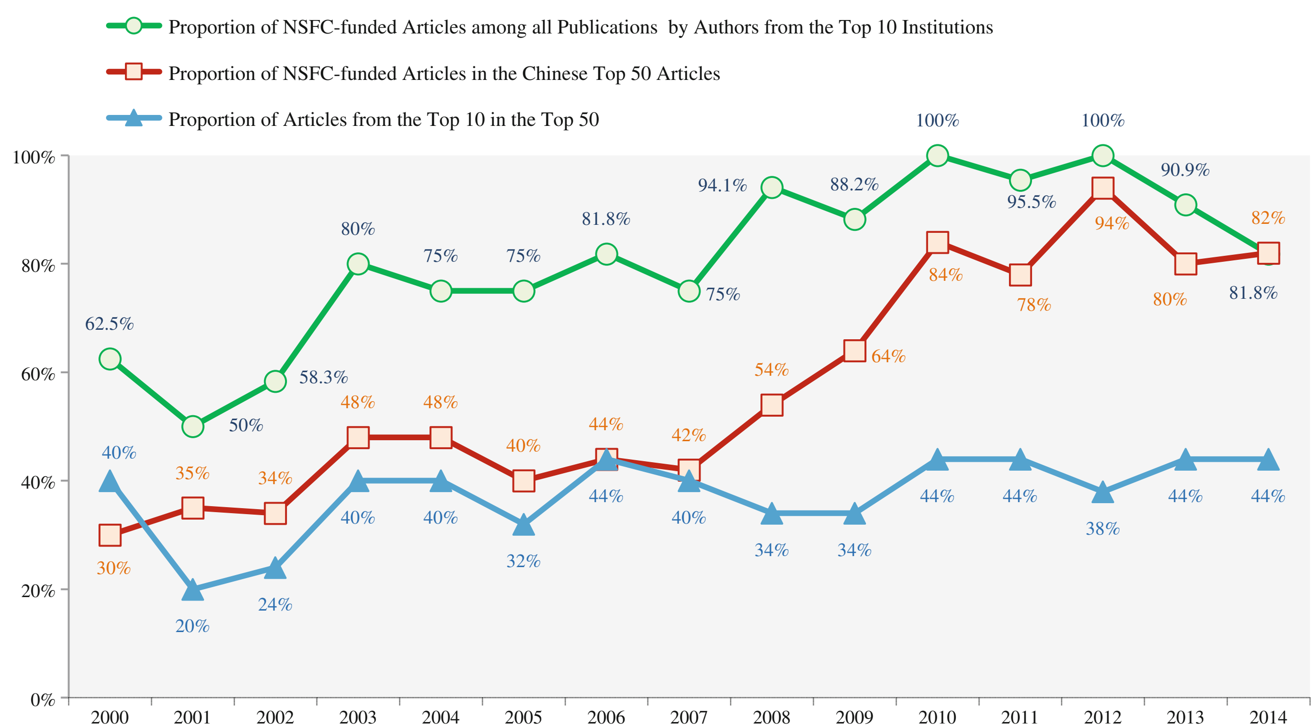


Fig. 6.32 Proportion of NSFC-funded SCI/SSCI-indexed articles in Chinese top 50 citation in geographical information science during the period 2000–2014. *Note* The Top 10 institutions refer to those with top 10 NSFC's annual funding for geographical information science during the period 2000–2014, including Wuhan University, Institute of Remote Sensing and Digital Earth of CAS, Institute of Geographic Sciences and Natural Resources Research of CAS, Beijing Normal University, Nanjing Normal University, Cold and Arid Regions Environmental and Engineering Research Institute of CAS, Information Engineering University of PLA, Peking University, Nanjing University, Sun Yat-sen University, University of Electronic Science and Technology of China, Tongji University, Chinese Academy of Surveying and Mapping, and National Geomatics Center of China

Table 6.3 Analysis of top 1000 highly cited SCI/SSCI articles in geographical information science during 2000–2014

Periods	% of articles by American authors	% of articles by Chinese authors	% of articles with NSFC funding by Chinese authors	% of articles from Top 10 institutions with NSFC funding to articles by Chinese authors	% of articles from Top 10 institutions with NSFC funding to articles funded by NSFC
2000–2004	49.4	1.3	69.2	53.8	71.4
2005–2009	41.3	3.0	50.0	56.7	88.2
2010–2014	30.1	9.5	82.1	56.8	98.1
2000–2014	49.4	1.3	69.2	69.2	77.8

Note The Top 10 institutions refer to those with top 10 NSFC's annual funding for geographical information science during the period 2000–2014, including Wuhan University, Institute of Remote Sensing and Digital Earth of CAS, Institute of Geographic Sciences and Natural Resources Research of CAS, Beijing Normal University, Nanjing Normal University, Cold and Arid Regions Environmental and Engineering Research Institute of CAS, Information Engineering University of PLA, Peking University, Nanjing University, Sun Yat-sen University, University of Electronic Science and Technology of China, Tongji University, Chinese Academy of Surveying and Mapping, and National Geomatics Center of China

those years, with a minimum of 20 % and maximum of 44 % (in 2014). The proportion of publications from the top 10 institutions with most NSFC funds generally increased, from 62.5 % in 2000 to 81.8 % in 2014, with an average of about 95 % during the last 5 years. In conclusion, the top 10 institutions had produced 37 % of influential SCI/SSCI-indexed articles in China, NSFC projects had been a dominant role in the publication of these influential papers, and about 60 % of all the top 50 highly cited papers in SCI/SSCI journals were funded by NSFC.

The number of highly cited papers in China was accelerating, but the total number of highly cited papers had remained limited. Among the international top 1000 highly cited SCI/SSCI articles, Chinese authors contributed 13 in 2000–2004 and 95 in 2010–2014. The top 1000 highly cited papers in various periods (Table 6.3) indicate that the U.S. authors contributed 494 papers (49.4 %) in 2000–2014, while Chinese authors contributed only 13 (1.3 %). In the past 15 years, the proportion of papers by the U.S. authors decreased by 19.3 %, while that by Chinese authors increased by 8.2 %. Considering papers published by Chinese authors, those funded by NSFC continued to increase, with the proportion increasing from 69.2 % in 2000–2004 to 82.1 % in 2010–2014. The proportion of papers published by the top 10 institutions rose from 53.8 % in 2000–2004 to 56.8 % in 2010–2014. Among the papers funded by NSFC, the proportion of those published by the top 10 institutions increased from 71.4 % in 2000–2004 to 98.1 % in 2010–2014. The above data indicate that high-level research achievements increased rapidly over the past 5 years. More than 80 % of these results were supported by NSFC. More than 90 % of the highly cited papers supported by NSFC

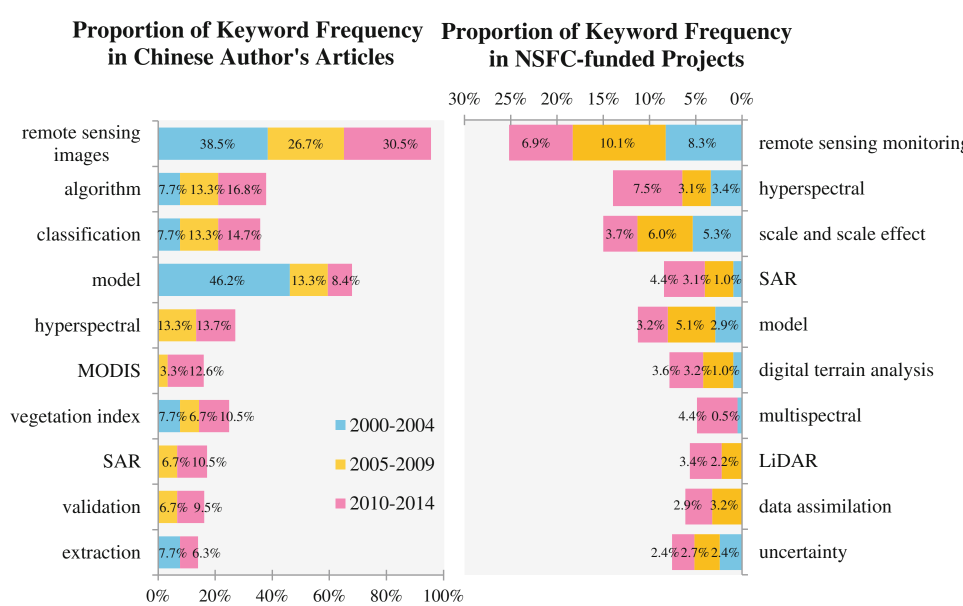


Fig. 6.33 Comparative diagram of prominent keywords in the articles by Chinese authors among the top 1000 highly cited SCI/SSCI-indexed articles with those in NSFC-funded projects in geographical information science during the period 2000–2014

were from the top 10 institutions funded by NSFC geographical information science projects, and highly cited papers from those institutions accounted for about 56 % of all highly cited papers published by Chinese authors.

To further analyse the relationship between the research topics of the highly cited Chinese publications and funding by NSFC, we sorted the keywords of the top 1000 highly cited Chinese papers in SCI/SSCI journals and calculated the proportion of the top 10 keywords versus the total number of papers with Chinese authors (referred to as the "paper-based top 10 keywords"). We also sorted keywords of research projects funded by NSFC and calculated the proportion of the top 10 keywords versus total number of projects supported by NSFC (referred to as "the project-based top 10 keywords"). Comparing the paper-based and project-based keywords in Fig. 6.33, we found that 40 % of those keywords were identical, including *remote sensing images monitoring*, *hyperspectral*, *SAR*, and *model*. This indicates that NSFC projects laid the foundation for influential research achievements in Chinese geographical information science. Considering the overall pattern of the paper-based keywords, almost all were remote sensing-related topics, including *classification*, *extraction*, *vegetation index*, *model and algorithm*, and *validation*. This was mainly caused by the fact that publications in remote sensing involve more than geographical information system. This also indicates that issues studied by remote sensing were more general than geographical information system, leading to more citations. Based on the top 10 keywords in projects, topics of both remote sensing and geographical information system were included, such as *digital terrain analysis and uncertainty*. This shows that remote sensing and geographical information system in NSFC grants maintained the same development pace, and there was cutting-edge research in both, aimed at addressing different issues. From the change of keyword proportion in various periods, the paper-based keywords, i.e., *MODIS, remote sensing images, SAR* and *validation*, increased greatly over the past 5 years. Meanwhile, the project-based keywords, i.e., *remote sensing monitoring* and *SAR*, did not show the same trend. *MODIS* and *validation* were not in the list of the project-based keywords, indicating that the number of projects funded by NSFC remained inadequate. However, research into data validation was still mainly supported by NSFC, although it also was insufficiently funded. Almost all authors of highly cited per paper publications in this subject were supported by NFSC, such as **Li Zhaoliang** from Institute of Geographic Sciences and Natural Resources Research of CAS, **Xiao Zhiqiang** from Beijing Normal University, **Yang Guijun** from Beijing Academy of Agriculture and Forestry Sciences and **Wang Zifeng** from Beijing Normal University. *SAR* and *hyperspectral* remote sensing, which occupied a certain proportion of top 10 keywords of projects during 2000–2004, were not on the list of the top 10 keywords of papers until 2005–2009, which shows that NSFC-funded projects were important for accumulating research achievements and forming mainstream directions. Thus, we infer that certain topics in the top 10 keywords of projects, such as *uncertainty* analysis, *LiDAR*, *multispectral* remote sensing, and *digital terrain analysis*, may see very influential achievements in the next 5–10 years.

6.4 Summary

During the past 30 years, motivated by the requirements of global change research and the development of the earth observation technology, geographical information science has developed in the fields of quantitative inversion of land surface parameters, remote sensing image processing, positioning, land-surface change monitoring, and digital terrain models. Integration between remote sensing and geographical information system (GIS) has strengthened. The integrated application and supporting role of geographical information science continue to increase. Fundamental research into remote sensing has gradually extended from mechanisms, models and inversion methods to that into geographical application of remote sensing products. Extraction of remote sensing information has developed from single-sensor to collaborative application of multiple sensors, from mono-temporal data to data sequences, and from single-source applications to involvement with geographical models. Geographical information system (GIS) updates rapidly with research topics ever changing. In general, research of geographical information science has demonstrated major features of interaction and extension of research field boundaries, greater integration of different fields, and emphasis on applications. Trends of geographical information science in China has well matched their global import, with specific emphases on high-resolution image acquisition, high-accuracy positioning, and land-surface information extraction, as a result of meeting the needs of high-resolution digital mapping and remote sensing land-surface monitoring of change caused by territorial resources, agriculture, the water environment and geological hazards. The number of publications had increased rapidly in both the SCI/SSCI mainstream journals and the CSCD journals during 1986–2015. Sixty percent of the SCI/SSCI-indexed articles and 68 % of the CSCD-indexed articles in the mainstream journals were published during the last decade. SCI/SSCI-indexed articles published by Chinese authors reached 21.6 % in the last 5 years. The per capita publication figure reached 2.9, 3.2 times that of 10 years ago. Average citation of the top 100 highly cited papers in SCI/SSCI mainstream journals show that China has risen to rank third while the United State has maintained at the top. Nevertheless, the average citations of all papers published by Chinese authors remain less than the average of the top 20 countries (regions), only larger than Brazil and Chinese Taiwan. This indicates that the study of geographical information science in China has room for improvement.

NSFC had a major role in Chinese geographical information science research. In the past 30 years, of the top 100 authors with the most publications in both the SCI/SSCI and CSCD journals, 81 % were supported by NSFC. There are 30 researchers among the top 100 authors with the most publications in both the SCI/SSCI and CSCD journals. Their works were supported by 375 projects from NSFC. Seventy-seven percent of papers by Chinese authors in the SCI/SSCI journal and CSCD journals, were funded by NSFC during the last decade. Among the top 50 highly cited papers published by Chinese authors in SCI/SSCI journals, 83.6 % were supported by NSFC during 2010–2014, 2.1 times that of 2000–2004. The proportion of papers by Chinese authors in the international top 1000 highly cited SCI/SSCI-indexed papers in 2010–2014 was 8.2 % higher than that in 2000–2004. Of the international top 1000 highly cited papers, 82.1 % of those by Chinese authors were funded by NSFC. Institutions with greater funding from NSFC have become more competitive in the study of geographical information science. Examples are the Institute of Remote Sensing and Digital Earth of CAS, Wuhan University, Institute of Geographic Sciences and Natural Resources Research of CAS, Beijing Normal University, and Nanjing Normal University. In propelling international development of fundamental research in geographical information science, promoting the development of earth system science, and providing service to acquisition and analysis of earth observation datasets, these institutions and NSFC projects have played a prominent role.

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Environmental Geography

7

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Abstract

Environmental geography is an emerging science using geography's perspective and knowledge to study environmental issues. This chapter analyses the keywords of publications on 66 SCI/SSCI indexed mainstream journals and 3 CSCD core journals in environmental geography from 1986 to 2015. Environmental geography has focused on the source apportionment, surface processes, health effect and risk assessment of pollution, and established distinguishing characteristics in large scale distribution, long-term transportation and multiphase transformation of pollutants in the past 30 years. China's environmental geography research has been following closely with international hot topics while complying with China's real situation and has gained substantial achievements in many fields, such as soil pollution and remediation; the accumulation and biological effects of pollutants in water body; the mechanism, effects and simulation of air pollution, and the environmental behaviors and multi-phase transportation of organic pollutants. Since 2008 NSFC has set up environmental geography as a branch of geography, including environmental pollution, regional environmental quality and regional sustainable development in an effort to balance the development of environmental geography in both microscopic and macroscopic scales. Chinese researchers have contributed 18 % of the SCI/SSCI-indexed articles globally in the recent 5 years. In the past 10 years, 65 % of the SCI/SSCI-indexed articles and CSCD-indexed articles by Chinese authors have been sponsored by NSFC. Moreover, 56 and 68 % of the top 100 Chinese authors with the most publications in the SCI/SSCI and CSCD journals are supported by NSFC in the past 30 years, respectively.

Keywords

Environmental geography • Research topics in environmental geography • NSFC-funded projects for environmental geography • Chinese scholars and institutions of environmental geography

No field is more central to the study of human occupation of the Earth than geography. Modern environmental science, with its focus on land use, pollution, and environmental impact is firmly rooted in the geographic tradition. In fact, without geography's contributions, environmental science would not exist as we know it today (William and John 2005). To address an increasing number of environmental issues, geographers have established an emerging geographical sub-discipline—environmental geography. Environmental geography examines environmental issues from a geographical point of view, using geographical knowledge and terms. Contributions made by geography to the environmental sciences include integrated approaches that account for space, dimension, and distribution, and the concept that landscapes arise from interactions between man and nature. Extensive research into increasingly complex environmental issues in environmental geography has led to a cross-disciplinary approach using research methods from fields including

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environmental chemistry, atmospheric chemistry, geochemistry, biology, and environmental engineering. Environmental geography has existed for only about 30 years combined with the changing nature of environmental issues, means that disciplinary theories and methods are still developing. To advance the establishment of the sub-discipline of environmental geography within geographical sciences in China, in 2008 the NSFC set up four application codes, namely Fate, Process and Effects of Environmental Pollutants, Quality and Security of Regional Environment, Natural Resource Management, and Regional Sustainable Development. The analysis below is based on 66 SCI/SSCI-indexed mainstream journals for environmental sciences (environmental geography), including 21 comprehensive journals related to environmental geography and 45 professional journals for environmental geography.

Figure 7.1 shows the number of papers published in 66 SCI/SSCI-indexed mainstream journals in environmental geography and the contributions made by Chinese authors over the last 30 years. There were 261,072 environmental geography papers published in the SCI/SSCI-indexed journals (some papers published before 1990 were not included in the Web of Science database), of which 58.3 % were published in the last 10 years. Of those papers, 25,905 (9.9 %) were published by Chinese authors, of which 88.1 % were published in the last 10 years. The number of papers published by Chinese authors accounted for 15 % of papers worldwide over the last 10 years, and 18 % in the last 5 years. Of the papers published by Chinese authors, 15,730 were funded by NSFC, of which 95.1 % were published in the last 10 years. Over the last 30 years, the proportion of NSFC-funded papers compared with the number of papers published by Chinese authors was 60.7 %. Before 2001–2005, the proportion of papers published by Chinese authors funded by NSFC was less than 28 %, but this proportion increased to 50.2 % from 2006 to 2010 and reached 73.6 % in the last 5 years.

Figure 7.2 shows the total number of papers published in the three Chinese core environmental geography journals and the proportion of NSFC-funded papers over the last 30 years. The three Chinese core environmental geography journals were *Environmental Science*, *Acta Scientiae Circumstantiae*, and *China Environmental Science.* There were 11,885 Chinese papers in environmental geography in total, of which 58 % were published in the last 10 years. NSFC-funded papers accounted for 6429, of which 69.8 % were published in the last 10 years. The proportion of papers funded by NSFC over the last 30 years was 54.1 %. Before 1996–2000, the proportion was less than 43 %, but reaching 69.4 % in the period from 2001 to 2005, 70.1 % from 2006 to 2010 and 60.8 % in the last 5 years. Examining the number of times each paper in environmental geography cited in CSCD journals, papers funded by NSFC over the last 30 years were cited more than non-NSFC-funded papers in every 5-year period. Overall, each paper was cited 23 times on average, 6.6 times higher than the papers not funded by NSFC. From 1996 to 2000, each paper funded by NSFC was cited 46.8 times on average, 17.6 times higher than those not funded by NSFC during the corresponding period. These results demonstrate that NSFC geographical sciences has played an irreplaceable role in the development of environmental science in China, especially environmental

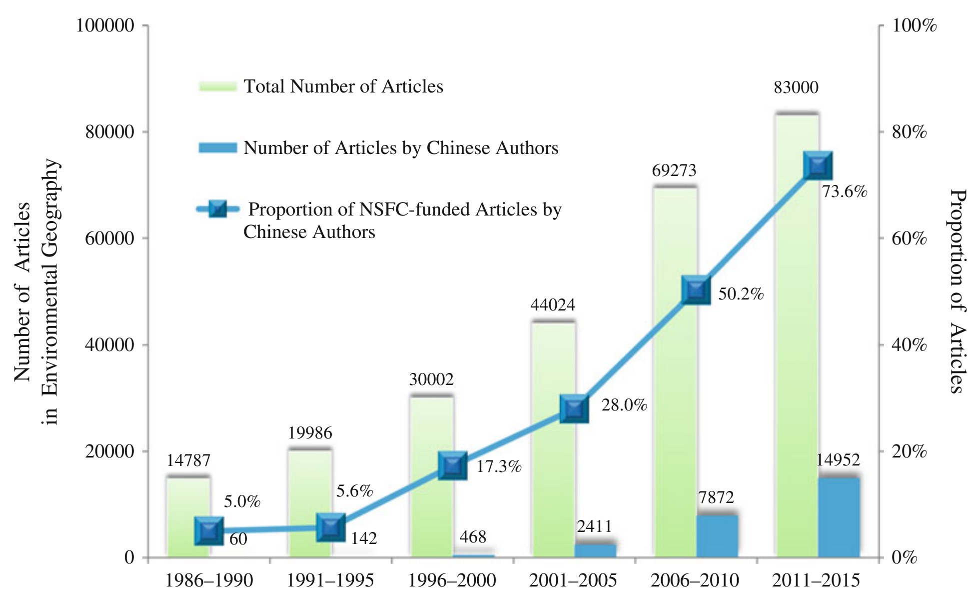
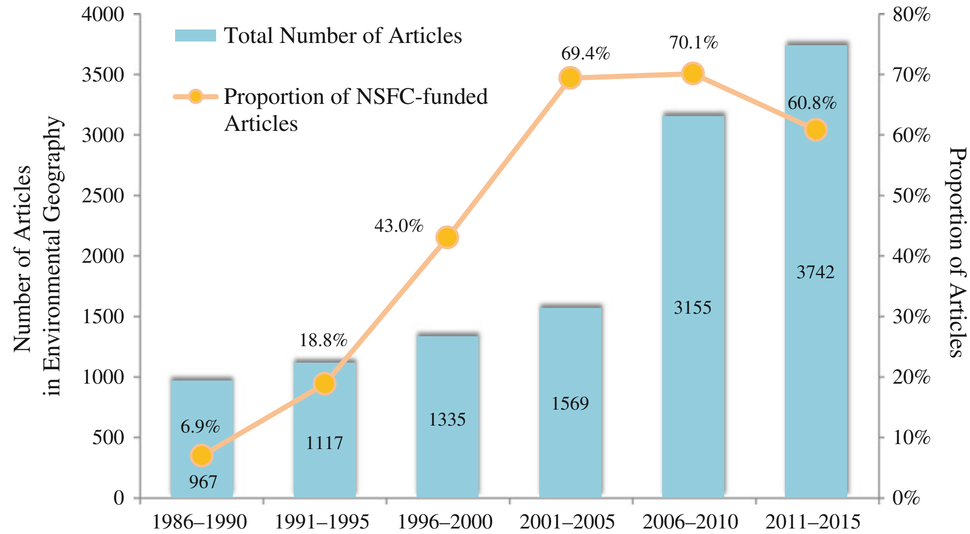


Fig. 7.1 Number of SCI/SSCI-indexed articles and proportion of NSFC-funded articles by Chinese authors in environmental geography during the period 1986–2015

Fig. 7.2 Number of CSCD-indexed articles and proportion of NSFC-funded articles in environmental geography during the period 1986–2015



geography. The number of citations per paper in environmental geography in CSCD journals was not only higher than for papers in human geography (21.1) and geographical information science (17.8), but was equivalent to those for physical geography (23.4). Moreover, the average citation of the NSFC-funded papers was 1.7 times that of non-NSFC funded papers, indicating that geographical sciences has relatively strong research base in terms of launching environmental science research.

Table 7.1 shows the number of citations per paper of the top 100 most-cited environmental geography papers in the SCI/SSCI mainstream journals of each country (region), representing the highest level of research findings for environmental geography for each country. Over the last 30 years, China's ranking among the top 20 countries based on citations per paper had increased from a ranking of 18th from 1986 to 1995, to 14th from 1996 to 2000, 5th from 2001 to 2005, and in the top three after 2006. The number of citations per paper of the top 100 papers from 2006 to 2010 in China was close to the United Kingdom (UK); over the past 5 years, it was twice that of the UK. However, a definite gap still existed compared with the United States of America (USA), the top ranked country. If the citation count per paper of all papers published was taken into account, the number of citations per Chinese paper was 11.6, 26.7, and 20.2 in the periods of 1986–1990, 1996–2000, and 2006–2010, respectively. Comparing the average level of the top 20 countries (regions) with the number of citations per paper for the corresponding period (respectively 22.4, 29.7, and 19), China has reached the average value recently, with its ranking increasing from 19th to 14th to 5th, indicating that the research achievements of China's environmental geographers have been recognised by international peers.

7.1 General Characteristics of the Research Topics Over the Past 30 Years

This section analyses the co-occurrence relationship between the popular keywords, and illustrates the overall characteristics of environmental geography research in the last 30 years, centring on the popular keywords in the SCI/SSCI mainstream journals and in CSCD core journals from 1986 to 2015.

Examination of the cluster analysis of popular keywords from papers in the SCI/SSCI mainstream journals for environmental geography in 1986–2015 (Fig. 7.3) indicates that environmental geography showed research hotspots in soil pollution processes and remediation, accumulation of drainage basin water pollutants and their biological effects, and atmospheric pollution processes, effects, and simulations. The details are as follows. (1) In terms of **soil pollution**, the influence of *sewage sludge* utilization on soil, pollutant *adsorption*, *desorption*, and *degradation* in soil and other translocation and transformation processes, *nitrification* and *denitrification* of forest soil and other soil nitrogen cyclic processes, *phytoremediation*, and *bioremediation* of contaminated soil were all important research topics. (2) In terms of **water pollution**, *bioconcentrations* of pollutants *in fish* (*rain trout*), pollutant *toxicology*, *toxicity* and *bioaccumulation*, water *nitrogen* and *phosphorus* cycles and *eutrophication* mechanisms, *porous media* and *ground water*

Table 7.1 Top 20 countries (regions) of average cites per paper for highly cited SCI/SSCI-indexed articles in environmental geography during the period 1986–2015

Rank	Countries (Regions)	1986–1990	1991–1995	1996–2000	2001–2005	2006–2010	2011–2015
1	USA	330.8	487.6	478.6	468.8	294.3	96.8
2	China	11.6	26.4	78.8	164.8	143.0	87.2
3	Canada	137.5	165.3	187.1	188.5	121.7	43.0
4	UK	93.5	155.5	237.5	199.6	145.5	43.0
5	Spain	25.5	80.6	107.8	113.4	107.3	38.1
6	South Korea	3.6	21.1	38.2	96.3	68.0	36.8
7	Australia	48.5	53.8	89.1	114.3	90.4	34.2
8	Switzerland	53.4	85.0	118.3	146.5	121.7	32.6
9	Germany	85.1	86.6	155.0	156.2	118.0	32.2
10	Italy	49.8	68.8	101.1	115.7	83.1	30.5
11	France	50.7	82.1	112.1	109.1	88.9	29.1
12	Japan	69.6	82.5	79.7	117.6	77.3	27.3
13	Netherlands	12.6	98.4	143.5	129.6	80.6	26.7
14	India	27.5	31.7	62.3	114.3	107.0	25.7
15	Denmark	37.3	60.9	118.8	93.2	74.6	22.9
16	Sweden	102.6	100.8	102.8	176.7	89.4	21.5
17	Belgium	23.1	43.2	67.5	105.0	72.9	21.2
18	Taiwan, China	11.3	23.7	59.2	88.2	76.5	21.1
19	Norway	41.4	54.5	67.7	82.5	63.3	17.9
20	Brazil	23.7	30.0	46.4	59.6	51.8	14.8

Note Top 20 countries (regions) were selected based on average cites of the top 100 highly cited articles in each county (region) out of 25 countries (regions) with the largest number of articles from the 66 SCI/SSCI mainstream journals in environmental geography; that is, total cites of the 100 articles were divided by 100, with listing by descending order for the period 2011–2015 in the last column

pollutant *migration*, (*endocrine disrupting compounds*) *EDCs* and *antibiotics* in *wastewater* and health risks from other new organic pollutants were all important research areas. (3) In terms of ***air pollution***, influence of *ozone* (O_3) and SO_2 on *forest* and *lake* ecological systems, *emission* of *aerosols* and *particles*, *long-range transport*, *source apportionment*, *exposure* of *Hg* and *risk assessment* were important topics of research. (4) In terms of **multimedia environmental behaviour of pollutants**, *degradation*, *photodegradation* and *microbial degradation* of *polycyclic aromatic hydrocarbons* (*PAHs*), *polychlorinated biphenyls* (*PCBs*), *pesticides*, *dioxins*, *organochlorine pesticides* (*OCPs*) and other organic pollutants in the environment, colloid surface pollutant forms, adsorption and transformation, exposure processes, and the effect of pollutants on living organisms were all important research foci. In addition, *nanoparticles*, *dioxins*, *China*, *brominated flame-retardants* (*BFRs*), *climate change*, and other keywords reflected the attention paid by environmental geographers to research on emerging pollutants and topical scientific issues. *Modelling* was one of the main research methods applied by environmental geographers.

Analysis of the occurrence frequency and cluster characteristics of high-frequency keywords in papers in CSCD journals since 1986 (Fig. 7.4) shows that environmental geography had focused on soil pollution, bioaccumulation and bioremediation research, drainage basin water pollution, eutrophication and biological effects research, air pollution, pollutant source apportionment, greenhouse gas emissions, multimedia pollutant adsorption, degradation, and other environmental behaviour research. (1) In terms of **soil contamination**, **biological accumulation** and **remediation**, *soil pollution concentration*, *spatial and temporal pattern*, *transport and transformation*, *plant enrichment* and *accumulation*, *speciation* and plant availability, and ecological and health risks were all important topics of research. *Cd*, *Pb*, *Hg*, *As*, Zn, *Cu* and other *heavy metals*, and *PAHs* were the pollutants of most concern, and screening and

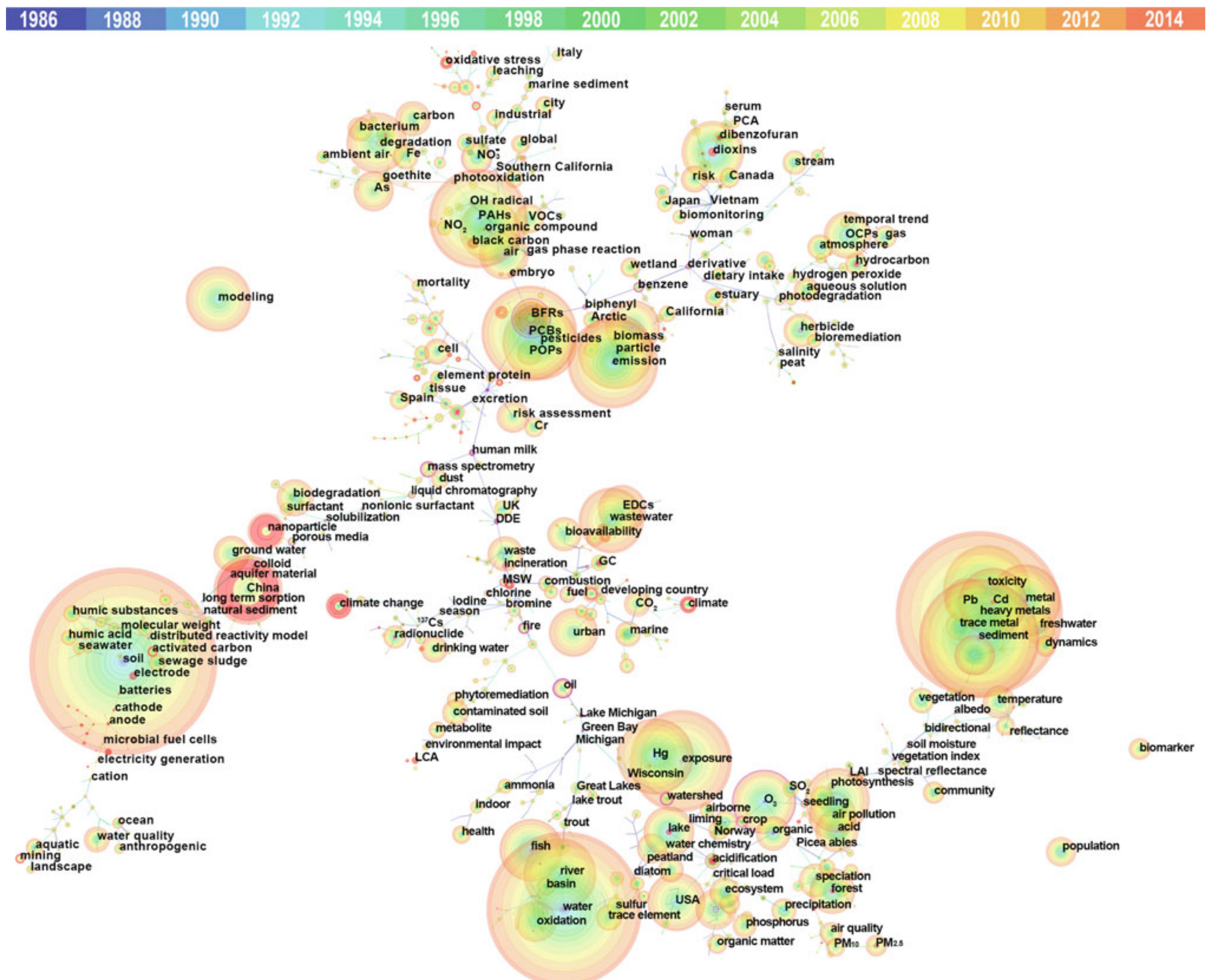


Fig. 7.3 Co-occurrence network of keywords in SCI/SSCI mainstream journals of environmental geography during the period 1986–2015

rhizosphere *degradation* of *over-accumulated plant*s become the research hotspots for *soil remediation*. (2) In terms of **water pollution**, *eutrophication* and biological effects, *speciation*, *desorption*, *transport and transformation*, *toxicity* and *bioavailability* of pollutants in sediments formed the main content of research. Watershed-scale *non-point source pollution* load estimation research was carried out extensively, based on *land use* type using *remote sensing*, *geographical information system* (*GIS*), and other geographical methods. The *nitrogen* and *phosphorus transport and transformation* in water body and eutrophication processes were widely studied, and *Taihu Lake* was the most researched water body in China. (3) In terms of **air pollution**, pollution *source apportionment* and *greenhouse gas emission*, emission of SO_2, *acid precipitation/acid rain*, and the influence of acid precipitation on vegetation and water were major focus of research in the early period. Atmospheric particulates (PM_{10}, $PM_{2.5}$), *aerosol* pollution, and *source apportionment* has become the main focus of research in the most recent period, and *Beijing* and *Shanghai* were the two cities on which research was most focused. Driven by research on global change, *wetland* and *paddy soil greenhouse gas emission* research appeared recently, becoming a popular topic in environmental geography research. (4) In terms of **multiphase environmental behaviour of pollutants**, *adsorption* behaviour of pollutants was the first and foremost area of research, followed by research on *biodegradation* and *degradation*, and reaction *dynamics*.

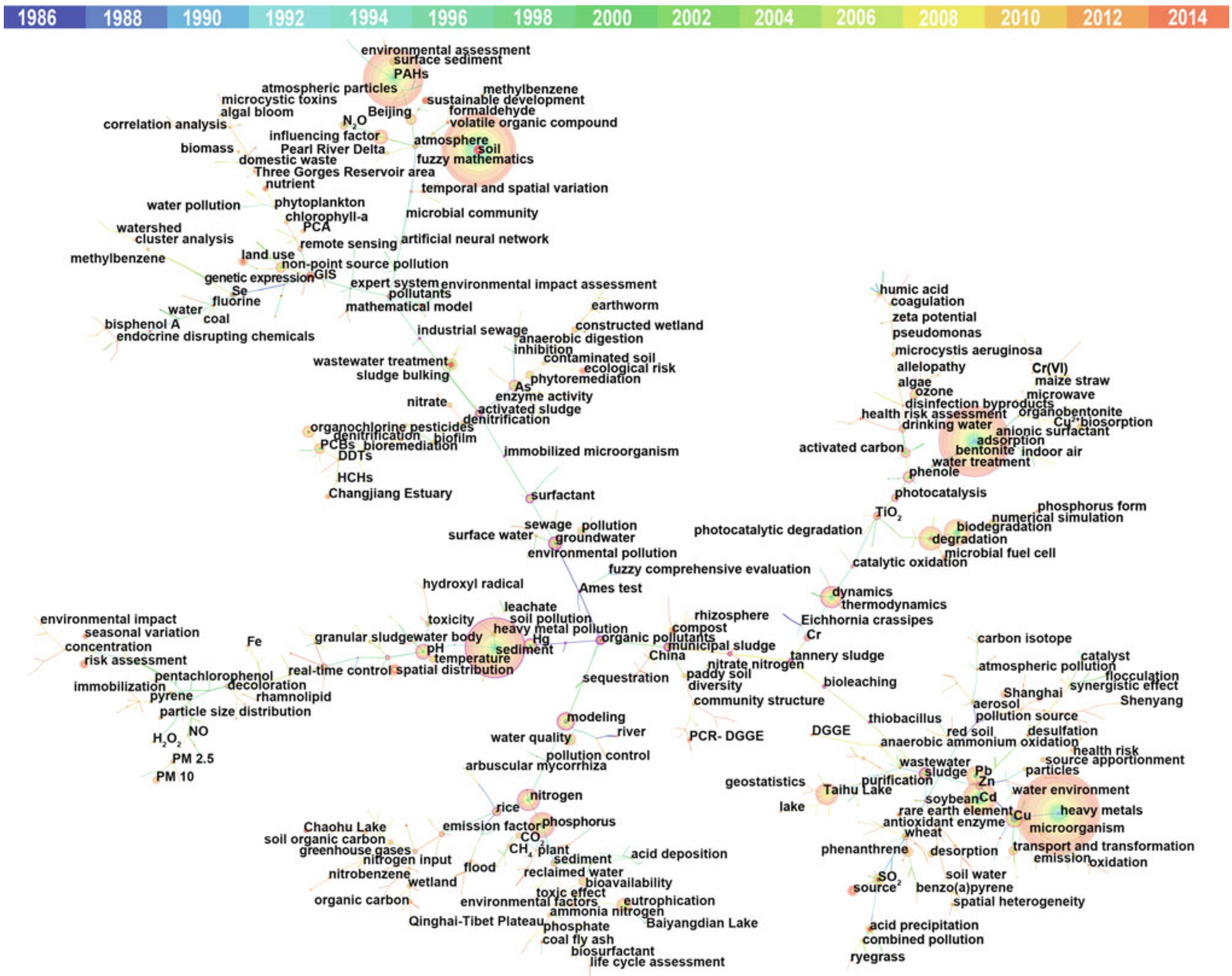


Fig. 7.4 Co-occurrence network of keywords in CSCD journals of environmental geography during the period 1986–2015

7.2 Change of Research Topics in Various Periods

The period from 1986 to 2015 was divided into 5-year periods (or 10-year periods) to analyse the characteristics of international research topics reflected by SCI/SSCI-indexed mainstream journal papers and the characteristics of Chinese research topics reflected by CSCD core journal papers. The differences between Chinese and foreign popular research topics were analysed through comparison of keywords for popular research topics between Chinese authors and authors from other countries (regions) in SCI/SSCI-indexed mainstream journal papers.

7.2.1 Period of 1986–1995

Figure 7.5 shows the evolution of research topics in SCI/SSCI-indexed mainstream journal papers for environmental geography from 1986 to 1995. There was a range of research topics within environmental geography for this period. The two main nodes were *biological samples* and *biotransformation*, indicating that environmental geography research in this period was centred on the biological or ecological effects of pollutants. Research using *organics, organic compound*, SO_2, *dioxins*, and *determination* as the keywords was important. The main research topics of this period were as follows. (1) Air pollution and its ecological

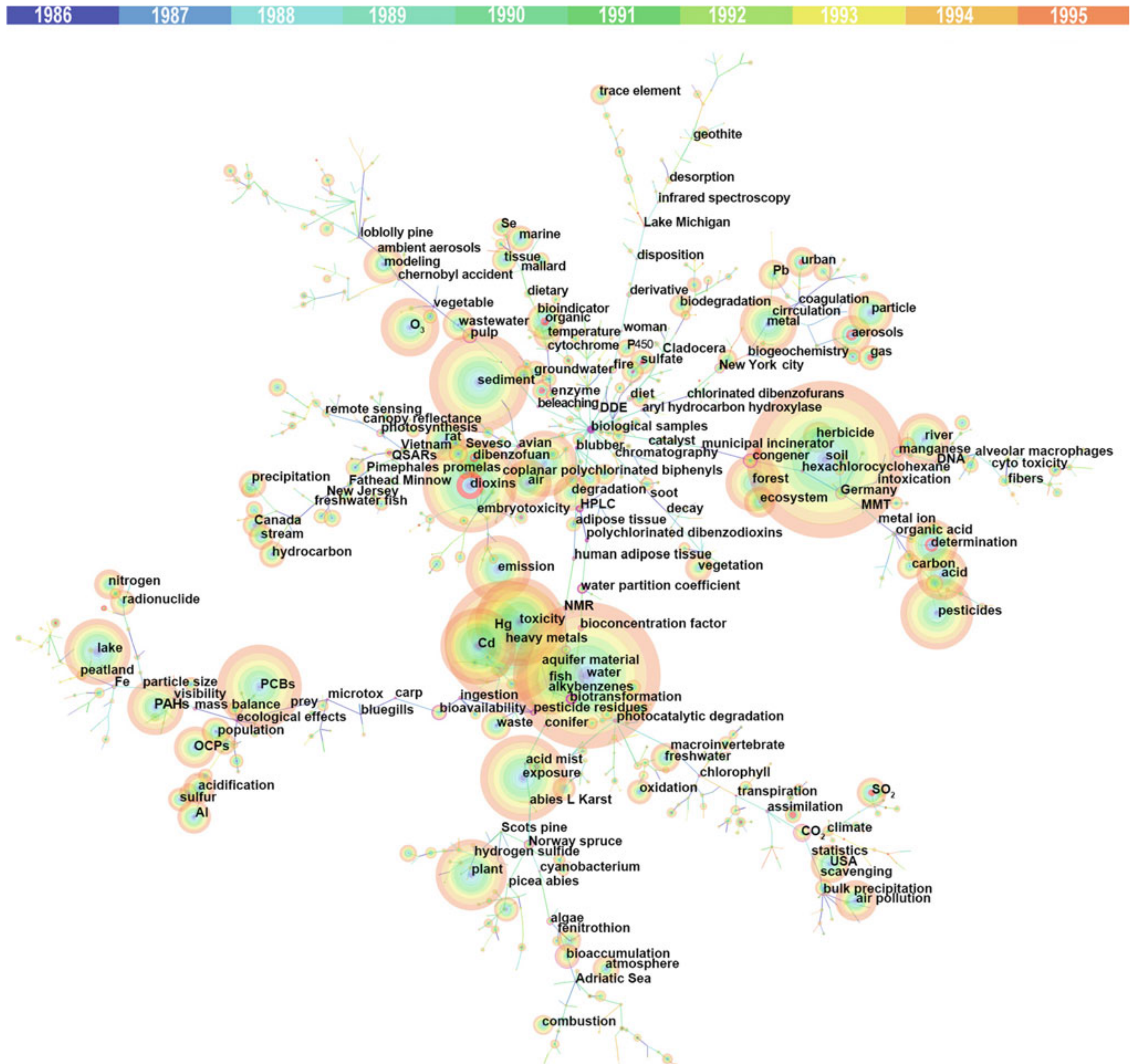


Fig. 7.5 Co-occurrence network of keywords in SCI/SSCI mainstream journals of environmental geography during the period 1986–1995

effect. The keywords of this research topic were relatively variable, including the influence of *ozone* (O_3), SO_2, and *acid precipitation* on *lakes* and vegetation (*vegetable*, *plant*, *spruce*), atmospheric *emission*, *exposure*, and *health risks of aerosols*, *particles*, *dioxins*, *Pb*, and other pollutants. (2) Soil pesticide pollution and carbon cycle. The keyword *soil* was directly connected with *herbicide*, linked together with the keywords *pesticide*, *forest*, *ecosystem*, and *carbon*, indicating that pollutants and the carbon cycle of soil and forest ecosystem, pesticides, and herbicide, were popular topics in environmental geography research over this period. (3) Water environment pollution, biotransformation and enrichment, toxicity, and ecological effect were high frequency keywords. Pollutants such as *heavy metals*, *cadmium* (*Cd*), *mercury* (*Hg*), *PCBs*, *PAHs*, *OCPs*, *nitrogen*, and *phosphorus*, were linked via the keywords of higher centrality such as *ecological effect*, *bioavailability*, *biotransformation*, and *biological samples*.

Figure 7.6 shows the research hotspots as reflected in Chinese core journal papers in environmental geography

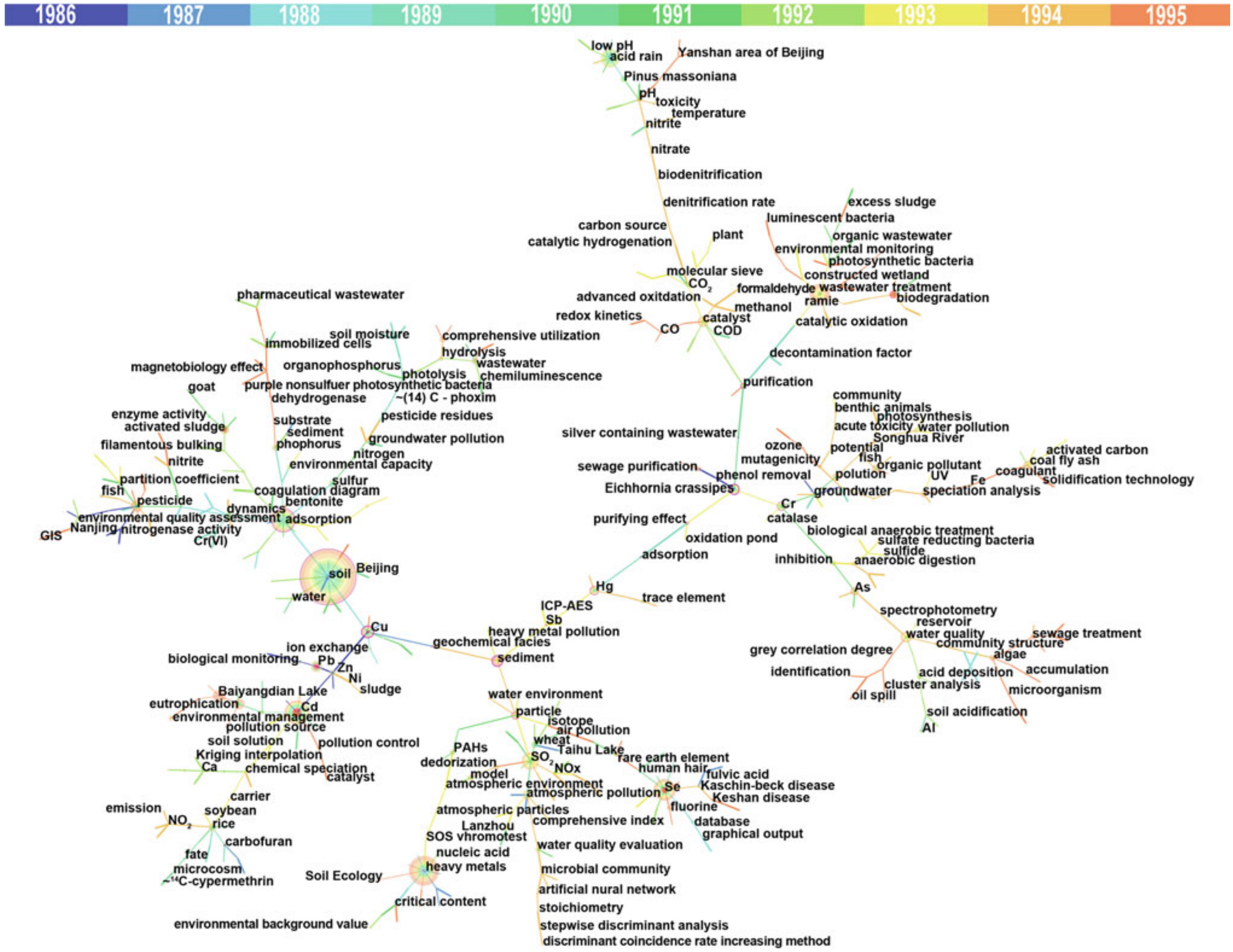


Fig. 7.6 Co-occurrence network of keywords in CSCD journals of environmental geography during the period 1986–1995

from 1986 to 1995. During this period, there were few SCI/SSCI-indexed mainstream journal papers published by Chinese mainland scholars. Therefore, Chinese core journal papers tended to reflect the research topics of China's environmental geographers. It can be seen that Chinese environmental geographers examined the environmental behaviour and spatial processes of heavy metals, pesticides and other pollutants in soil, water bodies, the atmosphere, and biological systems, and launched environmental evaluation, planning and management by applying a comprehensive approach to geography and spatial and/or quantitative methods. After 10 years of development, the fundamental pattern of environmental geography research was formed. (1) **Soil heavy metal and pesticide pollution**, including *heavy metals*–contaminated *soil* caused by *sludge* in agricultural use, *wastewater* irrigation, and *wastewater treatment*, as well as *pesticide residues* in the soil caused by pesticide application. (2) **Water pollution** studies were focused on the *Songhua River* and *Lake Taihu*, and the main topics of research were the *accumulation* and *toxicity* effects of *Hg*, *Cr*, *As* and organic pollutants in groundwater, *water*/*sediment* interface, benthos, and *fish* bodies. (3) **Air pollution** research examined topics such as the influence of SO_2 in air on *wheat* and *acid precipitation/acid rain* on *Pinus massoniana*, and the common geographical study areas were *Lanzhou*, *Beijing*, and *Yanshan*. Compared with the topics of soil and water bodies, research on the atmosphere was relatively weak.

Figure 7.7 shows the comparison between Chinese and foreign research popular keywords in SCI/SSCI-indexed

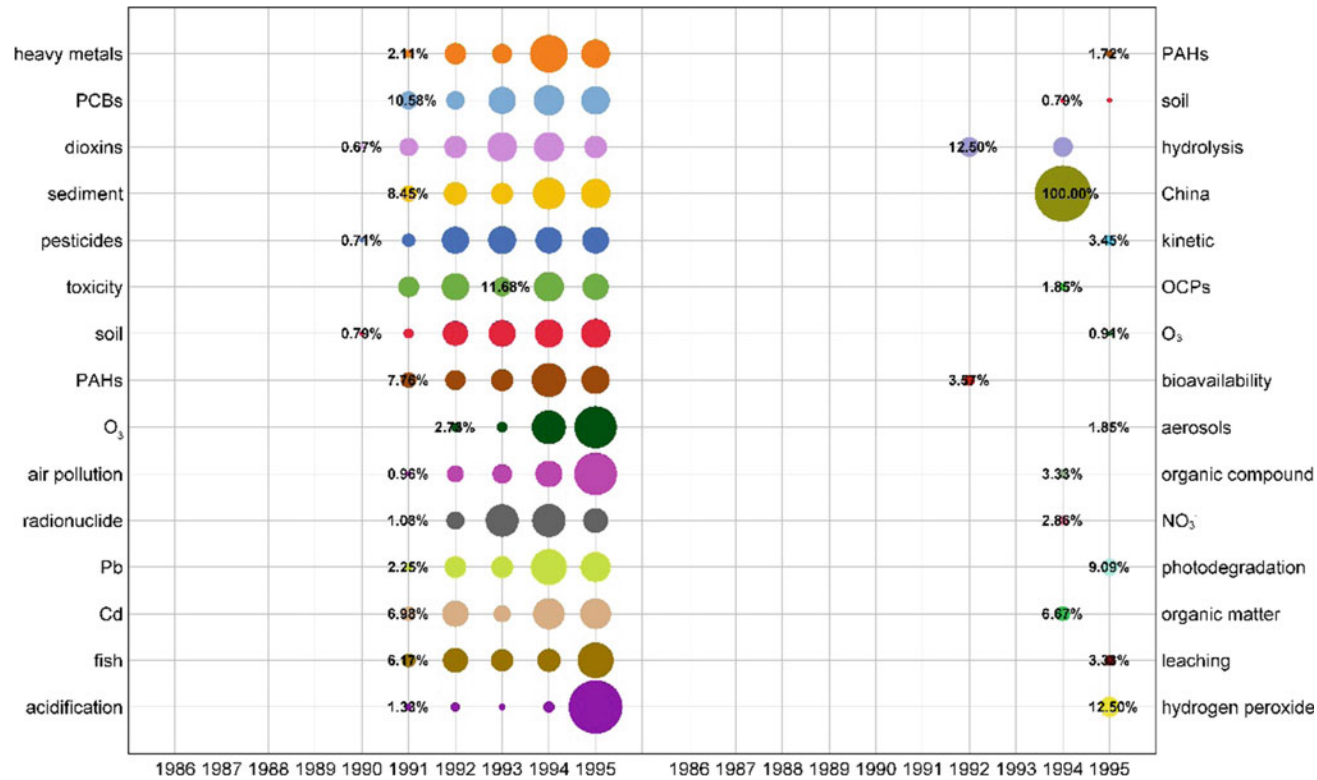


Fig. 7.7 Comparative diagram of prominent keywords by Chinese authors and others in SCI/SSCI mainstream journals of environmental geography during the period 1986–1995. *Note* Right panel shows keywords used by Chinese authors and left panel shows those used by the authors from other countries (regions). Size of circles represents the proportion of keyword frequency in a single year to its total frequency in 1986–1995. Each keyword has the same colour. Keywords are listed in descending order according to their total frequencies in the above period

mainstream journal papers for environmental geography from 1986 to 1995. The total number of journals and papers collected was larger than that for other sub-disciplines of Geographical Sciences, and the total keyword frequency was high. However, the top 15 keywords used by Chinese authors tended to appear only once. Over this same period, among the papers not published by Chinese authors the frequency of the top 15 keywords were all more than 75 times. The main research topics were as follows: pollution by *heavy metals* such as *cadmium* (Cd) and *lead* (*Pb*) was of most concern during this period, followed by *dioxins, PCBs* and *pesticides*, and *air pollution* such as *ozone* (*O_3*) and *acidification*, while there were relatively fewer research papers on *PAHs* and *radionuclide*. Research on the phases (*sediment*, *soil*) of the earth surface was far greater than that on the atmosphere. In terms of scientific problems, toxicology research (*toxicity*, *fish*) received relatively more attention. Viewed from the speed of growth of keywords over these 10 years, *acidification*, *O_3* and *air pollution* increased most rapidly. Among the papers published by Chinese authors during this period, the most frequently used keywords ranked in the top 15 were *soil*, *O_3*, and *PAHs*, identical to those from authors of other parts of the world. Other keywords by Chinese authors ranked in the top 15 reflected research on the chemical processes and biological effectiveness of organic pollution in soil, such as *hydrolysis* and *leaching*, organics (*OCPs*, *organic compounds*, *organic matters*) and *bioavailability*. Chemical processes of atmospheric pollution such as *aerosols, photodegradation* and *NO_3^-* were also popular research topics for Chinese authors during this period.

7.2.2 Period of 1996–2000

Figure 7.8 shows the evolution of research topics reflected by SCI/SSCI-indexed mainstream journal papers for environmental geography from 1996 to 2000. Geographic elements such as soil and water became the core of environmental geography research, and the pollutants concerned were heavy metals, polychlorinated biphenyl (PCBs), polycyclic aromatic hydrocarbon (PAHs), and mercury.

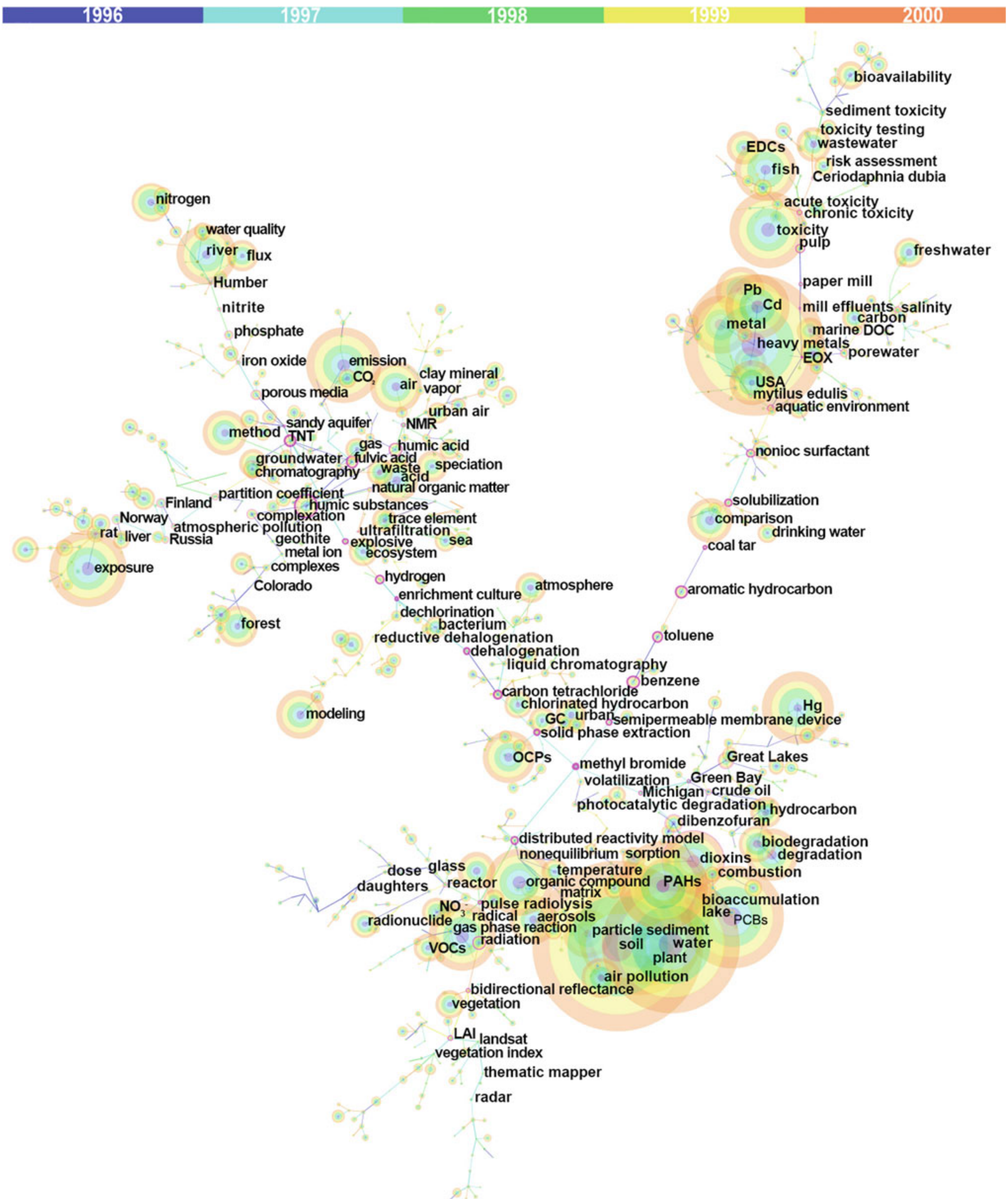


Fig. 7.8 Co-occurrence network of keywords in SCI/SSCI mainstream journals of environmental geography during the period 1996–2000

Emission, sedimentation, transport, adsorption, accumulation, degradation, and other environmental biogeochemical processes became popular research topics, and the nodes linking keyword networks were mostly pollutant names, pollutant environmental behaviour or mineral names. Compared with 1986–1995, environmental media was closely related to pollutants during this period, research topics in environmental geography were relatively definite and concentrated, and the research system of environmental geography was further perfected. Research topics or hotspots were as follows. (1) *Bioaccumulation*, *degradation*, and *biodegradation* of organic pollutants (*PAHs*, *PCBs*, *pesticides*, *dioxins*, *herbicides*) in soil, plant, water, lake, and sediment systems. (2) Heavy metal pollution covered two cluster groups, with the important keywords being *heavy metals, mercury* (*Hg*), *cadmium* (*Cd*), *metal*, *lead* (*Pb*), *USA*, *trace metal*, *health*, *China, Great Lakes*, and *chromium* (*Cr*), indicating that heavy metals were the main environmental geography research objects of this period. Research was extensively carried out in the US, China, and the Great Lakes region. (3) Pollutant bioavailability, toxicity and risk assessment keywords such as *toxicity*, *fish*, *EDCs*, *bioavailability*, and *risk assessment* indicated that the toxicity of EDCs on fish had become a major topic for environmental geography research. (4) Air pollution and ecological effect keywords were relatively variable, but *emission* of air pollutants (*particles*, *aerosols*, *ozone*, O_3, *VOCs*, *organic compounds*), influence of *acid precipitation* on *vegetation* and *forest*, and *exposure* of air pollutants to living organisms and crowds were the key points of research. (5) River and groundwater nitrogen and phosphorus pollution and flux covered two cluster groups, and keywords such as *river*, *nitrogen*, *flux*, *ecosystem*, *groundwater*, and *water quality*, indicated that attention was paid to research on the translocation and transformation (*nitrification*, *denitrification*) processes of nitrogen in surface water and groundwater and flux.

Figure 7.9 shows the research hotspots reflected by Chinese core journal papers in environmental geography from 1996 to 2000. Sustainable development and environmental impact assessment had become the features of environmental geography research in China. Remote sensing technology and geographical spatial data were applied more extensively in environmental geography research, and climatic change was a focus for environmental geographers. (1) Research into pollutant environmental behaviour, and eutrophication in water comprised the *adsorption, desorption*, *transport and transformation*, *occurrence*, *bioavailability*, etc., as well as the *degradation* process of *organic pollutant*s. *Yangtze River* water quality change and eutrophication of *Taihu Lake* had become the main research areas. (2) Soil pollution comprises the *adsorption* process of pollutants in *agricultural soil* and *forest soil* and *modelling*. (3) Environmental management and pollutant surface process simulation comprised *sustainable development*, *environmental impact assessment*, *strategic environmental assessment* and *environmental planning*. *Mathematical models*, *GIS*, *expert systems*, *artificial neural network*, *numerical simulation*, *regional analysis*, and other keywords related to simulation emerged as popular topics. The keyword *GIS* first appeared on a Chinese environmental geography paper in 1997, and has been used extensively in environmental geography as a method and tool. (4) Air pollution and climate change research focused on air pollution was relatively minor during this period. Research was mainly focused on *aerosols*, SO_2, and *acid rain*. The keyword *climate change* appeared in 2000 in the co-occurrence network of keywords in the Chinese environmental geography papers.

Figure 7.10 compares popular keywords in SCI/SSCI journals between Chinese authors and others during the period 1996–2000 (the diagram description see the note of Fig. 7.7). The keyword frequency of the top 15 keywords of Chinese authors was more than three. Over these 5 years, among the papers with non-Chinese authors, the frequency of keywords ranked in the top 15 appeared more than 139 times. The popular topics were as follows: *heavy metals* such as *cadmium* (*Cd*), *lead* (*Pb*), and *mercury* (*Hg*) were still the pollutants of most concern during this period. *Hg* rose to the second most frequently used keyword. Research on *Pb* and *Cd* increased by 1.3–1.6 times more than during the previous 10 years, and research on *PAHs* increased by about 1.6 times. Research on *PCBs* and *pesticides* continued to increase steadily, as did work on *air pollution*, while research on *ozone* (O_3) increased by 1.3 times. In terms of media on the Earth's surface, the research on *sediment* and *soil* remained greater than *air pollution*. In terms of scientific issues, toxicology research (*toxicity*, *fish*) increased by about 40 %, and *bioaccumulation* was ranked at 14 among the top 15 high-frequency keywords, with total term frequency of 163 times. Examining the speed of growth of keywords over these 5 years, keywords such as *mercury* (*Hg*), *PAHs*, and *cadmium* (*Cd*) had the fastest growth. During this period, among the top 15 high-frequency keywords from Chinese authors, six keywords—*soil*, *heavy metals*, *PAHs*, *sediment*, *air pollution*, and *lead* (*Pb*)—were identical to the most frequently used keywords from the authors of other regions, indicating that environmental geography in China had sim-

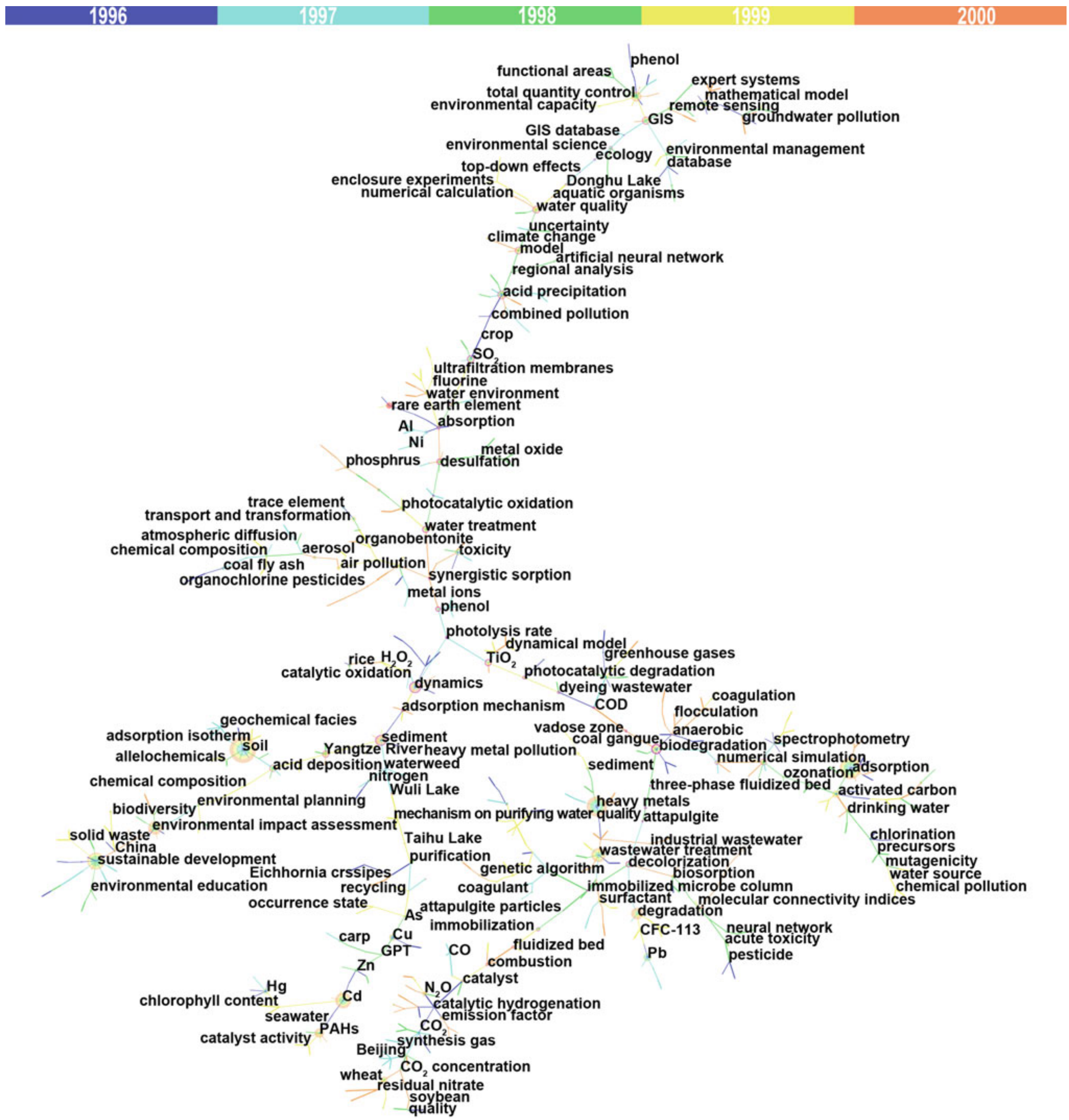


Fig. 7.9 Co-occurrence network of keywords in CSCD journals of environmental geography during the period 1996–2000

ilar concerns in terms of research on heavy metals and PAHs in sediments and soils as well as research on air pollution from 1996 to 2000. Other keywords ranked in top 15 had also reflected the influence of a geographical way of thinking on the research of pollutants, such as research on time and space laws (*distribution*, *seasonal variation*), and influence factors (*emission factor*, *agriculture*). Keywords such as *air quality*, *sewage sludge*, *acid rain*, *China*, and *Hong Kong* expressed the concern of Chinese authors for China's growing environmental problems.

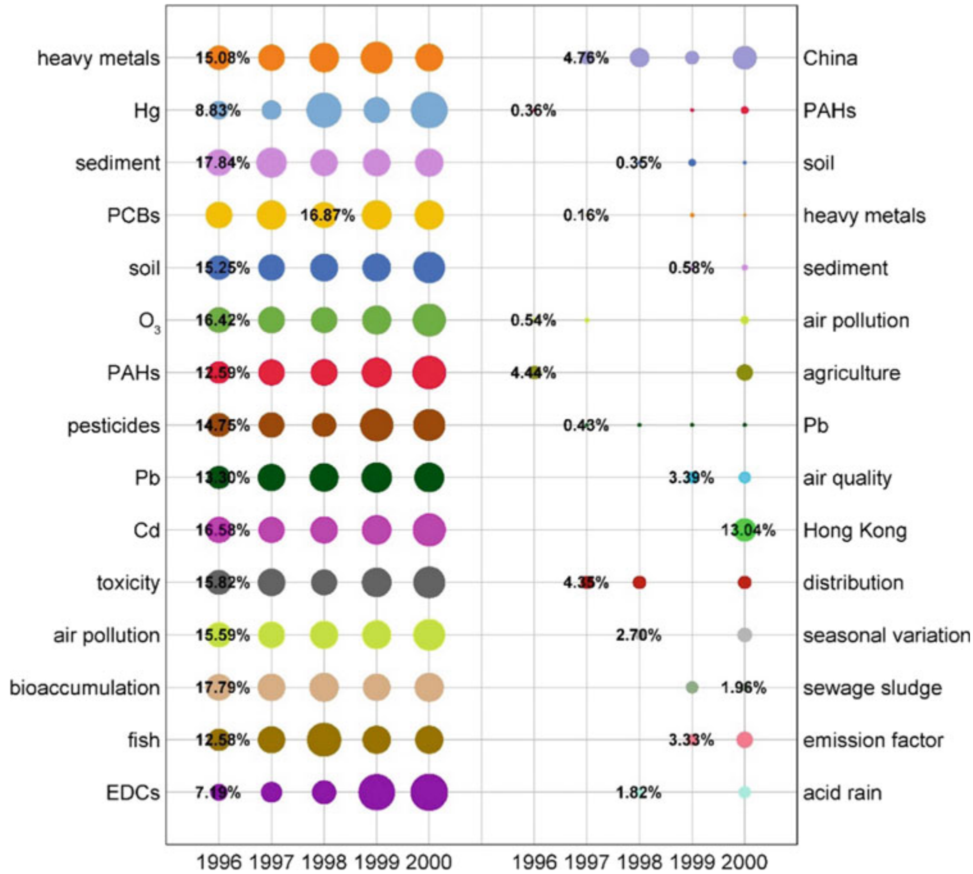


Fig. 7.10 Comparative diagram of prominent keywords by Chinese authors and others in SCI/SSCI mainstream journals of environmental geography during the period 1996–2000

7.2.3 Period of 2001–2005

Figure 7.11 shows the evolution of research topics reflected by SCI/SSCI-indexed mainstream journal papers for environmental geography from 2001 to 2005. The most prominent feature was that research was focused on soil, water, sediments, plants and air pollution, as well as the micromechanics and interface process of pollutant transport and transformation. The core of environmental geography research, the status of geographical elements, was more prominent. Nodes connecting keyword networks were mostly environmental colloids or pollutant environmental behaviour. *Complexation*, *surface chemistry*, *geochemistry*, and other keywords appeared on the main context nodes or branched context nodes, indicating that surface chemical and geochemical methods had been integrated into pollutant behaviour research. Iron and manganese oxides (*ferrihydrite*, *goethite*, *iron oxide*, *manganese oxide*), *clay mineral* and organic colloids (*fulvic acid*, *biomass*), appeared on the main context nodes or branched context nodes, further indicating that the interface processes of pollutant colloids had become one of the main topics of research for environmental geographers. Keywords such as *modelling*, *USA*, *China*, and *ecosystem* appeared in the form of isolated map delineation, indicating that modelling had become an important method in environmental geography research of this period, while the US and China had extensive research programmes into environmental geographical issues.

The main environmental geography research topics of this period were as follows. (1) Environmental behaviour and bioavailability of heavy metals and organic pollutants in multimedia included keywords such as *heavy metals*, *soil*, *water*, *sediment*, *PAHs*, *PCBs*, *cadmium* (*Cd*), *plant, organic compound*, *lead* (*Pb*), and *bioavailability*. (2) Pollutant atmospheric emission and source apportionment topics included a variety of keywords, such as *emission*, *particle*, *mercury* (*Hg*), *ozone* (O_3), *aerosols*, *VOCs*, $PM_{2.5}$, *precipitation*, *air quality*, PM_{10}, and *source apportionment.* These words indicate that attention was paid to research on the air pollutant emissions as well as their source apportionment. (3) Pollutant exposure, bioaccumulation, and transformation were represented by the aggregation of *exposure*, *degradation*, *EDCs*, *bioaccumulation*, *biodegradation*, *herbicide*, *marine*, *chlorinated hydrocarbon*, *tissue*, *rainbow trout*, and other keywords. (4) Research into the transport and transformation of nutrients in surface water/groundwater were indicated by keywords such as *lake*, *nitrogen*, *acid*, *groundwater*, *determination*, *carbon*, *phosphorus*, *risk assessment*, *surface water*, *radionuclide*, *dynamics*, and *nutrient*. (5) Land-cover remote sensing monitoring showed

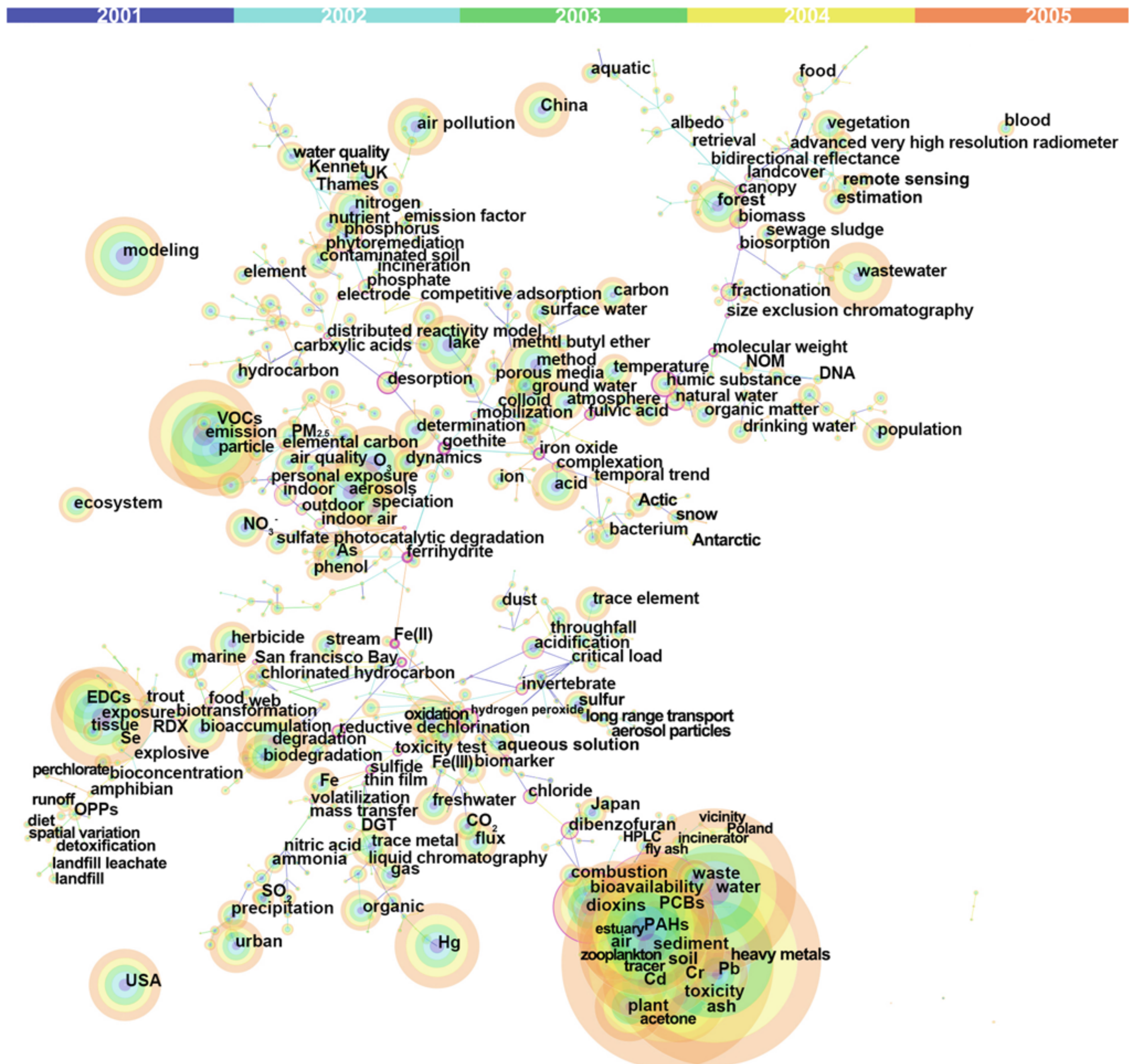


Fig. 7.11 Co-occurrence network of keywords in SCI/SSCI mainstream journals of environmental geography during the period 2001–2005

keywords such as *forest*, *vegetation*, *estimation*, *remote sensing*, and *mapping*.

Figure 7.12 shows the research hotspots reflected by Chinese core journal papers in environmental geography from 2001 to 2005. In general, research in environmental geography during this period was consistent with that of the previous two periods. However, the research focus was slightly different, and there was more research overall. Research topics such as risks, non-point sources, and soil adsorption emerged, and more attention was paid to water pollution. Although research on greenhouse gas emissions and atmospheric aerosols had increased, they were still low compared with research on soil and water. (1) Keywords for combined soil pollution processes and remediation included the *adsorption*, *desorption*, and *degradation* process in multi-contaminated soils of heavy metals such as *Cu*, *Cd*, and *Pb* and *organic pollutants*, pollutants *bioavailability*, and *toxicity*. *Bioremediation*, and *phytoremediation*, were the main contents of the remediation topic. (2) Features of spatial and temporal *distribution*, *source apportionment*, *bioavailability*, and *risk assessment* of sediments focused on *PAHs*, *OCPs*, *PCBs*, and *Tianjin* Area. (3) The emission of atmospheric particles, aerosols and greenhouse gases were reflected by keywords such as *emission* of *nitrogen oxide*,

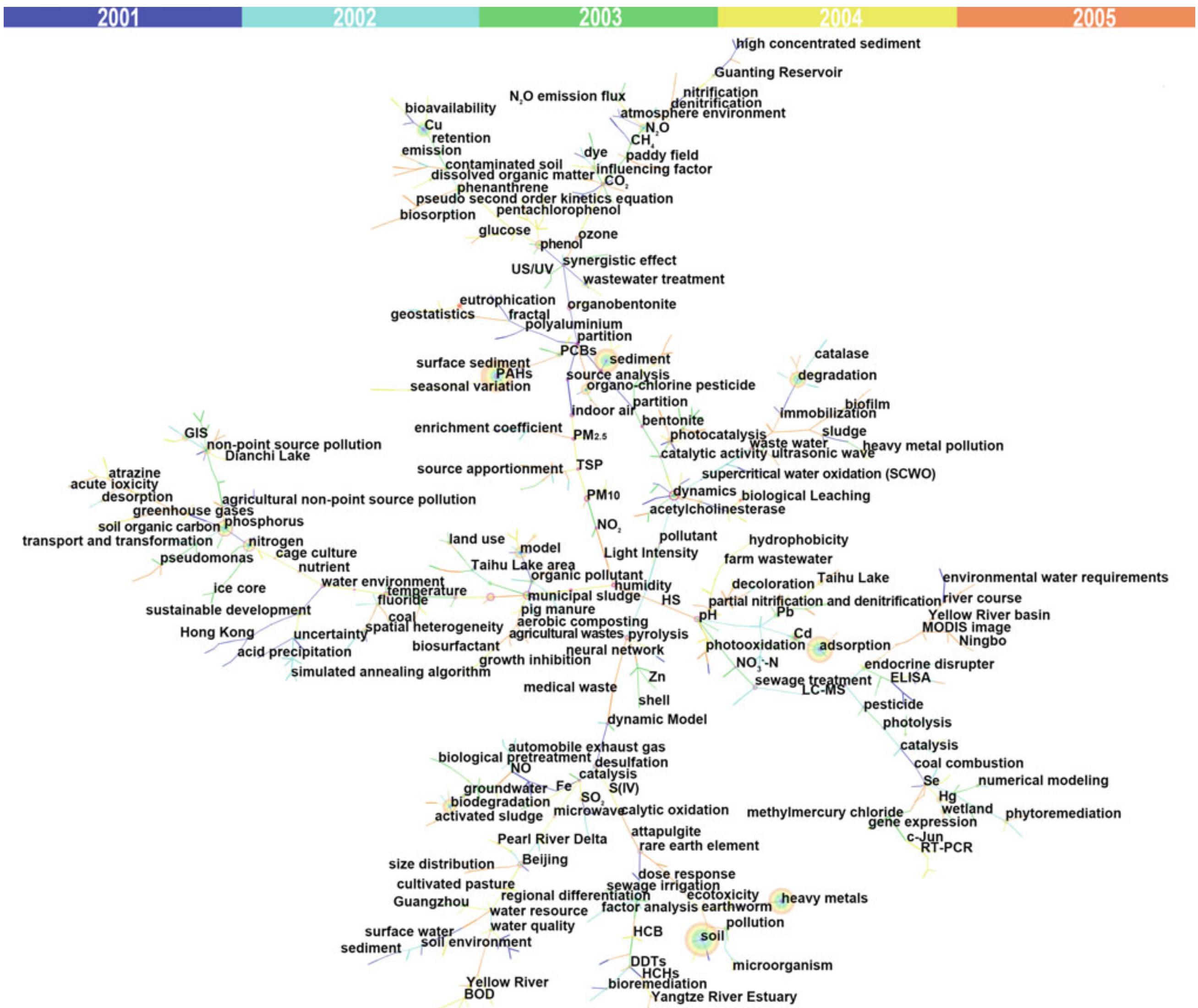


Fig. 7.12 Co-occurrence network of keywords in CSCD journals of environmental geography during the period 2001–2005

methane, and *carbon dioxide*, *emission of* $PM_{2.5}$, PM_{10}, and *TSP particles*, and *aerosols*, as well as air pollutants transport *modelling*. (4) *Non-point source pollution modelling* and *water eutrophication* used methodological keywords, such as *geographical information system* (*GIS*) and elemental tracer to research the influence of *land use*/*land cover* change on nonpoint source as well as water eutrophication arising therefrom.

Figure 7.13 compares popular keywords in SCI/SSCI journals between Chinese authors and others during the period 2001–2005 (the diagram description see the note of Fig. 7.7). The total number of journals and papers increased from the previous 5 years, and the top 15 keywords selected by Chinese authors were used more than 14 times. In the same period, among papers that were published by non-Chinese authors, the top 15 keywords were used more than 225 times. Research topics were as follows. The total term frequency of *heavy metals* and *metal* exceeded 60 %. Research on *Cd* had grown by about 50 % since the previous 5-year period, and research on *Pb* and *Hg* had grown by 7–10 %. Research papers on *PAHs* and *PCBs* had grown by about 1.1 times and 50 %, respectively, compared with the previous 5 years, becoming the No. 2 and 3 pollutants. Research on *air pollution* had increased by about 60 %, although research on *ozone* (O_3) had only grown by about 18 %. The keyword *particle* was ranked No. 15 with a total term frequency of 235, indicating that more attention was paid to research on air pollution during this period. *EDCs* became the seventh pollutant research topic during this period with the total term frequency of 286 times. Research on *pesticides* grew by about 40 %. In terms of the earth's surface media, research on *soil* grew by about 50 % from

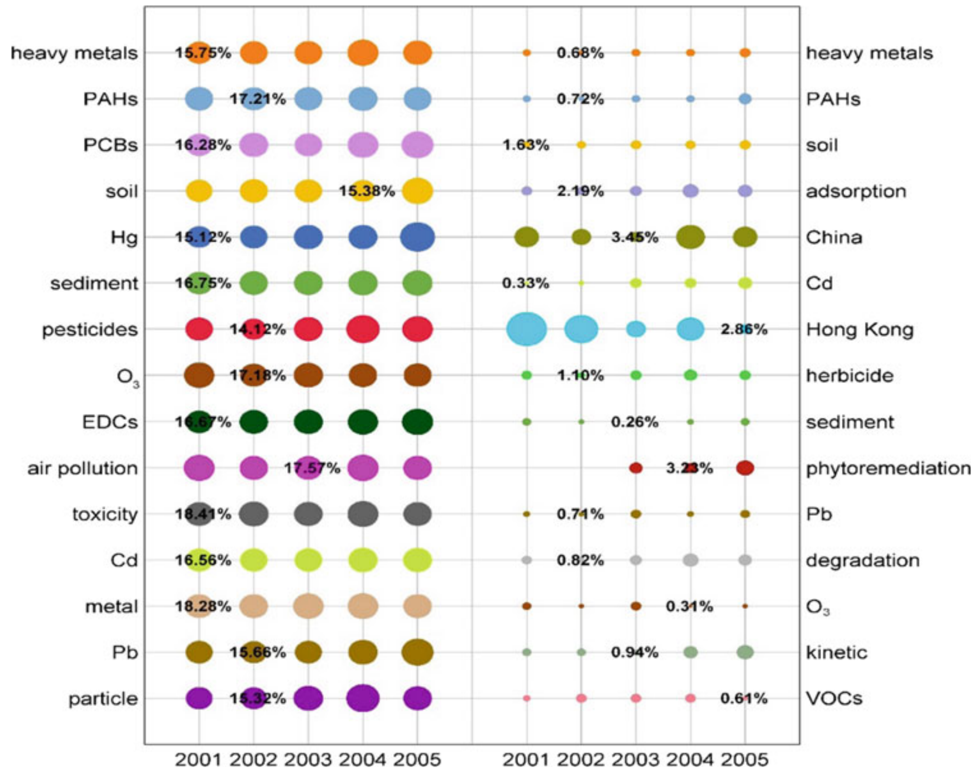


Fig. 7.13 Comparative diagram of prominent keywords by Chinese authors and others in SCI/SSCI mainstream journals of environmental geography during the period 2001–2005

2001 to 2005, exceeding *sediment* for the first time, while research on both far exceeded that on *atmosphere*. In terms of scientific issues, research on *toxicity* grew by about 40 % and it remained the most popular research topic. Looking at the speed of growth in keywords over these 5 years, the 15 high-frequency keywords grew at a constant speed overall, although some keywords such as *Hg*, *PCBs*, and *particle* showed a faster growth.

Among the papers published by Chinese authors during this period, there were six keywords with a total term frequency ranked in the top 15, namely *heavy metals*, *PAHs*, *soil*, *Cd*, *sediment*, and O_3, which were identical to those from authors of other regions. The frequency of searches for keywords *heavy metals* and *PAHs* had increased about 15- and 9-fold, respectively, compared with that in 1996–2000, and were ranked first and second, respectively, in top 15 keywords with the same ranking order of international authors. Similar to the international trend during this period, *soil* became the most researched earth surface medium, and the total term frequency of keywords from Chinese authors grew about 7-fold compared with that in 1996–2000. This indicated that topics focused on by China environmental geography from 2001 to 2005 were well synchronized with international research. Research on *Cd* was ranked No. 1 among heavy metals for the first time with a total term frequency of 34 times, indicating that Chinese environmental geographers had lagged about 5 to 10 years behind international scholars focusing on this heavy metal. The research popularity of *Hg*, which emerged internationally in 1996, still failed to become a research focus for Chinese authors at this time. Other keywords ranked in the top 15 reflected that Chinese environmental geographers of this period paid more attention to the environmental behaviours of pollutants (*adsorption*, *kinetic*, *degradation*), and were deeply concerned about China's real environmental issues such as contaminated soil remediation (*phytoremediation*) and pesticide (*herbicide*).

7.2.4 Period of 2006–2010

Figure 7.14 shows the evolution of research topics reflected by SCI/SSCI-indexed mainstream journal papers in environmental geography from 2006 to 2010. It can be seen that the focus of environmental geography research of this period was more varied. Geographic elements, pollutants, exposure, and toxicity research had been combined organically, and keywords with geographical characteristics, such as *spatial* and *temporal* had occurred. *China* appeared in the top 10 keywords for the first time. The keywords such as *perfluorinated compounds* (*PFCs*), *pharmaceuticals and personal care products* (*PPCPs*), *atmospheric chemistry*, *translocation*, *porous media*, $PM_{2.5}$, *natural attenuation*, and *landfill* appeared on the main or branched context nodes, indicating that they had become the focus of environmental geography, and were integrated into the methods of

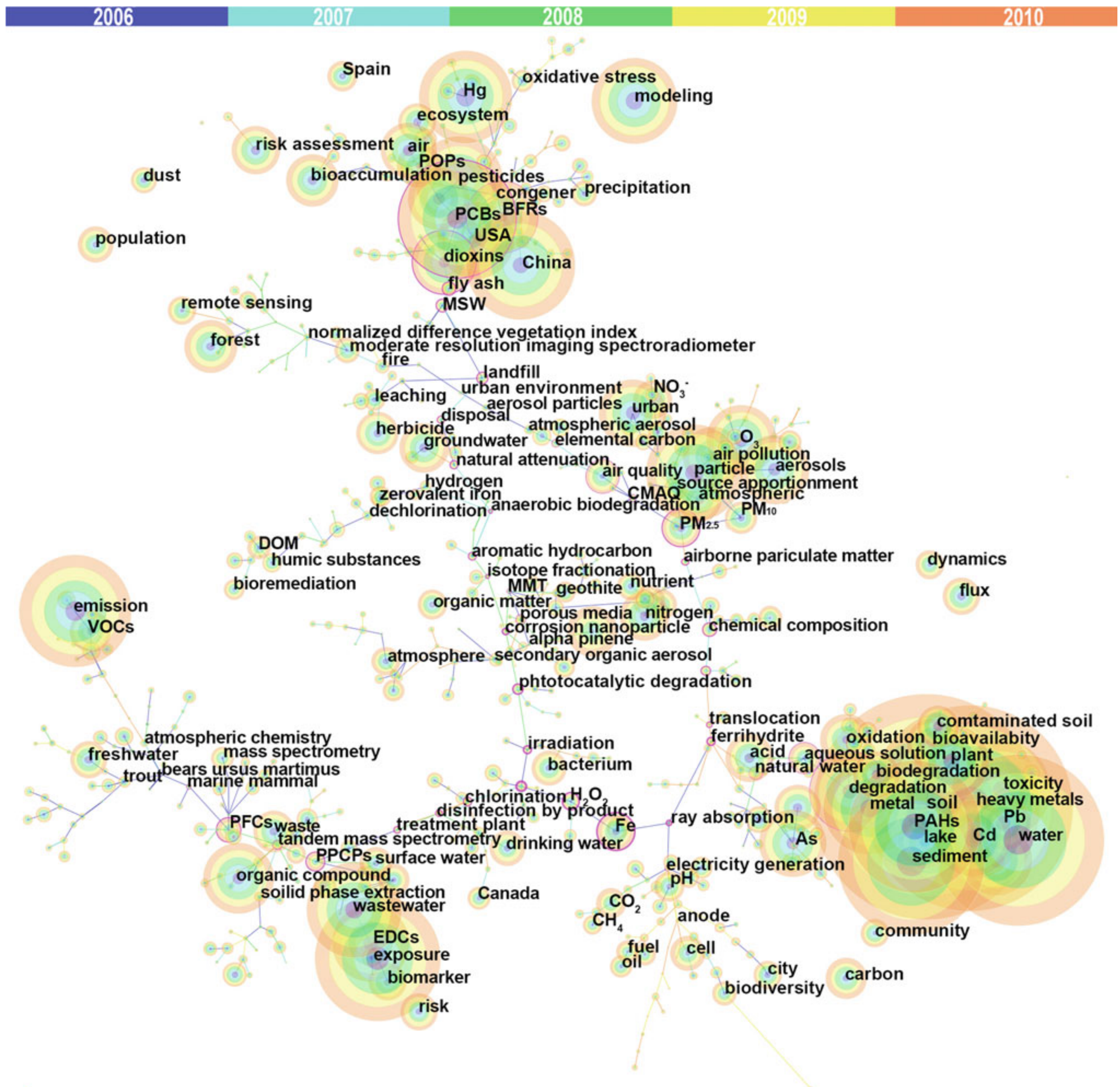


Fig. 7.14 Co-occurrence network of keywords in SCI/SSCI mainstream journals of environmental geography during the period 2006–2010

atmospheric chemistry. Isolated keywords such as *pollutant*, *temporal and spatial variation*, *modelling*, *flux*, *risk assessment*, and *climate change* had also been included in environmental geography research, indicating that environmental geography had not only focused on pollutant transport and transformation and its environmental effect, but expressly paid attention to the large-scale environmental geography issues.

In summary, research topics in environmental geography during this period were as follows. (1) Pollutant behaviour at the soil, water, and sediment interface, bioavailability, and ecotoxicology: keywords ranked according to frequency were *soil*, *heavy metals*, *water*, *sediment*, *PAHs*, *toxicity*, *metal*, *river*, *degradation*, *cadmium* (*Cd*), *plant*, *fish*, *arsenic* (*As*), *lead* (*Pb*), *lake*, *oxidation*, and *bioavailability*. *Soil remediation* (*phytoremediation*, *stabilization*) was also covered by this research topic. (2) Pollutant bioaccumulation, exposure and risk was expressed by the aggregation of keywords such as *bioaccumulation*, *oxidative stress*, *temporal trend*, *atmospheric deposition*, *human exposure*, *biotransformation*, *spatial distribution*, *phytotoxicity*, *ecological risk assessment*, and *emission inventory*. (3) Air pollution and pollutant source apportionment: keywords ranked according to frequency were *emission*, *particle*, *ozone* (O_3), *aerosols*, *urban*, *air pollution*, *forest*, *nanoparticle*, *volatile organic chemicals* (*VOCs*), *nitrate* (NO_3^-), $PM_{2.5}$, *air quality*, PM_{10}, *remote sensing*, *atmosphere*, and *source apportionment*, indicating that attention was paid to urban air pollution, pollutant emission and *global*-scale *long range transport*, *CMAQ* and source apportionment. The keywords *Beijing* and *Shanghai* appeared in this topic, indicating that the air pollution problems of Beijing and Shanghai had been widely focused on by domestic and foreign scholars. (4) New organic pollutants in wastewater, surface water and groundwater and their exposure and toxicity were recurring topics. Research was carried out into the *chronic toxicity*, *acute toxicity*, *genotoxicity*, and *ecotoxicity* of *EDCs*, *antibiotics* and other new organic pollutants in water environment (*wastewater*, *freshwater*, *drinking water*, *surface water*) the effects on *trout*, *zebrafish*, and other aquatic organisms as well as the potential impacts on *children*. (5) Non-point source pollution: keywords ranked according to frequency were *nitrogen*, *groundwater*, *herbicide*, *phosphorus*, *stream*, *organic matter*, *nutrient*, *leaching*, *desorption*, *catchment*, and *runoff*, indicating that research was focused on the leaching process of nitrogen and phosphorus and herbicides, catchment-scale transport processes and non-point source load estimation.

Figure 7.15 shows the research hotspots reflected by Chinese core journal papers of environmental geography from 2006 to 2010. For the first time, *Taihu Lake* appeared in the high- frequency top 10 keywords and *heavy metals* was ranked first among the top 10 keywords, indicating that the Chinese government was concerned by heavy metal environmental pollution and lake pollution. The keywords *Yellow River*, *Yangtze River Estuary*, *GIS*, and *distribution* appeared in the co-occurrence network of keywords. The key focus of environmental geography research during this period was still the adsorption and degradation process of heavy metals and PAHs in soil and water. Extensive research was carried out on environmental problems in the water of Taihu Lake, and space process, spatial–temporal pattern, spatial and temporal change, and other geographical characteristics became more prominent. Topics related to environmental evaluation, planning, and management, had almost disappeared. (1) Heavy metal pollution, spatial

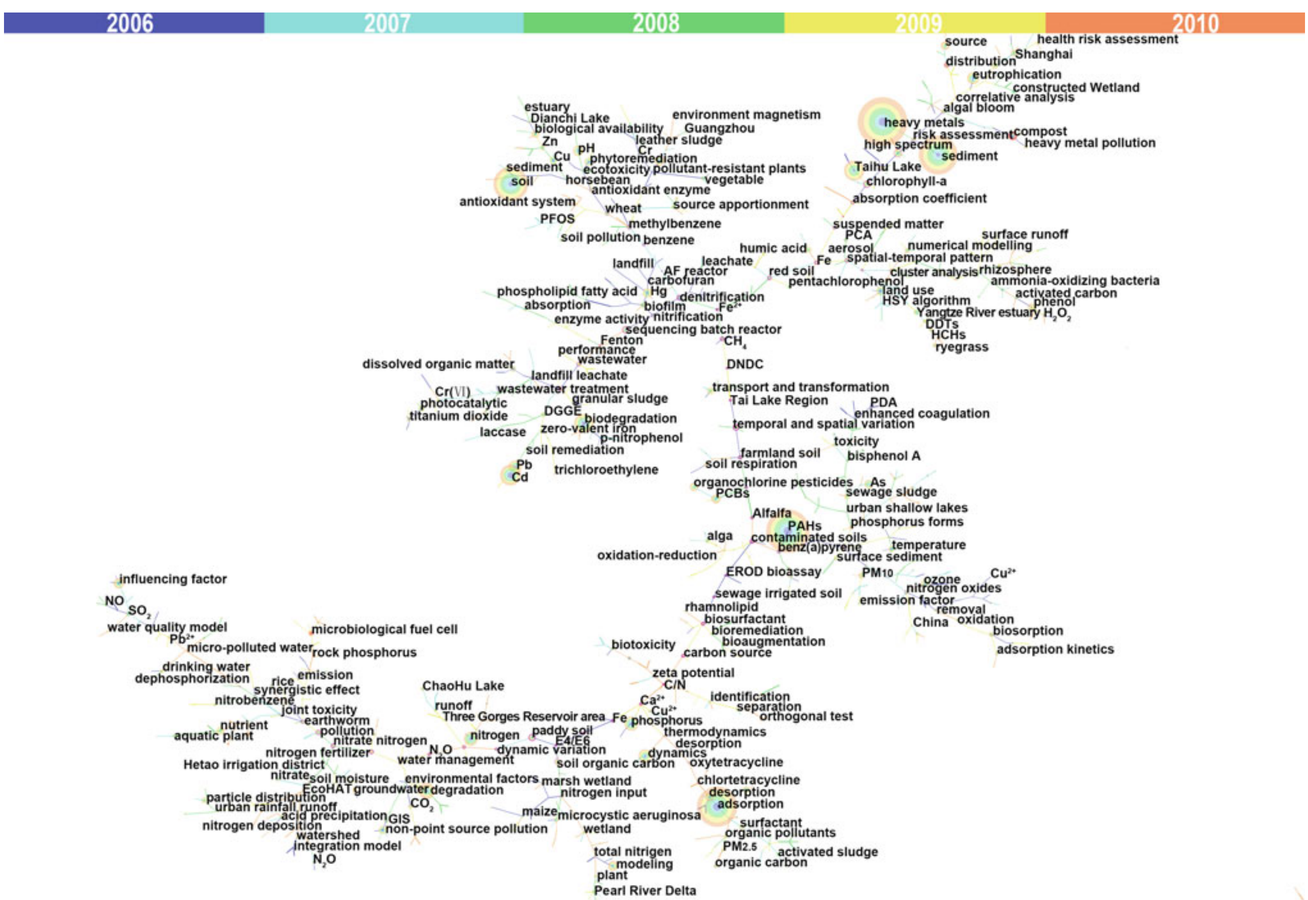


Fig. 7.15 Co-occurrence network of keywords in CSCD journals of environmental geography during the period 2006–2010

distribution, and risk assessment in sediments were topics of research as shown by the keywords *heavy metals*, *sediments*, *spatial distribution*, and *risk assessment* being used in combination. (2) The environmental behaviour of PAHs and other organic pollutants were expressed by the aggregation of keywords such as *PAHs*, *thermodynamics*, *dynamics*, *desorption*, *adsorption*, and *contaminated soil*. (3) *Soil contamination* and *soil remediation* used a relatively loosely clustered set of keywords. This may be related to the high number of keywords for remediation technology, and different remediation technologies against different kinds of pollutants and polluted media. (4) *Non-point source pollution* and *eutrophication* of lakes mainly comprised load estimation of catchment-scale *nitrogen* and *phosphorus*, and the occurrence process and mechanism of water eutrophication. (5) Air pollution had a low frequency of use and a high variety of keywords, which indicated that there were few relevant papers on air pollution from environmental geographers published in Chinese journals.

Figure 7.16 compares popular keywords in SCI/SSCI journals between Chinese authors and others during the period 2006–2010 (the diagram description see the note of Fig. 7.7). The total number of journals and papers had increased further compared with the previous 5 years, the use of high-frequency keywords had grown by about 36 %, and each of the top 15 keywords from Chinese authors was used more than 26 times. In these 5 years, among the papers published by non-Chinese authors, each of the keywords ranked in the top 15 was used more than 318 times. The trends in the popular topics reflected by keywords were as follows: *heavy metals* had grown by about 36 %, and research on *mercury* (*Hg*) had grown by about 50 % more than the previous 5-year period. While *mercury* (*Hg*) remained the No. 1 heavy metal, research on *cadmium* (*Cd*) grew by about 25 % compared with the previous 5 years, and *arsenic* (*As*) jumped to the second place in heavy metal research with a total frequency of 405 times, surpassing research on *cadmium* (*Cd*). *Lead* (*Pb*) did not appear among the top 15 high-frequency keywords. Research papers on both *PAHs* and *PCBs* grew by about 40 % compared with the previous 5 years, continuing to be the second and the third pollutant. The total frequency of *EDCs* during this period grew by about 57 %, rising from the seventh pollutant in 2001–2005 to the sixth in 2006–2010. Research on *pesticides* grew by more than 50 % during this period, being the fifth pollutant. Research on the *air pollutant ozone* (*O_3*) only increased by about 25 %, being the seventh pollutant. *BFRs* were ranked the ninth pollutant appearing 360 times. In terms of media on the earth's surface, research on *sediment* in this period grew by about 40 %, and that on *soil* grew by about 24 %. After falling below the total use of *soil* as a keyword for 5 years, *sediment* again surpassed *soil*, and the total term frequency amount of *soil* and *sediment* were still greater than that of *atmosphere*. In terms of scientific issues,

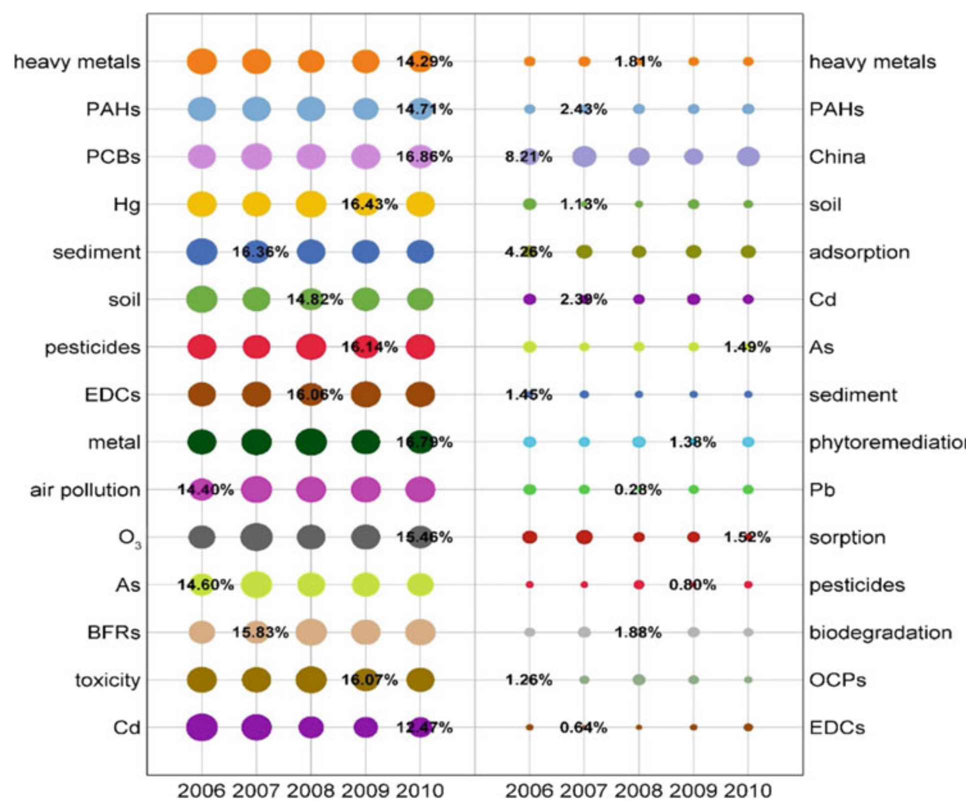


Fig. 7.16 Comparative diagram of prominent keywords by Chinese authors and others in SCI/SSCI mainstream journals of environmental geography during the period 2006–2010

toxicology research increased by about 21 %, making it one of the most popular research topics. Examining the rate of growth of keywords in these 5 years shows that the 15 high-frequency keywords grew at constant speed.

Among the papers published by Chinese authors during this period, there were eight keywords ranked in the top 15, namely *heavy metals*, *PAHs*, *soil*, *cadmium* (*Cd*), *arsenic* (*As*), *sediment*, *pesticides*, and *ozone* (O_3), that were identical with the most frequently used keywords by authors of other regions. Use of the keywords *heavy metals* and *PAHs* doubled compared with the period from 2001 to 2005, ranked respectively first and second in the high-frequency keywords. This was the same keyword ranking order as international authors. During this period, international research on *sediment* had surpassed *soil*, but although China's research on *sediment* during this period had grown, *soil* was still the most researched medium of the earth's surface. *Arsenic* (*As*) was the international heavy metal research topic that emerged in the co-occurrence network of keywords during 2006–2010, and Chinese authors showed a similar growth in research interest. *PCBs* had been an international research focus for more than 20 years, but this had not become one of the high-frequency keywords researched by Chinese authors. *EDCs* were one of the high-frequency international research topics from 2001 to 2005, and became a popular topic of Chinese environmental geographers during this period. High-frequency keywords applied by Chinese scholars still reflected the fact that China's environmental geographers paid more attention to physicochemical process research (*adsorption*, *absorption*) and contaminated soil remediation (*phytoremediation*) research during this period. Their concern for bioprocesses was limited to *biodegradation*. Chinese scholars also focused on pesticides (*pesticides*, *OCPs*), which resulted from the relatively severe pesticide residues in Chinese soil.

7.2.5 Period of 2011–2015

Figure 7.17 shows the evolution of research themes reflected by SCI/SSCI-indexed mainstream journal articles for environmental geography from 2011 to 2015. It can be seen that the environmental geography had already formed a relatively complete research system, taking the four geographical elements of water, soil, atmosphere, and organisms as the core; *persistent organic pollutants* (*POPs*), *heavy metals*, *aerosols*, *nanoparticles*, *carbon*, *nitrogen*, and *phosphorus* as the main research objects; and the biogeochemical process such *emission*, *transport*, *transformation*, *exposure*, and *toxicity* as main lines. During this period, close attention was paid to hotspots (*China*), topical issues (*non-point source pollution* and *eutrophication*), exposure and toxicity of new pollutants (*nanoparticles*). Ranking of the keyword *China* rose from seventh in 2006–2010 to fourth in 2011–2015, indicating that Chinese scholars had made an impact on environmental geography research. *Nanoparticle* appeared in the top 10 most frequent keywords for the first time, indicating that both domestic and foreign scholars focused on the application of new nanomaterials in the environmental fields as well as their environmental behaviours. *Wastewater* has also appeared in the top 10 keywords for the first time. Briefly, popular research topics for environmental geography during this period were as follows. (1) Interface pollutant behaviour, bioavailability, and pollution risk assessment of soil, water, and sediment: This theme covered two cluster groups; one contained keywords (ordered by frequency) such as *soil*, *water*, *heavy metal*, *sediment*, *PAHs*, and *metal*; and the other contained keywords such as *China*, *PCBs*, *BFRs*, *POPs*, *OCPs*, *dioxin*, and *human exposure*. (2) Exposure and toxicity of nanoparticles: This theme contains keywords such as *exposure*, *nanoparticle*, *toxicity*, *freshwater*, *biomarker*, and *oxidative stress*, indicating that a new pollutant—nanoparticles—was a focus of research. (3) Environmental behaviours of pollutants in water. The cluster spots of keywords were small and scattered. The main keywords (ordered by frequency) were *mercury* (*Hg*), *degradation*, *pesticides*, *EDCs*, *plant*, *fish*, and *bioaccumulation*. (4) Air pollution mainly contained keywords (order by frequency) such as *emission*, *particles*, *aerosols*, *air pollution*, *ozone* (O_3), and *air quality*, among which the research on *carbon*, $PM_{2.5}$, *biomass*, and PM_{10} only took up a small amount of attention. (5) Emerging organic pollutants in wastewater and drinking water. This theme covered two cluster groups, one of which contained keywords such as *wastewater*, *antibiotics*, *PPCPs*, while the other cluster contained keywords such as *drinking water*, *surface water*, and *PFCs*. The two cluster groups were connected through keywords such as *tandem mass spectroscopy* and *aquatic environment*, indicating that attention was being paid to the identification of emerging organic pollutants and their influence on human health.

Figure 7.18 shows the research foci reflected by Chinese core journal articles in environmental geography from 2011 to 2015. The top 10 most frequent keywords included *heavy metal*, *adsorption*, *soil*, *sediment*, *PAHs*, *phosphorus* (*P*), *cadmium* (*Cd*), *Taihu Lake*, *influence factor*, and *nitrogen* (*N*). The keyword *nitrogen* (*N*) appeared in the top 10 keywords for the first time, possibly related to the fact that China has carried out extensive research on eutrophication and aerosols. *Volatile organic compound*, *groundwater*, and *non-point source pollution*, which also showed an upward trend. The connection between the keywords *lead* (*Pb*), *cadmium* (*Cd*), *mercury* (*Hg*) and *heavy metal* was loose, indicating that intensive research has been carried out independently on major types of heavy metals. The main themes in this period were as follows. (1) Heavy metal

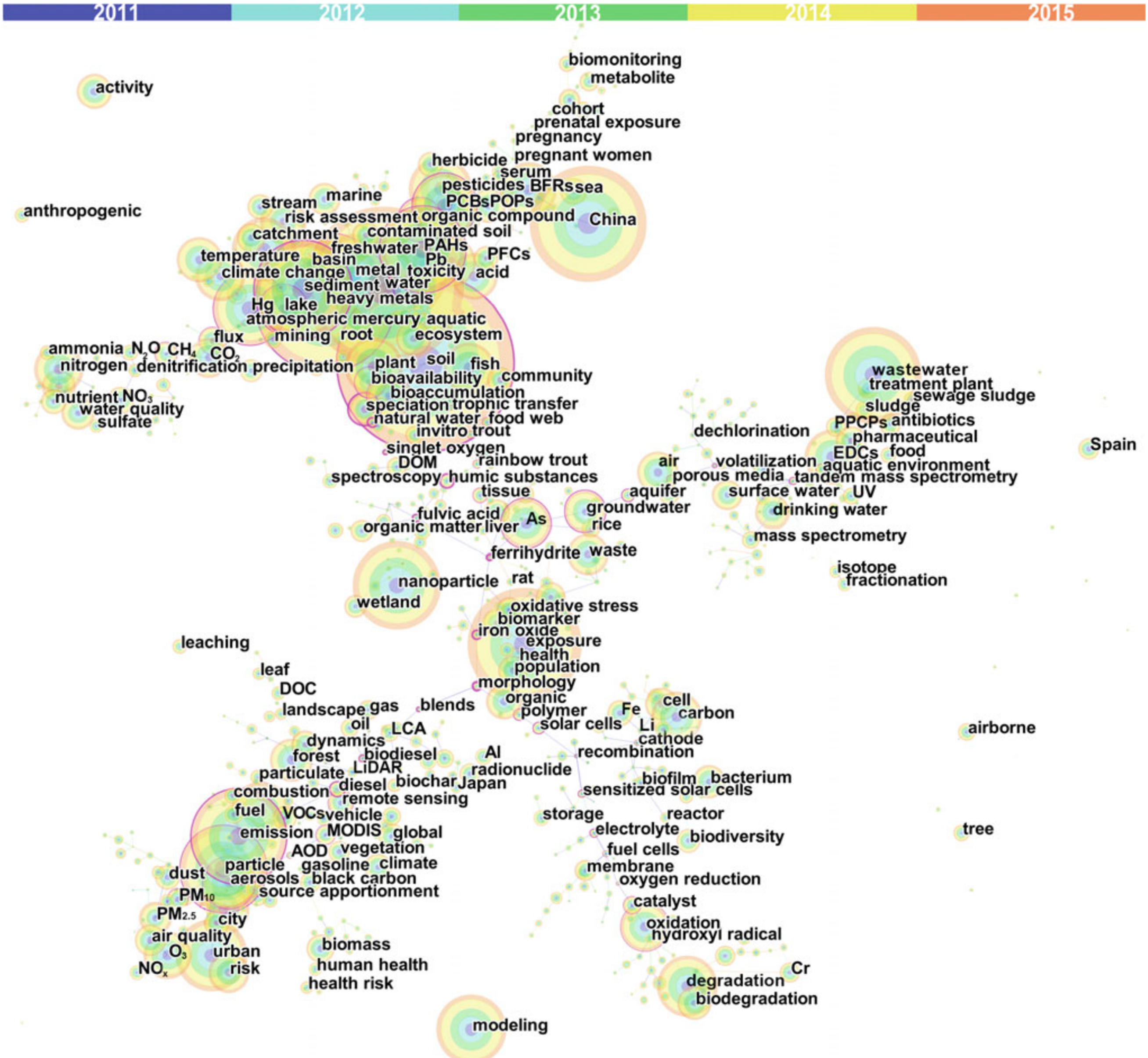


Fig. 7.17 Co-occurrence network of keywords in SCI/SSCI mainstream journals of environmental geography during the period 2011–2015

pollution, such as *Cd, Pb, and Hg* covered the *concentration*, *speciation*, *bio-availability*, *distribution* pattern, *health risk*, and *source apportionment* of heavy metals in the environment. (2) Adsorption and degradation behaviours of pollutants: the main keywords (order by frequency) were *adsorption*, *influence factor*, *biodegradation*, and *dynamics*, and the content covered the adsorption/desorption thermodynamics, dynamics and influence factors of pollutants, and biodegradation, adsorption, absorption, and transformation of pollutants. (3) Organic pollutants, such as PAHs and PCBs, included keywords such as *soil*, *PAHs*, *spatial distribution*, and *source*, and the content covered the spatial distribution, source and potential ecological risk of pollutants. (4) Eutrophication of water included keywords (ordered by frequency) such as *sediment*, *phosphorus* (*P*), *Taihu Lake*, *nitrogen* (*N*), *risk assessment*, *eutrophication*, and *water quality*, and the content covered the spatial distribution pattern and transport and transformation of nitrogen and phosphorus. Close attention was paid to the problem of eutrophication in *Taihu Lake*, *Chaohu Lake*, and *Dianchi Lake*. (5) Air pollution and greenhouse gas emission used the main keywords *ozone*, *volatile organic compound*, *$PM_{2.5}$*, *PM_{10}*, *Beijing*, *carbon dioxide*, *emission factor*, *sulphur dioxide*, and *nitrogen oxide*, and the content covered the source, emission factors, emission inventory, and health risk of air pollutants.

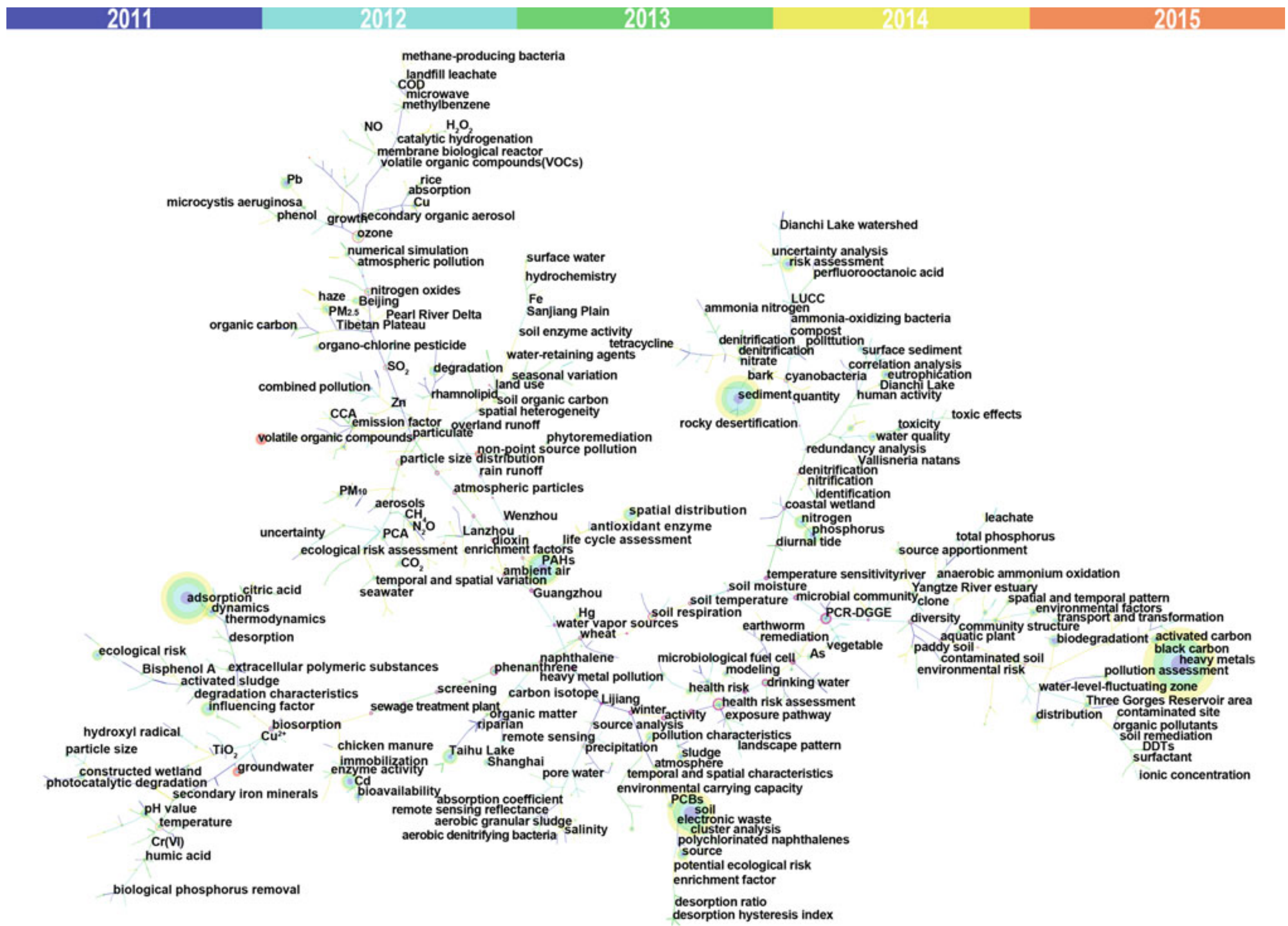


Fig. 7.18 Co-occurrence network of keywords in CSCD journals of environmental geography during the period 2011–2015

Figure 7.19 compares popular keywords in SCI/SSCI journals between Chinese authors and others during the period 2011–2015 (the diagram description see the note of Fig. 7.7). The total number of journals and papers as well as the total frequency of high-frequency keywords further increased over the previous 5 years, and frequency of the top 15 keywords from Chinese authors also increased by about 40 %. Over these 5 years, popular research topics as reflected by most frequent keywords used by non-Chinese authors ranked in the top 15 were as follows: heavy metal (*heavy metals*, *metal*) remained the pollutant of most concern during this period. *Mercury* (*Hg*) remained the No. 1 heavy metal pollutant, and *arsenic* (*As*) remained a popular research topic. *PAHs*, *PCBs*, *pesticides*, *EDCs*, and *BFRs* were still pollutant hotspots. *Nanoparticle* entered the top 15 high-frequency keywords as a new pollutant. *Particles* became a research focus again after a period of lower interest from 2006 to 2010, and attention to *air pollution* exceeded *sediment*. It is worth mentioning that *climate change* first appeared in the research of environmental geography as a high-frequency keyword in this period and was ranked in the top 5. This shows that the research focus of international environmental geographers had shifted from environmental pollution to global integrated environmental problems and macro-environmental problems. This also indicates the significant influence of climate change on regional environments.

Among the papers published by Chinese authors within this period, there were nine keywords ranked in the top 15 that were the same as those used by authors from other regions. These were *heavy metals*, *PAHs*, *soil*, *arsenic* (*As*), *BFRs*, *sediment*, *EDCs*, *PCBs*, and *mercury* (*Hg*). Research into *BFRs* was a new international research focus that appeared between 2006 and 2010, but the research interest of Chinese scholars into this pollutant was approximately 5 years behind their international colleagues. During this period, Chinese scholars were focused on research into the heavy metal *cadmium* (*Cd*) and *phytoremediation*, which may be closely related to the threat of cadmium pollution in soil in China. However, *cadmium* (*Cd*) was no longer one of the top 15 keywords internationally. In addition, research on *toxicity* that had lasted over 20 years from 1986 to 2010

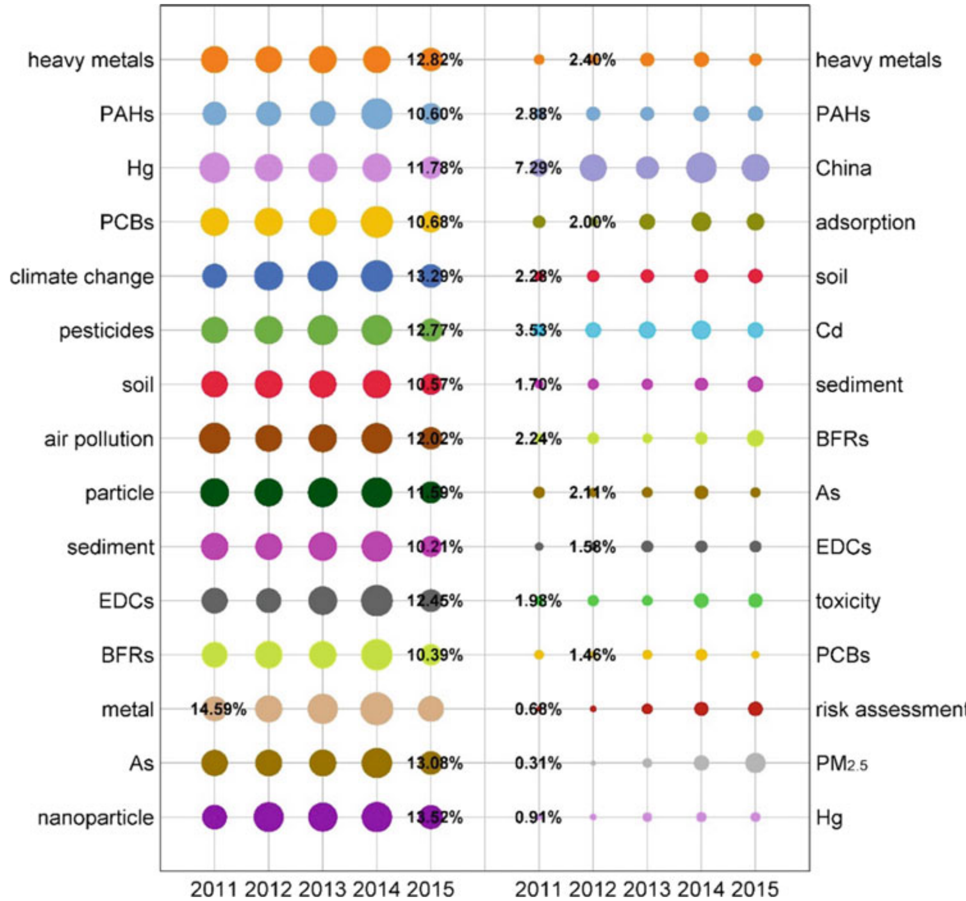


Fig. 7.19 Comparative diagram of prominent keywords by Chinese authors and others in SCI/SSCI mainstream journals of environmental geography during the period 2011–2015

internationally was no longer a popular research topic, although the keyword was one of the top 15 for Chinese scholars during this period. Chinese scholars continued to pay close attention to research on the chemical behaviour (*adsorption, sorption*) of pollutants.

7.2.6 Analysis of Driving Factors for Disciplinary Development over the Past 30 Years

As a sub-discipline of geographical sciences, environmental geography researches the movement, transformation, and effect of pollutants under different spatial and temporal scales in the geographical environment by taking environmental problems as the orientation and geographical method as the chief means. It also integrates methods from other disciplines. A series of changes have occurred in the types of pollutants, their environmental behaviour and effects, and the places affected which have been the focus of environmental geography over the past 30 years.

Type of Pollutants and Mode of Occurrence With an improvement in the accuracy of instruments and the thoroughness of analysis methods, the ability of environmental geography to identify the type and mode of occurrence of traditional pollutants in the earth's surface media has gradually improved, and research on emerging pollutants has developed. Heavy metal has always been the major pollutant researched by environmental geography, but the focus at different times has varied. The changes in emphasis from the atmospheric emission and air pollution of heavy metals, to the adsorption and desorption process of heavy metals in soil, then to the toxicity, bio-availability, and risk assessment of heavy metals in soil, water and sediment, and the remediation of contaminated soil have reflected that research on heavy metals has been continuously enriched and expanded. In addition to heavy metals, the pollutants of most concern have changed from PAHs, PCBs and dioxins to emerging pollutants such as PFCs, EDCs, PPCPs, antibiotics, and nanoparticles. More pollutants with close relationships to human health have become research topics. China is in a stage of rapid economic development, and is an important area where traditional and emerging pollutants coexist. The country provides important case studies for environmental science research, and especially for research in environmental geography.

Environmental Processes and Behaviour of Pollutants Over the past 30 years, the emphasis of environmental geography has shifted from analysis of pollutant concentrations in environmental media to the identification of the form of pollutants, and analysis of the bio-availability of pollutants. There was also a focal shift from macroscopic characteristics of the transport and transformation of pollutants to microcosmic mechanisms at the molecular, atomic, and nano scale; and shift from studies on small-scale temporal and spatial variations in pollutant processes at the micro-interface to studies on the process simulation of temporal and spatial variation at large scales, such as surficial mediums at regional and global scales. These changes not only reflected the disciplinary development characteristics of the combination of microscopic and macroscopic scales in environmental geography but also provided an important scientific basis for solving practical environmental problems. From another perspective, it is the influence of environmental problems on the disciplinary development and interdisciplinary characteristics of environmental geography that enables environmental geographers to research the environmental processes and behaviours of pollutants to show the multi-scale, multi-interface, and multi-process characteristics.

Environmental and Human Health Effects of Pollutants The exposure to and toxicity of pollutants have always been the foci of environmental geography, but the emphasis of exposure and toxicity research in different periods has varied. From 1986 to 1995, exposure research emphasized the effect of exposure to ozone and acid mist on trees, and toxicity research emphasized the effect of toxicity on forests and ecological systems. From 1996 to 2000, exposure research focused on the effect of exposure to pollutants on the human body, while toxicity research emphasized experimental methods and simulations of toxicity on aquatic organisms. From 2001 to 2005, exposure research examined the exposure of rainbow trout to endocrine disrupters, while toxicity research examined the toxicity of heavy metals and PAHs in soil, water and sediment, and the toxicity of lead on children. From 2006 to 2010, exposure and toxicity research focused on the exposure to and toxicity of pollutants such as endocrine disrupters, lead and cadmium to fish and children, and the exposure, toxicity, and pollutant were classified into the same category. Finally, from 2011 to 2015, exposure and toxicity research emphasized the exposure to and toxicity of nanoparticles to water fleas and biomarkers. The research history of the exposure and toxicity of pollutants indicates that, to serve the ecosystem health and food chain transfer health outcomes, human health and the sustainable development of communities are the most fundamental aims and driving forces for development of research on the exposure and toxicity of pollutants.

7.3 Disciplinary Development and Research Teams in China

To assess the trends of disciplinary development, this section analyses the proportion of applications and funded projects in environmental geography to the total number of those in the NSFC geographical sciences. We also discuss the number of applications and funded projects in different branches of environmental geography. Also analysed the types of pollutants chosen by researchers in NSFC-funded projects. The conditions of teams in research institutions in China are analysed by the following indicators: the number of publications in the SCI/SSCI journals per researcher in these institutions, collaborative networks of Chinese authors with publications in SCI/SSCI or CSCD journals, and institutions with which the most-cited SCI/SSCI-indexed articles were affiliated, and institutions of NSFC-funded projects in these institutions.

7.3.1 Numbers and Proportions of NSFC Applications and Funded Projects for Environmental Geography

In the past 30 years, both the number of projects applied for and funded by NSFC in environmental geography had been increasing, especially from 1996 to 2005 (Fig. 7.20). Although the growth during the last 10 years had slowed down, the proportion of the projects applied for and funded by NSFC in environmental geography has reached about a quarter of the total in geographical sciences. The proportion of projects funded by NSFC grew a little faster than those applied for between 2006 and 2010 compared with the previous 5-year period. This is mainly because some application orientations in environmental geography were increased by NSFC during this period, and the partial funding of projects were encouraged.

Figure 7.21 shows the proportion of the applications in each branch of environmental geography during the period 1986–2015. It can be seen that, the most important achievement made by the NSFC over the past 30 years is that a disciplinary frame system comprising studies of pollutants, ecological environment, resource management, and regional sustainable development, has been constructed. (1) In terms of pollutant research, *proportion of applications for the Fate, Process and Effects of environmental pollutants* has increased in the last 10 years, revealing the transport and transformation mechanism of pollutants in the geographical environment and the process thereof has been simulated. (2) *Quality and Security of Regional Environment* is another

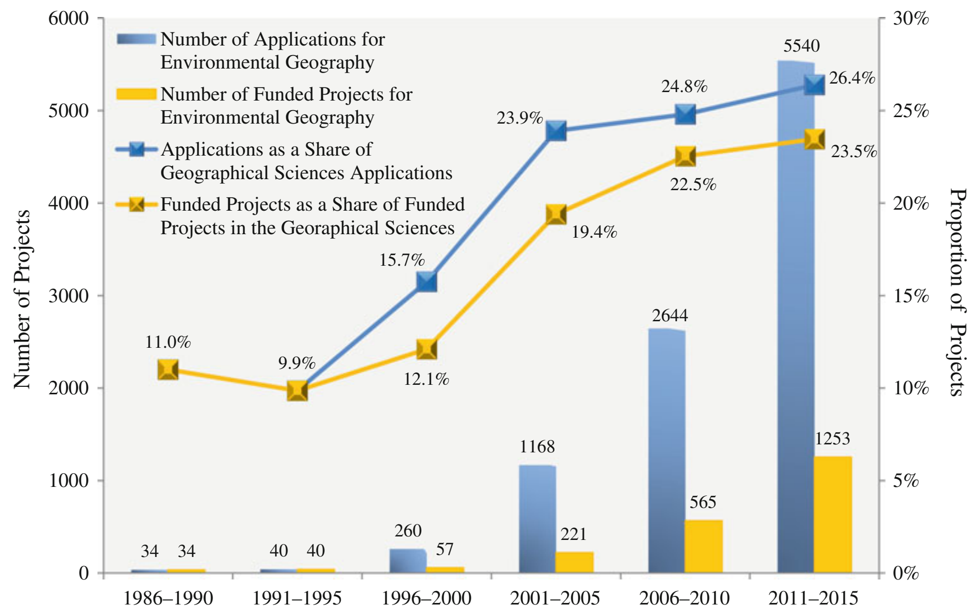


Fig. 7.20 Proportions of NSFC projects for environmental geography during the period 1986–2015. *Note* Non-funded proposals from 1986 to 1997 were not recorded in the NSFC database. Therefore, number of applications and NSFC-funded projects are identical from 1986 to 1995, as shown in the figure

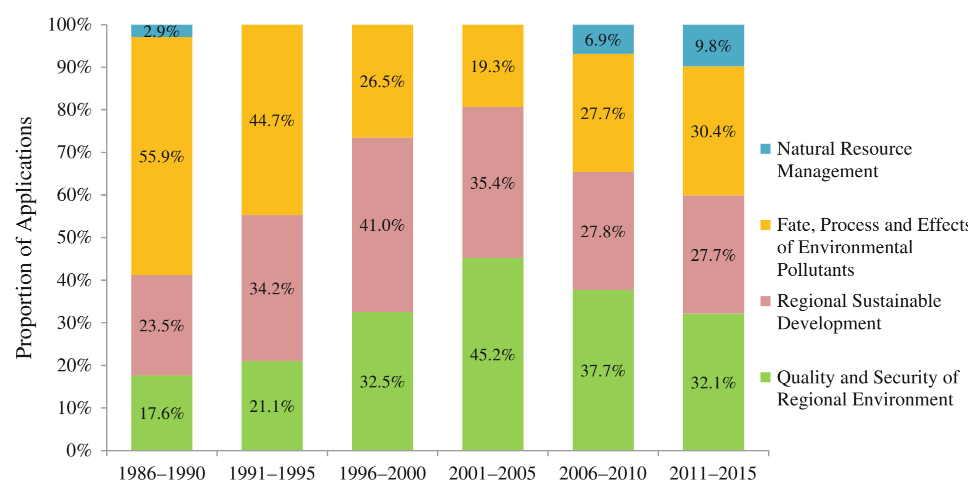


Fig. 7.21 Proportions of NSFC applications of branches of environmental geography during the period 1986–2015. *Note* Non-funded proposals from 1986 to 1997 were not recorded in the NSFC database. Therefore, the proportion of applications shown in the figure is the proportion of funded projects during the period

important branch for NSFC-funded environmental geography. In the last 5 years, the quantity of projects applied for by the research focused on *risk assessment of natural hazards and public security* within this branch accounted for 10.2 % of the total number of projects applied for environmental geography, growing more rapidly since 2005. The reason for this is mainly that, in recent years, more international attention has been paid to research on the risk assessment of natural hazards. In addition, the establishment of a project application code of *Risk Assessment of Natural Hazards and Public Security* by NSFC-funded geographical sciences in 2008 greatly increased research applications for this topic. (3) From 1986 to 2007, there were few projects applied for in relation to natural resource management. However, since the establishment of the application code of *Natural Resource Management* by NSFC-funded geographical sciences in 2008, the applications for this branch have grown quickly. (4) *Regional Sustainable Development* research grew steadily before 2000. Although research has declined over the last 15 years, the proportion of applications remains about 28 %. In recent years, the investigation of indicators of sustainability assessment and the establishment of the theoretical and methodological systems for sustainability assessment have gradually become the research foci.

7.3.2 Object of Studies in NSFC-Funded Projects

The research objects of studies in NSFC-funded environmental geography projects included natural hazards, different types of natural resources and degraded ecosystems and various types of pollutants. The main types of natural hazards were described in Chap. 4 Physical Geography. Although there were various types of natural resources and degraded ecosystems and research projects focused on them had increased, there was generally a low proportion of research in this environmental geography. This section will focus on introducing the types of pollutants researched by NSFC environmental geography.

Figure 7.22 shows the number of NSFC-funded environmental geography projects with different types of pollutants as the research subject. There were 11 main types of pollutants researched in NSFC-funded environmental geography projects, among which heavy metal and persistent organic pollutants (POPs) have been intensively studied. The degree of concern about various pollutants has changed over time. (1) **Heavy metal pollutants**. Heavy metals including copper, cadmium, lead, zinc, arsenic, mercury and chromium were the pollutants of great concern for environmental geography-funded projects. There were 323 funded projects over the past 30 years, accounting for 37.1 % of the total projects of pollutant research. Of which 225 were funded in the last 5 years. The most common research direction in heavy metal research was the environmental behaviour of pollutants, including the environmental behaviour of heavy metals in the soil, fluvial deposits and suspended solids, and soil–plant systems. In recent years, research on the environmental behaviours of heavy metals in the urban atmosphere and soil, as well as of synergistic actions between heavy metals and nanoparticles, has begun to increase. A relatively new research direction in heavy metal research was polluted environment remediation, which began to be emphasized after 2000. Approximately 77 % of projects were funded in the past 5 years. In recent years, studies have been conducted on the phytoremediation mechanism and technology for farmland soil pollution. The research foci were on the combined action mechanisms of heavy metals and organic pollutants and the remediation technologies for compound contaminated soils. In addition, many studies were carried out in environmental geography into the form and bio-availability of heavy metal pollutants and the biological accumulation and magnification of heavy metal pollutants. (2) **Persistent organic pollutants** (**POPs**). These types of pollutants have been a concern since the 1990s, and the number of research projects which were funded by environmental geography ranked second only to those on heavy metals. There were 245 funded projects altogether over the past 30 years, accounting for 28.2 % of the total projects of pollutant research. Of which 165 projects were funded in the past 5 years. Persistent organic pollutants (POPs) include perfluorinated compounds (PFCs), polycyclic aromatic hydrocarbon (PAHs), dichlorodiphenyl trichloroethane (DDT), hexachlorocyclohexane (HCH), polybrominated diphenyl ethers (PBDEs), polychlorinated biphyeyl (PCBs), and organochlorine pesticides (OCPs). Over the past decade, the number of projects on POPs in soils increased greatly in terms of polluted environment remediation research, and studies of the mechanisms of physical and chemical remediation have evolved to focus on the biological degradation process, especially the actions of soil microorganisms. Another direction of study on POPs was the environmental behaviour of pollutants. In the past 10 years, the behaviours of POPs in various environmental media have been successively researched in environmental

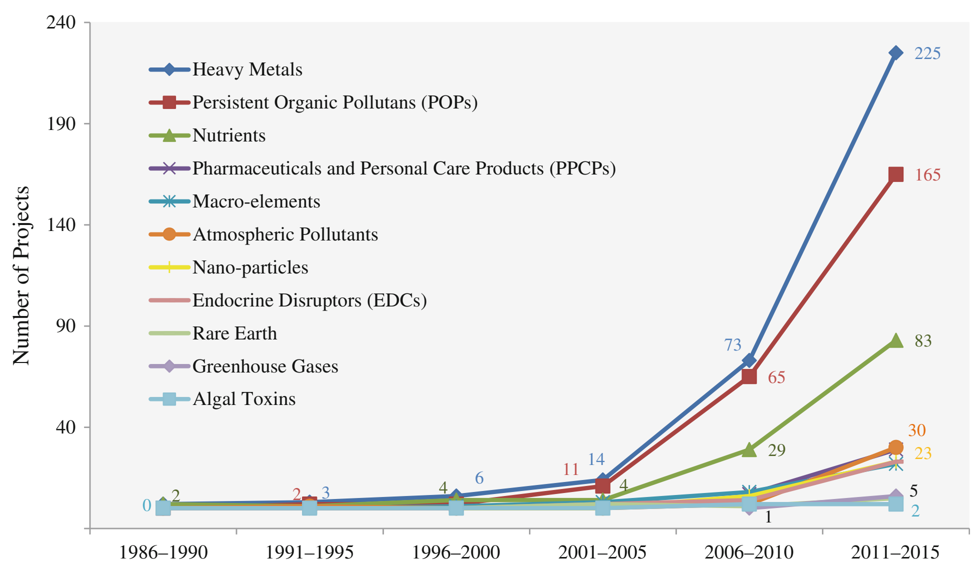


Fig. 7.22 Number of NSFC-funded projects studied on different types of pollutants in environmental geography during the period 1986–2015

geography projects. In addition, there was a significant number of projects in the research fields of health risks and ecological risks from POPs, the form and bio-availability of POPs, and the emission and influence factors of POPs. For the important POPs, such as PAHs, the research frontier has tackled environmental multimedia outcomes, emissions and long-distance transportation simulation. (3) **Nutrients**. Those include nitrogen, phosphorus, and chemical fertilizers. In the early years, there were many research projects on the output flux of heavy metal elements and nutritive salts at river mouths, as well as some discussions on the geographical laws for what constituted suspended solids, and element transport in the main rivers in China. Since the late 1990s, attention has begun to shift to the biogeochemical cycling processes of nitrogen and phosphorus in a drainage basin or lake water, the waterbody-sediment interface and the water-sediment interface. Since the late 2000s, there have been more mechanistic studies on nutritive salt gathering and non-point source pollution formation, combined with studies on hydrological models, especially diffused watershed pollution and lake eutrophication in the case of highly-intensive farmland utilization. The isotope tracer technique has played an important role in analysing diffused pollution sources and pollutant composition. Ocean colour remote sensing provided an important method for building an underwater light field structure for eutrophic water bodies so that the biogeochemical process of nutritive salt was combined with studies on lake ecological–hydrological processes and ecosystem change processes. Recent years have seen slightly increased studies on the control and removal mechanisms of nitrogen and phosphorus nutritive elements in water bodies. Investigations of the control and removal processes and mechanisms of nutritive salts such as nanoparticles, algae and microorganisms in eutrophic lakes, water source reservoirs, and urban wetlands has become a research focus. (4) **Other pollutants**. About 20 % of studies examined other pollutants. PPCPs, EDCs and nanoparticles have been studied recently. The number of research projects over the past 5 years accounted for 80 % of the mentioned 20 % of pollutants studied, while the number of popular atmospheric pollutant studies in the past 5 years in China covered up to 90 % of the mentioned 20 % of pollutants research projects. This reflects the fact that environmental geography projects are focused on carrying out research based on the most severe environmental problems in China.

7.3.3 Research Teams

In terms of research teams, the analysis objectives includes the number of institutions applying for NSFC projects in environmental geography; the number of institutions publishing papers in SCI/SSCI or CSCD journals, authors and their collaborative networks; the mean number of SCI/SSCI-indexed articles that from institutions supported by NSFC environmental geography, and the top 5 institutions receiving the most funds form that source; the overall situation of the highly-cited SCI/SSCI-indexed articles published by Chinese authors (top 50 Chinese papers and top 1000 international papers), and top 10 institutions receiving the most NSFC funds. In the figure of collaborative network of Chinese authors (in SCI/SSCI and CSCD journals, Figs. 7.23 and 7.24), some author names are marked with abbreviations of their institutions in case of identical names. Abbreviations and full names and affiliation abbreviations of institutions are listed in Appendix D.

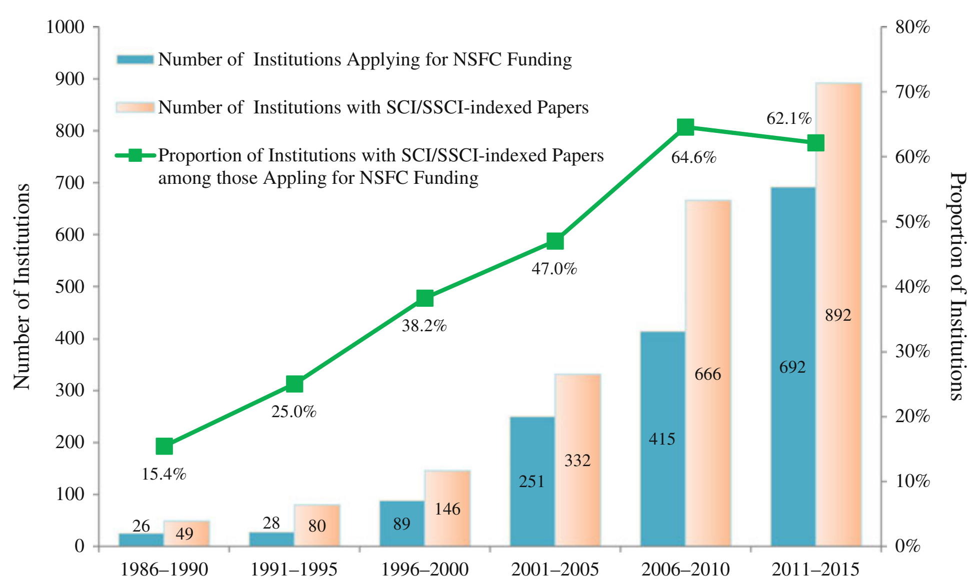


Fig. 7.23 Number of Chinese research institutions on environmental geography during the period 1986–2015

Figure 7.23 shows the number of institutions applying for NSFC environmental geography projects and the institutions (all Chinese authors) with publications in SCI/SSCI mainstream journals by 5-year interval from 1986 to 2015. In this figure, the green line represents the proportion of number of institutions with publications to all institutions applying for NSFC environmental geography projects. It was observed that the both the number of institutions applying for NSFC projects and that of institutions with publications in mainstream journals showed an increasing trend. The number of institutions with publications in SCI/SSCI mainstream journals in the past 5 years approached nearly 900, and the proportion of number of institutions with publications in SCI/SSCI mainstream journals to all institutions applying for NSFC environmental geography projects, exceeded 60 % in the past 10 years, but decreased slightly during the past 5 years. Statistics indicated that basic research teams for environmental geography or environmental science in China have expanded steadily and at a high degree of internationalization.

Figures 7.24 and 7.25 show the collaborative networks of Chinese authors who published papers in SCI/SSCI mainstream journals and CSCD journals of environmental geography from 1986 to 2015 (for the name and abbreviations of institutions publishing papers, see Appendix D). From these we can see that environmental geography projects aim to carry out studies on multiple interfaces and various geographical elements such as water, soil, atmosphere, and biology on the Earth's surface to gradually forming the present collaborative networks. In the figures, the core nodes with higher collaborative network centrality are the dominant institutions and important academic leaders of disciplinary branches and directions in environmental geography, and the branch nodes are the young and

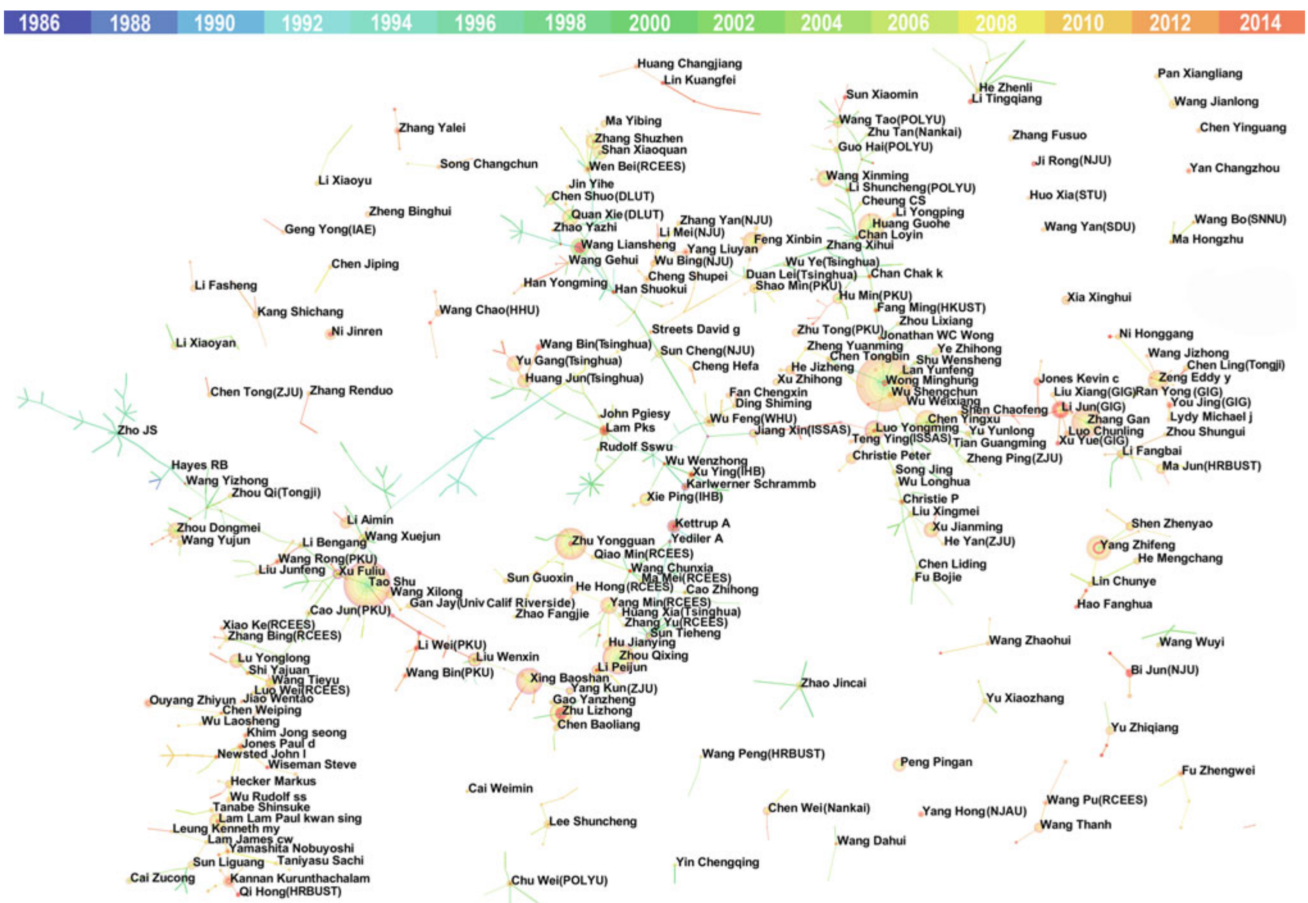


Fig. 7.24 Collaborative network of Chinese authors in SCI/SSCI mainstream journals of environmental geography during the period 1986–2015

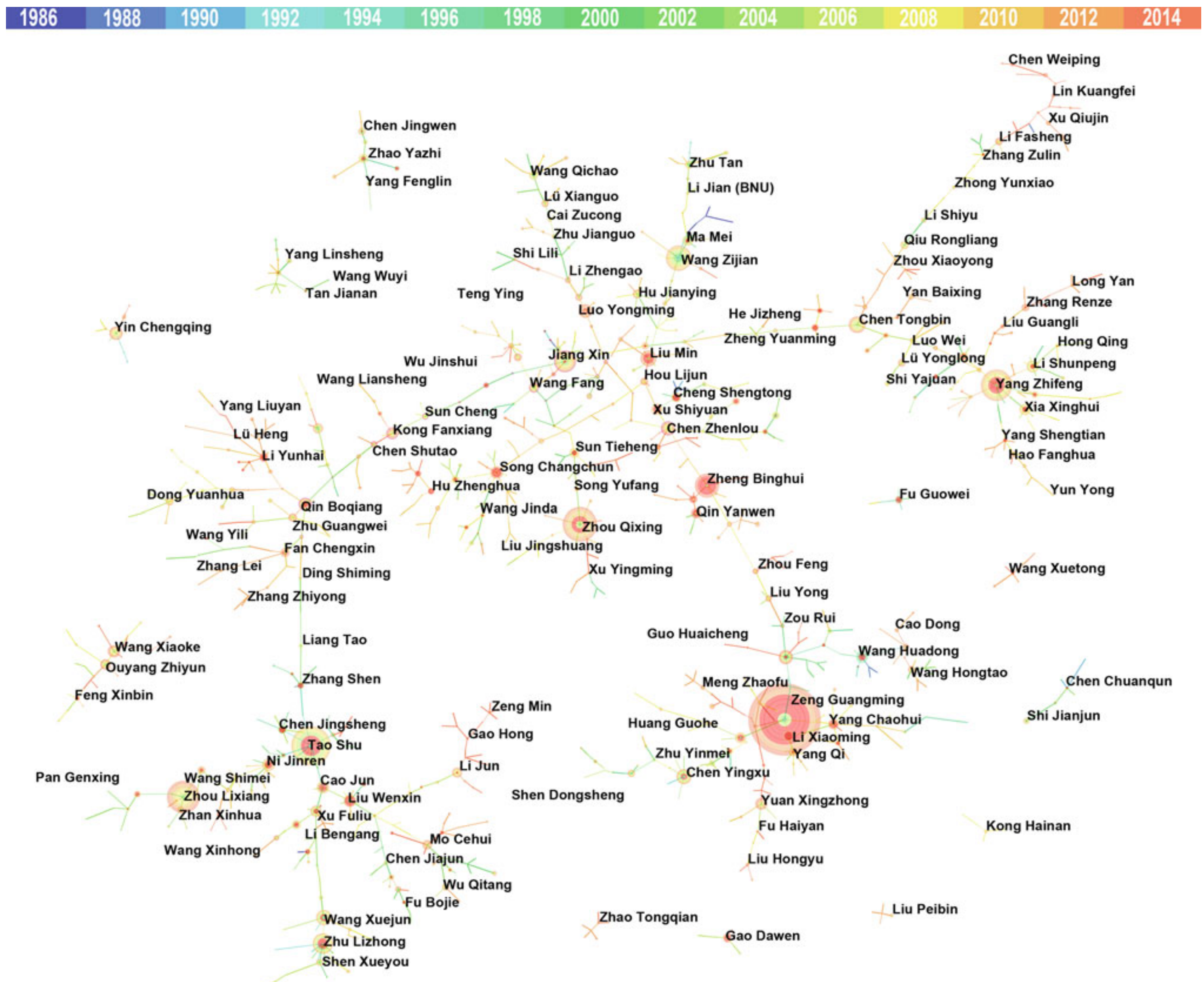


Fig. 7.25 Collaborative network of Chinese authors in CSCD journals of environmental geography during the period 1986–2015

mid-career academics and research workers in a research team. Below is an analysis of the common collaborative networks of Chinese authors shown in Figs. 7.24 and 7.25.

The Multidisciplinary Study of Environmental Geography and Pollutant Biogeochemistry

The collaborative networks with a focus on the multidisciplinary study of environmental geography and pollutant biogeochemistry were shown as follows. (1) A collaborative network of environmental geography dominated by **Tao Shu** (PKU), who conducted systematic and in-depth research on the emission, behaviour, fate, effect and other regional environmental processes of persistent organic pollutants (POPs) such as polycyclic aromatic hydrocarbons (PAHs) and established a multi-media model with spatial resolution. Together with other researchers, he has published nearly 200 academic papers in the SCI/SSCI mainstream journals including *PNAS*, *Environmental Science and Technology*, *Environmental Pollution*, *Chemosphere*, and *Atmospheric Environment*. The nodes displayed in the collaborative network included: **Wang Xilong**, **Wang Xuejun**, **Xu Fuliu**, **Liu Wenxin**, and **Liu Junfeng** (PKU); **Xing Baoshan** (University of Massachusetts) and **Gan Jay** (University of California Riverside). (2) Collaborative network led by **Zhang Gan** (GIG), who emphasised the study of geochemical processes and control principals in the region where there are harmful pollutants, and focused on research on the passive sampling and transport of atmospheric organic pollutants. **Zhang Gan** published more than 130 academic papers in the SCI/SSCI mainstream journals, especially in *Environmental Science and Technology*, *Environmental Pollution*, and *Science of the Total Environment*. The main network nodes included: **Luo Chunling**, **Li Jun**, and **Liu Xiang** (GIG), and **Kevin Jones**

(Lancaster University). (3) Collaborative network led by **Zeng Eddy**(GIG), who focused on the distribution, transport, recycling, and diffusion regularities of persistent organic pollutants (POPs) in the inshore oceanic environment as well as on their geochemical processes (such as accumulation) in aquatic organisms, and has published nearly 90 papers in the SCI/SSCI journals, especially in *Environmental Science and Technology*, *Environmental Toxicology and Chemistry*, *Environmental Pollution*, and *Science of the Total Environment*. His main collaborative nodes included: **Ran Yong**, **You Jing (**GIG), **Zeng Hui**, and **Ni Honggang** (PKU). (4) Collaboration network led by **Feng Xinbin** (GYIG), who focused on the study of biogeochemical cycle and health of heavy metals such as mercury, arsenic, and lead and published more than 90 academic papers in the SCI/SSCI journals, especially in *Nature Geosciences*, *Scientific Reports*, *Science of the Total Environment*, *Environmental Science and Technology*, *Environmental Pollution*, and *Atmospheric Environment*. (5) Collaboration network led by **Yu Gang** (Tsinghua), who focused on the environmental behaviour and risk assessment of persistent organic pollutants (POPs) and new types of organic pollutants and has published more than 70 academic papers in the SCI/SSCI mainstream journals, especially in *Chemosphere*, *Journal of Hazardous Materials*, and *Environmental Science and Technology*.

The Multidisciplinary Study of Environmental Geography and Ecology

The collaborative networks with a focus on the multidisciplinary study of environmental geography and ecology were shown as follows. (1) Collaboration network led by **Zhu Yongguan** (IUE/RCEES), who focused on the study of chemical and biological control mechanisms for the transport and accumulation of microelements and heavy metals in soil ecology and soil–plant systems, including studies on the rhizosphere processes, microbial molecular ecology, and plant molecular physiology, and who progressed the study of biotransformation mechanisms and control of microorganisms and plants for pollutants as well as antibiotics resistance gene contamination in the environment at a molecular level in recent years. **Zhu Yongguan** has published more than 140 academic papers in the SCI/SSCI journals, especially in *Environmental Science and Technology*, *Environmental Pollution*, *Environment International*, *Environmental Toxicology and Chemistry*, and *Environmental Management*. His main collaborative nodes included: **Sun Guoxin** (IUE), **Yang Min**, (RCEES), and **Andrew A. Meharg** (University of Aberdeen). (2) Collaborative network led by **Zhou Qixing** (NANKAI), who focused on the formation mechanisms and ecological remediation of environmental pollution and has led multidisciplinary research in pollution ecology and molecular toxicology. **Zhou Qixing** has published more than 30 papers in the SCI/SSCI journals, especially in *Journal of Hazardous Materials*, *Chemosphere*, *Environmental Pollution*, and *Environmental Science and Technology*. His main collaboration nodes included **Li Peijun**, and **Sun Tieheng** (IAE). (3) Collaborative network led by **Yang Zhifeng** (BNU), who focused on the study of ecological process of pollutants in the wet land and drainage basin and has participated in publishing more than 110 papers in the SCI/SSCI mainstream journals, especially in *Environmental Modelling and Assessment*, *Journal of Environmental Informatics*, and *Chemosphere*. His main collaborative nodes include **Shen Zhenyao**, **He Mengchang**, and **Lin Chunye** (BNU).

The Multidisciplinary Study of Environmental Geography and Pollution Control and Remediation

The collaborative networks with a focus on the multidisciplinary study of environmental geography and pollution control and remediation were shown as follows. (1) Collaborative network led by **Zhu Lizhong** (ZJU), who focused on the study of soil organic pollution remission and remediation and has published more than 50 papers in the SCI/SSCI journals, especially in *Environmental Science and Technology*, *Journal of Hazardous Materials*, *Environmental Pollution*, and *Chemosphere*. His main collaboration nodes included **Yang Kun**, **Chen Baoliang**, and **Gao Yanzheng** (ZJU). (2) Collaborative network led by **Huang Guohe** (NCEPU), who focused on studies of hydrology and water resources, soil and groundwater remediation and system simulation, solid waste restoration and management and has published more than 110 academic papers in the SCI/SSCI mainstream journals, especially in *Journal of Environmental Management*, *Journal of Environmental Informatics*, and *Journal of Hazardous Materials*. His main network node included **Li Yongping** (NCEPU). (3) Collaborative network led by **Wong Minghung** (HKBU), **Luo Yongming** (YIC/ISSAS) and **Chen Yingxu** (ZJU), who focused on studies of soil chemistry, and pollution control and remediation; **Wong Minghung** has published more than 200 papers in the SCI/SSCI mainstream journals, especially in *Environmental Science and Technology*, *Environmental Pollution*, *Chemosphere*, and *Environmental Geochemistry and Health*. **Luo Yongming** has published more than 80 papers in the SCI/SSCI mainstream journals, and **Chen Yingxu** has published more than 100 academic papers in the SCI/SSCI mainstream journals.

The Multidisciplinary Study of Environmental Geography and Environmental Chemistry

The collaborative networks with a focus on the multidisciplinary study of environmental geography and environmental chemistry were shown as follows. (1) Collaborative network led by **Wang Liansheng** (NJU), who focused on environmental chemistry studies of the environmental behaviour, quantitative structure and activity of organic pollutants, and has published more than 80 academic papers in the SCI/SSCI mainstream journals, especially in *Chemosphere*, and *Ecotoxicology and Environmental Safety*. His main network nodes included **Wang Gehui** (NJU). (2) Collaborative network led by **Quan Xie** (DLUT), who focused on the environmental chemistry study of organic pollutant transport and transformation. **Quan Xie** has published more than 70 academic papers in the SCI/SSCI mainstream journals, especially in *Environmental Science and Technology*, and *Chemosphere*. His main network node was **Chen Shuo** (DLUT). (3) Collaborative network led by **Zhou Dongmei** (ISSAS), who focused on the study of environmental chemistry of soil, especially the soil environmental chemistry of heavy metals and their pollution control, and has published more than 70 academic papers in the SCI/SSCI mainstream journals, especially in *Chemosphere*, *Journal of Hazardous Materials*, and *Environmental Science and Technology*. His main network nodes included **Wang Yujun** (ISSAS). (4) Collaborative network led by **Zhang Shuzhen** (RCEES), who focused on the environmental micro-interface reaction and behaviour, and bio-availability of heavy metals and persistent organic pollutants (POPs) and has published more than 70 academic papers in the SCI/SSCI mainstream journals, especially in *Environmental Pollution*, *Chemosphere*, and *Environmental Science and Technology*.

According to the statistical data on the top 200 Chinese authors with published papers in the SCI/SSCI mainstream journals for environmental geography (environmental sciences) from 1986 to 2015, there were 9174 papers, including 1338 and 1283 papers published in *Chemosphere* and *Environmental Science and Technology*, respectively, and 868 and 847 papers published in *Environmental Pollution* and *Journal of Hazardous Materials,* respectively. The number of papers published by Chinese authors on environmental geography (environmental sciences) in these four major international journals accounted for 47 % of the 9174 papers. The other of journals in which more than 200 papers were published were ranked by numbers as follows: *Journal of Environmental Sciences-China*, *Atmospheric Environment*, *Science of the Total Environment*, *Environmental Toxicology and Chemistry*, *Environmental Science and Pollution Research*, *Journal of Soils and Sediments*, and *Ecotoxicology and Environmental Safety*. Since 1985, the number of academic papers published by Chinese authors on environmental geography (environmental sciences) in the SCI/SSCI mainstream journals have increased year by year, especially since 2000. This is owing to the multidisciplinary characteristics of environmental geography, where it is not difficult to find that some authors of environmental geography have background knowledge in non-geographical sciences such as geochemistry, environmental chemistry or environmental engineering. The papers published by these authors were classified as the achievements of environmental geography because these authors or co-authors had been funded by NSFC environmental geography programmes. Other researchers in environmental science (including soil science) who had not been supported by NSFC environmental geography projects were not included in the statistics.

The author collaborative networks with a focus on **the multidisciplinary study of environmental geography and biogeochemistry** arising in CSCD journals are shown in Fig. 7.25. Besides those that were introduced in Fig. 7.24, the collaborative network led by **Liu Min** (ECNU) has made significant research progress in the behavioural processes and environmental effect of nutritive salts and persistent organic pollutants (POPs) in river mouths and coastal zones. The author collaborative networks with a focus on the multidisciplinary study of environmental geography and ecological water conservancy included: collaborative network led by **Zheng Binghui** (CRAES), who studied the pollution and control of lakes such as the Reservoir of the Three Gorges; and the collaborative network led by **Zeng Guangming** (HUNU), who carried out research on water environment pollution and remediation, especially in environmental biotechnology. The author collaborative network with a focus on the multidisciplinary study of environmental geography and pollution eco-chemistry included the collaborative network led by **Wang Zijian** (RCEES), who studied the bio-availability, ecotoxicology, ecology and health risks of persistent organic pollutants (POPs) and endocrine disrupting chemicals (EDCs).

The author collaborative networks with a focus on **the multidisciplinary study of environmental geography and pollution control chemistry** were shown as follows. (1) The collaborative network led by **Zhou Lixiang** (NAU), who studied the heavy metal pollution and remediation of soil and municipal sewage sludge composting. (2) The collaborative network led by **Chen Tongbing** (IGSNRR), who studied soil pollution and remediation, municipal sludge and urban solid waste disposition and recycling.

In addition, there were author collaborative networks led by **Jiang Xin** (ISSAS), with a focus on **the study of soil chemistry and contaminated soil remediation**, and the collaborative networks led by **Qin Boqiang** and **Kong Fanxiang** (NIGLAS) as well as by **Yin Chengqing** (RCEES), with a focus on the study of lake aquatic environments and water ecology.

Over the past 30 years, about 56 and 68 % of Chinese authors with publications in the SCI/SSCI and CSCD journals, respectively, were funded by NSFC projects. Thirty-two authors with the most publications in both

SCI/SSCI and CSCD journals, were granted 359 projects. Of the top 100 authors with the most publications in SCI/SSCI journals, 15 were once supported by the Young Scientists Fund (YSF), and 20 were funded by the National Science Fund for Distinguished Young Scholar (DYS Fund). The research teams led by **Tao Shu** (PKU) and **Fu Bojie** (RCEES) were funded by the Science Fund for Creative Research Groups (CRG Fund). The sum of funds supporting the Key Programme (KP), Major Programme (MP) and Major Research Plan (MRP) makes up 58.6 % of the total funds, and the proportion for General Programme (GP) is 16.9 %. Of the top 100 authors with the most publications in CSCD journals, 68 were supported by NSFC, 42 % of the total funds were granted to them as the General Programme (GP), and 41.8 % were granted as the Key Programme (KP), Major Programme (MP), and Major Research Plan (MRP). It is, therefore, concluded that the talent-oriented programmes and the importance-based types such as "Key" and "Major" NSFC programmes have played a major role in the international academic achievements of environmental geography in China.

Table 7.2 shows the top 5 institutions receiving various NSFC environmental geography projects, number of people supported and total funds at an interval of 5 years from 1986 to 2015. The number of people supported refers to the total of those funded by NSFC within a institution in each 5-year period. The same person was only counted once in the 5 years. Over the past 30 years, there were ten institutions ranking in the top five supported by NSFC, of which five were universities and five were research institutions. Peking

Table 7.2 Top 5 institutions with NSFC funding for environmental geography during the period 1986–2015

1986–1990			1991–1995			1996–2000		
Institutions	Number of PIs	Funding (10,000 yuan)	Institutions	Number of PIs	Funding (10,000 yuan)	Institutions	Number of PIs	Funding (10,000 yuan)
Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences	3	15.5	Peking University	3	131	Peking University	12	422
Peking University	3	13.5	Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences	3	44	Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences	4	195
Nanjing University	2	10	Beijing Normal University	3	26	Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences	7	105
Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences	1	8.5	Sun Yat-sen University	2	19.5	Research Centre for Eco-Environmental Sciences, Chinese Academy of Sciences	5	99.4
Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences	2	8	Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences	2	14	East China Normal University	4	68
Total of top 5	11	55.5	Total of top 5	13	234.5	Total of top 5	32	889.4
Total of non top 5	21	68	Total of non top 5	24	157.5	Total of non top 5	20	293.5
Total of environmental geography	32	123.5	Total of environmental geography	37	392	Total of environmental geography	52	1,182.9
Total of geography	294	1,362.3	Total of geography	374	3,840.6	Total of geography	422	9,984.9
2001–2005			2006–2010			2011–2015		
Institutions	Number of PIs	Funding (10,000 yuan)	Institutions	Number of PIs	Funding (10,000 yuan)	Institutions	Number of PIs	Funding (10,000 yuan)
Peking University	21	1,108.4	Peking University	20	1,743	Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences	48	5,161.4
Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences	16	878.8	Beijing Normal University	42	1,609	Peking University	27	4,489
Beijing Normal University	11	546	Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences	22	1,141.5	Beijing Normal University	44	3,239.6
Institute of Soil Science, Chinese Academy of Sciences	8	469	Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences	24	960	Research Centre for Eco-Environmental Sciences, Chinese Academy of Sciences	28	2,249.6
East China Normal University	6	346	Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences	15	718	Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences	27	1,919.4
Total of top 5	62	3,348.2	Total of top 5	123	6,171.5	Total of top 5	174	17,059
Total of non top 5	129	4,239.2	Total of non top 5	406	14,275	Total of non top 5	987	50,926.4
Total of environmental geography	191	7,587.4	Total of environmental geography	529	20,446.5	Total of environmental geography	1,161	67,985.4
Total of geography	890	33,800.6	Total of geography	2,197	90,823.6	Total of geography	4,821	304,971.3

University and the Institute of Geographic Sciences and Natural Resources Research of CAS have always been in the top five positions, indicating that they have prominent advantages for the study of environmental geography.

In Fig. 7.26, the per capita SCI/SSCI-indexed articles are those of institutions listed in Table 7.2, calculated by dividing total papers supported by NSFC in the 66 SCI/SSCI mainstream journals by the total number of peoples supported. The funding proportion refers to the sum of funds received from NSFC in the above-mentioned institutions to the total NSFC environmental geography funds in each five-year bin. In terms of the funding proportion of the top 5 institutions, there was a linear upward trend from 1996 to 2000, peaking at 75.2 %, followed by a rapid fall to 44.1 % from 2001 to 2005, and then to 25.1 % in the past 5 years, although the speed of decline has slowed. The linear upward process for funding proportion of the top 5 institutions revealed that such institutions had an absolute advantage in the study of environmental geography in that period. Since 2001, in step with a general increase in cross-disciplinary awareness in geographical sciences as well as strong strategic guidance from NSFC geographical sciences for interdisciplinary research, an increasing number of research institutions in environmental sciences began to join research teams in environmental geography so that competition for NSFC environmental geography funding resource increased. Stronger cross-disciplinary research and gradually improved research quality has resulted in a decentralization of funding, significantly reducing the funding proportion of research institutions with traditional environmental geography superiority. Per capita publications in environmental geography grew during every 5-year period. The number of such publication from 2001 to 2005 reached about 4. Since then the per capita number of such publication by the top 5 institutions from 2006 to 2015 had doubled and the per capita number of such publication by other institutions had increased by about 50 %. In each of the time periods, the per capita number of such publication by the top 5 institutions was higher than that of the other institutions, clearly showing that the top 5 institutions had still maintained their advantage in terms of research quality.

As the per capita publications increased, the number of highly cited papers in Chinese environmental geography went up rapidly. Figure 7.27 shows that the proportion of NSFC funded papers funded to the top 50 highly cited papers by Chinese authors in SCI/SSCI journals rose from 26 % in 2000 to 90 % in 2014, with a rapid increment especially after 2007. The proportion of papers by the top 10 institutions to the top 50 highly cited articles varied in different years, peaking at 42 % in 2005 and reaching its lowest value of 2 % in 2012. The proportion of papers published from the top 10 institutions with the most NSFC funds increased from 66.7 % in 2000 to 100 % in 2014. We can conclude that the dominant top 10 institutions in Chinese environmental geography had produced about a quarter of the most influential SCI/SSCI-indexed articles in China and NSFC projects had played a leading role in the production of such papers. Nearly 50 % of all top 50 most-cited articles in SCI/SSCI journals were funded by NSFC.

On the one hand, the production of highly cited papers in China has increased, but on the other hand, the number of highly cited papers has remained limited so far. Among the top 1000 international highly cited SCI/SSCI-indexed articles, there were 41 papers published by Chinese authors

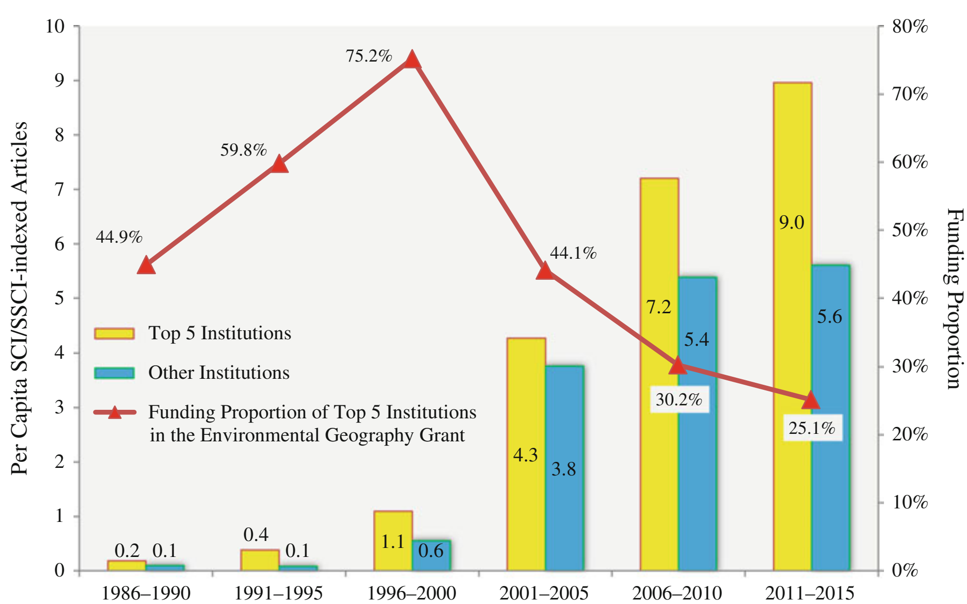


Fig. 7.26 Funding proportion of top 5 NSFC-funded institutions and their per capita SCI/SSCI-indexed articles in environmental geography during the period 1986–2015. *Note* Co-authors from different institutions were counted separately

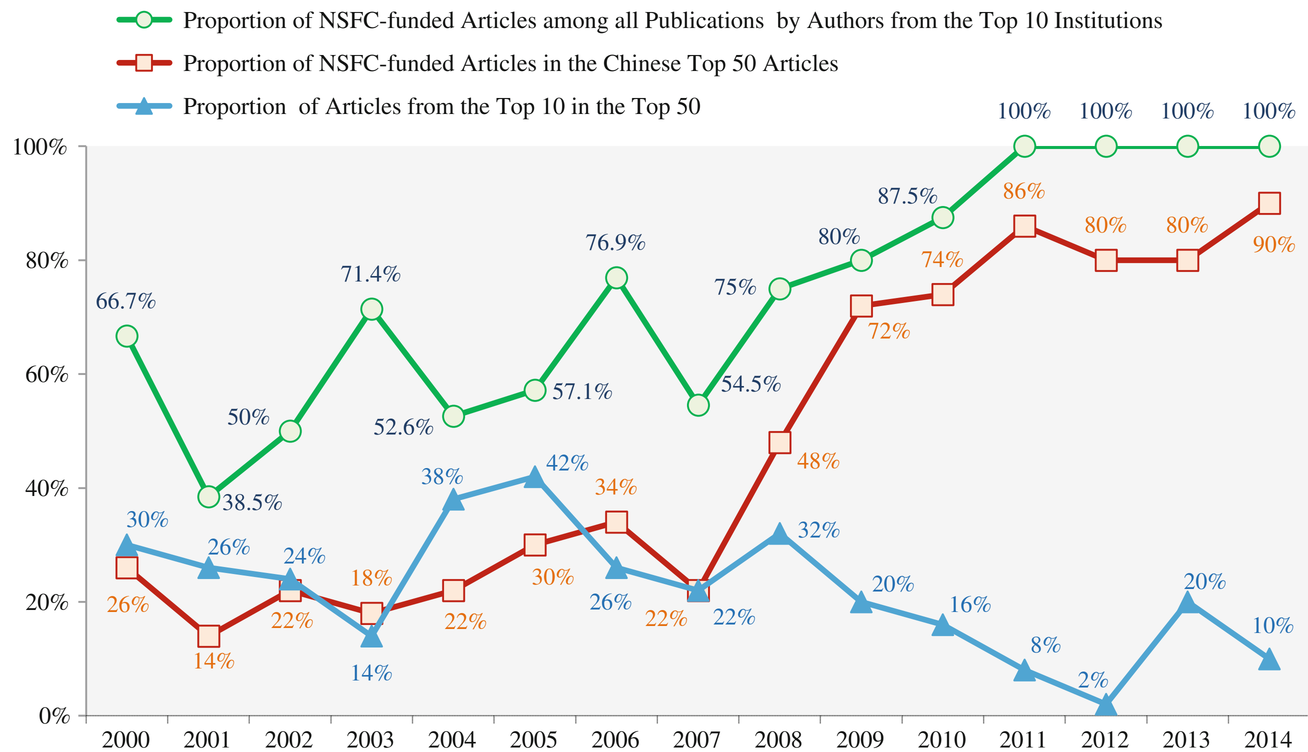


Fig. 7.27 Proportion of NSFC-funded SCI/SSCI-indexed articles in Chinese top 50 citation in environmental geography during the period 2000–2014. *Note* The Top 10 institutions refer to those with top 10 NSFC's annual funding for environmental geography during the period 2000–2014, including Peking University, Institute of Geographic Sciences and Natural Resources Research of CAS, Beijing Normal University, Nanjing Institute of Geography and Limnology of CAS, Institute of Soil and Water Conservation of CAS and Ministry of Water Resource, Nanjing University, East China Normal University, Nanjing Agricultural University, Chinese Agricultural University, Guangdong Institute of Eco-environment and Soil Sciences, Northeast Institute of Geography and Agricultural Ecology of CAS, Lanzhou University, Shenyang Institute of Applied Ecology of CAS, and Zhejiang University

Table 7.3 Analysis of top 1000 highly cited SCI/SSCI articles in environmental geography during the period 2000–2014

Periods	% of articles by American authors	% of articles by Chinese authors	% of articles with NSFC funding by Chinese authors	% of articles from Top 10 institutions with NSFC funding to articles by Chinese authors	% of articles from Top 10 institutions with NSFC funding to articles funded by NSFC
2000-2004	45.0	4.1	14.6	22.0	55.6
2005-2009	40.6	8.4	42.9	34.5	58.6
2010-2014	33.1	18.9	78.3	18.5	85.7
2000-2014	45.9	4.1	31.7	31.7	61.5

Note Top 10 institutions refer to those with top 10 NSFC's annual funding for environmental geography during the period 2000–2014, including Peking University, Institute of Geographic Sciences and Natural Resources Research of CAS, Beijing Normal University, Nanjing Institute of Geography and Limnology of CAS, Institute of Soil and Water Conservation of CAS and Ministry of Water Resource, Nanjing University, East China Normal University, Nanjing Agricultural University, Chinese Agricultural University, Guangdong Institute of Eco-environment and Soil Sciences, Northeast Institute of Geography and Agricultural Ecology of CAS, Lanzhou University, Shenyang Institute of Applied Ecology of CAS, Zhejiang University from 2000 to 2004 and 189 papers from 2010 to 2014. The top 1000 international highly cited papers during different periods (Table 7.3) indicate that, the U.S. authors contributed 459 (45.9 %) from 2000 to 2014, while Chinese authors contributed 41 (4.1 %). Over the past 15 years, the proportion of papers by U.S. authors decreased by 11.9 %, whereas that by Chinese authors increased by 14.8 %. Among the papers published by Chinese authors, the proportion of those funded by NSFC increased from 14.6 % in 2000–2004 to 78.3 % in 2010–2014. The proportion of papers published by top 10 institutions increased from 22 % in 2000–2004 to 34.5 % in 2005–2009, but then decreased to 18.5 % in 2010–2014. Of the papers funded by NSFC, the proportion of those published by the top 10 institutions increased from 55.6 % in 2000–2004 to 85.7 % in 2010–2014. The above-mentioned data indicate that internationally recognized high-level research achievements in Chinese environmental geography had increased rapidly in the past 5 years and nearly 80 % of these results were funded by NSFC projects. Approximately 85 % of highly cited papers supported by NSFC from the top 10 institutions were funded by NSFC environmental geography projects, and highly cited papers from those institutions accounted for nearly 20 % of all highly cited papers produced by Chinese authors. These research institutions in environmental geography were an important part of the high-level research institutions in Chinese environmental science more generally.

To further analyse the research themes of highly cited papers by Chinese authors and their relationship with research topics for NSFC projects, the keywords for Chinese authors of the international top 1000 SCI/SSCI-indexed articles in environmental geography were sorted by word frequency statistics to calculate the percentage of the ten keywords with the highest word frequency in the number of published papers by Chinese authors (hereinafter called "paper-based top 10 keywords"). The keywords for NSFC-funded projects in environmental geography also were sorted to calculate the proportion of the ten keywords with the highest word frequency in the number of NSFC projects in environmental geography (hereinafter called "project Top 10 keywords"). The analysis showed (see Fig. 7.28) that only 20 % of paper-based top 10 keywords and project-based keywords were identical, *heavy metals* and *PAHs*, indicating that the studies in Chinese environmental science have focused on these two types of pollutants, with a substantial research input and somewhat influential research achievements. According to the overall distribution of paper-based keywords, the studies of pollutant *performance* with focus on pollutant *adsorption, sorption* and *degradation* occupied a dominant research role, indicating that comparatively in-depth research was conducted on chemical processes. Research on media such as *water, waste water* and *particles* showed that the studies of water and atmosphere have made significant progress. According to the overall distribution of project-based keywords, there were many studies on *soil* and *sediment* and attention was paid to the *bioavailability of pollutants* and *environmental effects of pollutants*, and to *model*, reflecting the particular emphasis that environmental geography places on the study of ecological, regional and time processes of pollutants. From the perspective of changes in the proportion of keywords during different periods, the words *waste water*

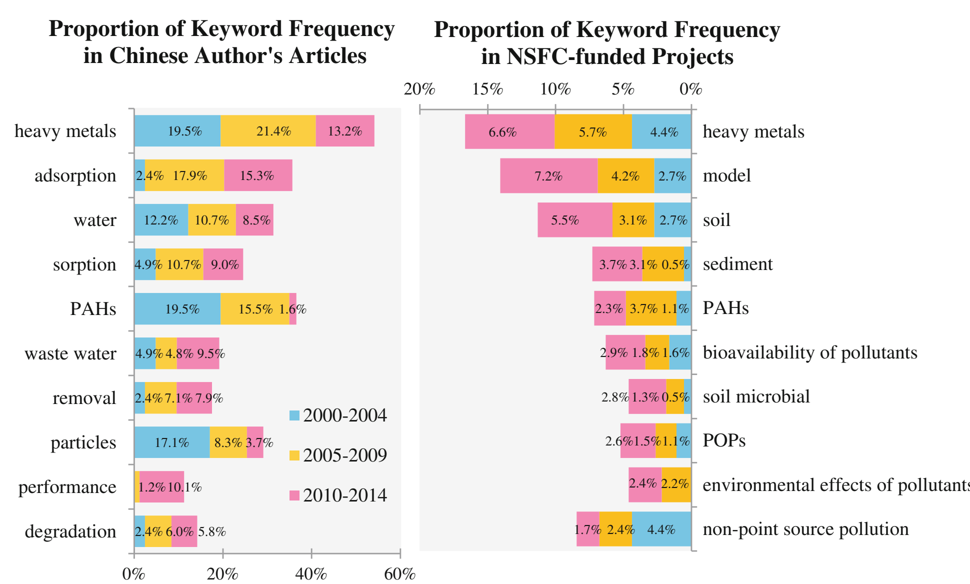


Fig. 7.28 Comparative diagram of prominent keywords in the articles by Chinese authors among the top 1000 highly cited SCI/SSCI-indexed articles with those in NSFC-funded projects in environmental geography during the period 2000–2014

and *performance* among the paper-based keywords have increased in the past 5 years, although the words *model* and *soil* among the project-based keywords have increased faster. It remains to be seen if influential achievements will be made in aspects of the model simulation studies of regional processes of pollutants and the processes of pollutants in soil over the next 5–10 years.

7.4 Summary

Driven by environmental problems, environmental geography has formed a comparatively well-developed research system over the past 30 years, along with improved measuring instrument precision and analytical methods. Extensive research has been conducted on the pollution, exposure and toxicology of heavy metals (mercury, cadmium, lead, and arsenic), and persistent organic pollutants (POPs) such as PAHs, PCBs, and pesticides in the soil, water, and sediment and in-depth investigations have been made into the emission, transmission and source apportionment of atmospheric particulates (aerosols). Research themes gradually focused on pollutant sources, earth surface processes, health effects, and risk evaluation and control. The large-scale spatial and temporal distribution, long-distance transmission and multi-media transport and transformation of pollutants have become major research subjects for environmental geography. By following both the international focus issues and those important in China, Chinese environmental geography has achieved significant research breakthroughs in aspects of heavy metal pollution and remediation of soil, eutrophication and controls in water bodies, regional environment processes of persistent organic pollutants (POPs), the health and medical geography of regional epidemics, and urban atmosphere environmental pollution and effects on human health. The number of SCI/SSCI-indexed articles and CSCD-indexed articles from 1986 to 2015 had increased rapidly, and about 58 % of these papers were published in the past 10 years. The proportion of SCI/SSCI-indexed articles published by Chinese authors reached 18 % in the past 5 years. The per capita publication figure was 1.8 times that of 10 years ago. The United States ranks first in terms of the average citations of the top 100 highly cited articles in the SCI/SSCI journals, and China has risen to the second place. Meanwhile, the average citations of all papers published by Chinese reached the average of the top 20 countries (regions), showing that the research achievements of Chinese environmental geographers have been taken seriously by their international counterparts.

NSFC has played an important role in Chinese environmental geography research. Over the past 30 years, among the top 100 authors with the most publications in the CSCD journals, 68 % were funded by projects granted by NSFC. Of the top 100 Chinese authors with the most publications in the SCI/SSCI journals, 56 % were funded by NSFC. Altogether, there were 32 scholars in the top 100 with the most publications in both the SCI/SSCI and CSCD journals. In the past 10 years, 65 % of the papers by Chinese authors in the SCI/SSCI and CSCD journals were funded by NSFC. Of the top 50 most highly cited papers in SCI/SSCI journal published by Chinese authors from 2010 to 2014, 97.5 % were funded by NSFC projects, 1.7 times that in 2000–2004. The proportion of top 1000 highly cited SCI/SSCI-indexed articles from Chinese authors from 2010 to 2014 increased by 14.8 % compared with 2000–2004, and 78.3 % of those were funded by NSFC projects. The effect of NSFC on Chinese environmental geography lies not only in funding high-level research projects, but also establishing in the disciplinary system of environmental geography and guiding the change in environmental geography from a focus on just the behavioural processes of pollutants to paying more attention to regional environmental quality, risk assessment of natural hazards, the effects of ecological restoration, and the sustainability of the resource environment. In addition, NSFC has promoted cross-disciplinary research between geographical sciences and environmental chemistry and between ecology and geochemistry by funding a large number of General Programme (GP), Key Programme (KP), and Major Programme (MP). In result, some institutions with international competitiveness of environmental geography research have been fostered including Peking University, Institute of Geographic Sciences and Natural Resources of CAS, Beijing Normal University, Research Centre for Eco-environmental Sciences of CAS, and Nanjing Institute of Geography and Limnology of CAS.

Reference

William MM, John GJ (2005) Preface. In: William MM, John GJ (eds) Environmental geography: science, land use, and earth systems. John Wiley & Sons, New York

Part III

Strategic Research Issues on the Geographical Sciences

Abstract

Part III focuses on nine strategic issues on the geographical sciences, including “global change and terrestrial ecosystems”, “terrestrial water cycle and water resources”, “land change”, “global cryosphere evolution and land surface processes on the Tibetan Plateau”, “economic globalization and local responses”, “regional sustainable development”, “remote sensing modelling and parameter inversion”, “spatial analysis and simulation”, and “tempo-spatial processes and modelling of environmental pollutants”. For each strategic issue, this part illustrates the future development trends at the macro level by analyzing the origin, implication and evolution of the issue, the sub-issues contained within it, research progress in the area, as well as representative achievements and current status. The part also provides a detailed analysis of current research trends for each strategic issue at home and abroad from 2000–2014 based on statistics such as the number of academic papers published in journals cited in the SCI/SSCI-indexed database and the CSCD core journals database; paper citations; subjects or keywords in the papers; and research projects and papers sponsored by NSFC. It can be argued that these nine strategic issues are not only prominent topics in the geographical sciences, but also comprehensive and interdisciplinary issues that receive widespread attention in related disciplines. An analysis of the research trends driving each strategic issue will greatly benefit the construction of the system of theories and methodologies essential to a comprehensive integration of the geographical sciences.

Keywords

Strategic issues in geographical sciences • Role of geographical sciences • Global change and terrestrial ecosystems • Terrestrial water cycle and water resources • Land use and land cover change • Cryosphere • Economic globalization and local responses • Sustainable development • Remote sensing modelling and parameter inversion • Spatial analysis • Tempo-spatial processes and modelling of environmental pollutants

8 Global Change and Terrestrial Ecosystems

Shilong Piao, Hongyan Liu, Zehao Shen, Jian Peng, Yangjian Zhang, Shuli Niu, Shiping Wang, and Jianguang Tan

Abstract

Anthropogenic global change has been dramatically influenced terrestrial ecosystem locally and globally during the last century, which become a severe challenge for our natural resource security and socio-economic sustainability. In this chapter, we review the state-of-art understanding on the research filed of Global Change and Terrestrial Ecosystems. Significant progresses have been achieved in such aspects as model simulations of vegetation dynamics, the macro-scale mechanism underlying biodiversity maintenance, and carbon cycling over the last 15 years. The future research requires better understanding on complex mechanisms of ecosystem dynamics, in order to project their future evolution, which is essential to design the adaptation strategies.

Keywords

Vegetation dynamics • Biodiversity • Carbon cycle • Nitrogen • Soil

A total of 40,084 SCI/SSCI-indexed articles are analyzed in the research area of global change and terrestrial ecosystems. Articles were identified from 58 international journals from 2000 to 2014. The number of journals that have published more than 15 of the relevant articles is 58 (Appendix E). The search query is as follows: "timberline" OR "treeline" OR "ecotone" OR "forest dieoff" OR "forest dieback" OR "tropical rainforest" OR "rain forest" OR "savanna" OR "desertification" OR "BIOME model" OR "plant functional *" OR "vegetation *" OR "Phenology" OR "Phenological *" OR "spring vegetation green *" OR "vegetation green-up date" OR "vegetation senescence" OR "leaf senescence" OR "* phenology *" OR "phylogeography" OR "island biogeography" OR "biological invasion" OR "species extinction" OR "species distribution model" OR "GPP" OR "NPP" OR "NEP" OR "vegetation productivity" OR "NDVI" OR "carbon source" OR "carbon sink" OR "gross primary productivity" OR "net primary productivity" OR "gross primary production" OR "net primary production" OR "plant productivity" OR "net ecosystem productivity" OR "NEE" OR "net ecosystem exchange" OR "* carbon cycle" OR "forest productivity" OR "nitrogen cycle" OR "climate change" OR "climate change impact" OR "vegetation feedback" OR "ecosystem feedback".

8.1 Overview

8.1.1 Development of Research Questions

Global change is the global environmental change induced by natural and human factors, which is here viewed as including three broad aspects: climate change, atmosphere constituent change (e.g., changes in the concentrations of CO_2 and other greenhouse gases), and land-use/land-cover change driven by pressures from population, economy and society, and technological advances. Global change has strongly impacted the environment for human survival and is very likely contributing to further environmental degradation. Thus it has become an important challenge facing the development of human society. The studies of global change and terrestrial ecosystems have originated from attention to the increasing greenhouse effects caused by the rise in the concentration of CO_2. Earlier studies focused primarily on the possible

S. Leng et al., *The Geographical Sciences During 1986–2015*,
Springer Geography, DOI 10.1007/978-981-10-1884-8_8

increase of vegetation productivity caused by rises in temperature and the concentration of CO_2. The establishment of the International Geosphere-Biosphere Program (IGBP) in the mid-1980s brought the studies of global change and terrestrial ecosystems to a new stage. As exemplified by the key research initiative of the IGBP—Global Change and Terrestrial Ecosystems (GCTE)—the studies in this field began to take into account at global and regional scales such comprehensive factors as atmosphere constituents, climate, human activities and other environmental changes to analyze the impacts on the structures and functions of terrestrial ecosystems, placing increasing emphasis on the interactions of natural and human factors and forecasting potentially complex changes in agriculture, forests, soil and ecosystems induced by global change. The Future Earth initiative launched in 2014 further integrated such global research programs as IGBP and also defined foci of study including global sustainable development, transformations towards sustainability, and dynamic planet. It incorporated the research on dynamic planet and the study of terrestrial ecosystems within the context of global change; signified the increase in research scales and multidimensional research perspectives; brought the studies in this field to a new stage in which research gradually began to serve the goal of sustainable development; and posed challenges to traditional global change studies that focused on the responses of ecosystems.

Since 1980, China has actively participated in all activities connected with international global change research programs, including preparation, organization, and implementation, as well as organized and implemented global change studies in China which correspond to international global change research programs. While remaining updated regarding the forefront of international research, the studies of global change and terrestrial ecosystems in China focused on geographic features in China; achieved unique regional research results, such as those related to monsoon evolution and terrestrial ecosystem dynamics, large-scale biodiversity patterns and processes, and Qinghai-Tibet Plateau ecosystem responses to climate change; and made significant contributions to the progress in international Earth Science.

8.1.2 Contributions by Scholars from Different Countries

In order to track the international frontier of the study of global change and terrestrial ecosystems and in the process aid Chinese researchers in crystallizing their research directions, this section uses bibliometrics analysis to examine and objectively evaluate the characteristics and progress of international research on global change and terrestrial ecosystems during the period of 2000–2014.

In 2014, China published 501 papers on global change and terrestrial ecosystems in SCI/SSCI-indexed journals, accounting for 11.9 % of the world's publications and ranking just after the United States (28.4 %) and before Australia, Germany and the UK (approximately 6 %). This proportion represented an obvious increase relative to proportions of 4.9 % during the period of 2005–2009 and 2.9 % from 2000–2004. Among the 20 countries that published the most papers in 2014, China displayed the fastest growth rate during the period 2000–2014, with an average annual growth of 18.6 %. This demonstrates that China's research in the field of global change and terrestrial ecosystems has made extraordinary progress over the past two decades. At the same time, the total number of SCI/SSCI-indexed papers published by Chinese researchers in 2014 was less than half that of those published by researchers from the United States.

In terms of citation frequency, the total frequency of cited papers by Chinese researchers reached 125 in 2014, ranking fifth in the world. The citation frequencies of the United States, the UK, Australia, and Germany rank from 1st to 4th, respectively. The total citation frequency of these latter four countries accounted for 61 % of that of the entire world. From 2000 to 2014, in the total citation frequency of papers by the 20 countries whose papers had been most cited, the proportion of the citation frequency of papers by Chinese authors had increased from 0.6 to 5.2 %, the second fastest rise behind Australia among the 20 countries. Citation frequencies declined to varying degrees for the United States, the UK, and Switzerland.

With respect to average citation frequency per paper, China was not prominent in 2014. It should be noted that the quality and quantity of papers are closely related. An increase in the number of publications can result in a concurrent increase in citation frequency and the opportunity for high-quality papers, which in turn will help to draw more attention to Chinese researchers' work from the international academic community. According to statistics on the most influential papers—here defined as those whose citation frequency ranked in the top 1 % (and hereafter referred to as "highly-cited papers")—during the period of 2010–2014, 33 papers from among the world's 1106 highly-cited papers were from Chinese researchers. The ranking of China rose from 17th during the period of 2000–2004 to 8th during the period of 2010–2014. Despite the gap with the top-ranking countries like the United States, the number of highly-cited papers from China has been steadily rising, indicating that the level of the studies by Chinese researchers in this field has begun to reach the international forefront and attract the attention of researchers worldwide.

Table 8.1 reflects the rapid development of China in the research field of global change and terrestrial ecosystems.

Table 8.1 Top 20 countries (regions) with the number and citations of SCI/SSCI-indexed articles on "Global Change and Terrestrial Ecosystems" during the period 2000–2014

	Number of articles						Cited frequency						Number of highly cited articles					
	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014
Rank	World	1,224	4,212	7,397	12,360	20,327	World	90,777	2, 404	473,934	497,799	187,953	World	268	0	1,404	1,435	1,106
1	USA	494	1,198	2,919	4,407	6,199	USA	43,902	890	226,227	208,659	71,439	USA	145	0	754	669	488
2	China	24	501	218	604	1,935	UK	13,615	219	50,414	48,932	17,788	UK	33	0	133	166	107
3	UK	141	259	598	923	1,400	Australia	2,705	189	18,062	25,688	12,556	Australia	11	0	48	69	77
4	Australia	45	274	282	546	1,335	Germany	4,423	166	30,672	30,842	11,606	Germany	16	0	78	79	63
5	Germany	70	261	413	757	1,233	China	547	125	5,802	12,418	9,474	France	3	0	43	60	48
6	Canada	48	190	309	596	945	Canada	2,500	89	16,385	20,518	8,419	Canada	10	0	49	50	44
7	France	36	139	270	456	742	France	1,614	88	14,524	22,014	7,194	Spain	2	0	26	37	34
8	Spain	30	131	202	397	685	Switzerland	3,743	61	10,872	13,272	5,950	China	1	0	9	22	33
9	Netherlands	24	95	217	359	479	Spain	1,170	55	9,424	14,343	5,860	Switzerland	8	0	30	36	32
10	Japan	29	95	225	364	453	Netherlands	1,360	47	14,529	17,101	4,906	Netherlands	3	0	42	58	27
11	Switzerland	21	80	107	249	451	Sweden	1,872	44	8,695	9,394	3,004	Sweden	10	0	33	31	18
12	Italy	16	86	84	212	370	Japan	716	36	6,275	6,933	2,595	Denmark	1	0	13	16	18
13	Sweden	31	67	165	218	354	Denmark	781	30	4,859	4,170	2,341	Japan	1	0	8	9	13
14	Brazil	12	86	95	133	339	Italy	1,388	39	4,194	7,641	2,218	Brazil	4	0	16	8	8
15	Finland	13	52	114	145	214	Brazil	1,173	41	4,574	4,045	1,789	Norway	4	0	9	15	8
16	Belgium	7	46	67	163	214	Finland	404	25	5,248	4,453	1,764	Finland	0	0	12	9	8
17	Denmark	18	41	90	97	210	Belgium	254	28	3,950	5,233	1,653	Belgium	0	0	13	12	7
18	South Africa	16	43	96	157	203	Norway	906	25	3,620	4,829	1,301	New Zealand	0	0	7	9	7
19	New Zealand	23	42	85	95	203	South Africa	1,037	25	4,067	4,377	1,260	Italy	2	0	12	18	6
20	Argentina	18	25	93	142	184	Argentina	3,086	3	6,495	3,399	950	South Africa	3	0	12	9	4

Note Countries (regions) ranked by the number of articles, cited frequency and number of highly cited articles during the period 2010–2014

This set of data can be summarized in terms of four main aspects. First, the number of publications by Chinese researchers ranks 2nd in the world and is still trending upward. Secondly, the total citation frequency of papers by Chinese researchers has risen to the 5th in the world. Thirdly, the average citation frequency per paper needs to be increased and there exists much room for improvement in the quality of the research output by Chinese researchers. Fourthly, the number of highly-cited papers of Chinese researchers has risen to a rank of 8th in the world and continues to show an increasing trend. It should be noted that since there is a time delay for papers to be indexed by SCI/SSCI, the figures in the statistics for 2014 are possibly lower than they would otherwise be.

8.1.3 Key Research Topics

In summarizing the keywords published since 2000, the main aspects of research of global change and terrestrial ecosystem may be classified into 21 major categories: "climate", "land use", "vegetation", "ecosystem", "ecotone", "community", "carbon", "productivity", "phenology", "diversity", "landscape", "soil", "nitrogen", "water", "remote sensing", "model", "region", "pattern", "disturbance", "dynamics", and "impact". These 21 major categories cover the main domains and key scientific issues in current research on global change and terrestrial ecosystems and represent the scientific frontier of studies in the discipline (Fig. 8.1).

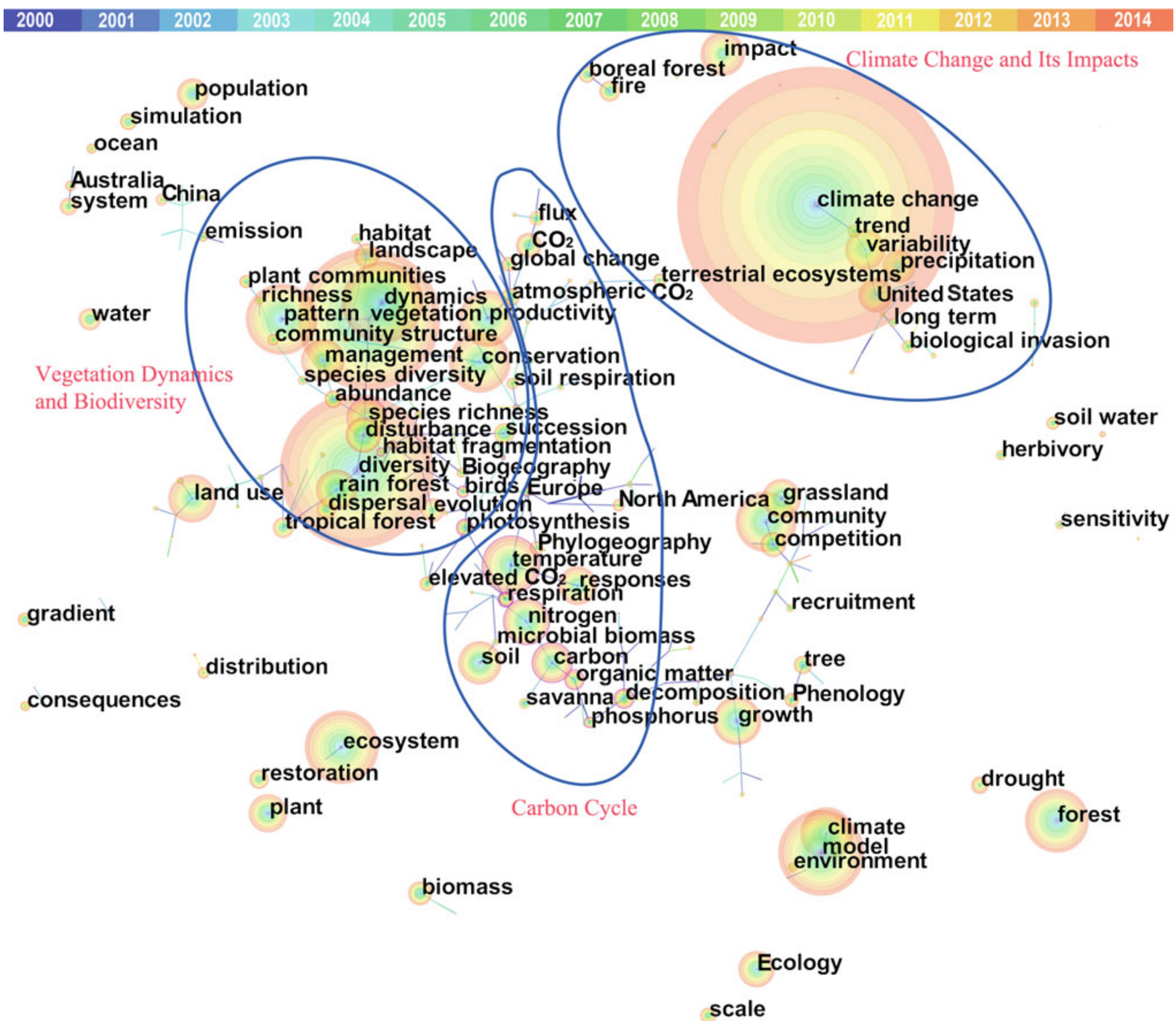


Fig. 8.1 Co-occurrence network of SCI/SSCI-indexed article keywords on "Global Change and Terrestrial Ecosystems" during the period 2000–2014

Among the 21 categories, the accumulated frequencies of the top 10 most frequently utilized categories account for 80 % of the total frequency. The frequencies of the categories "vegetation" and "climate" each account for about 13 % of the total, indicating that the vegetation-climate relationship, and vegetation patterns, dynamics and disturbances comprise the most frequently studied foci in the field (Fig. 8.2); and that this will remain a major area of research on global change and terrestrial ecosystems well into the future. The frequency of the category "carbon" accounts for

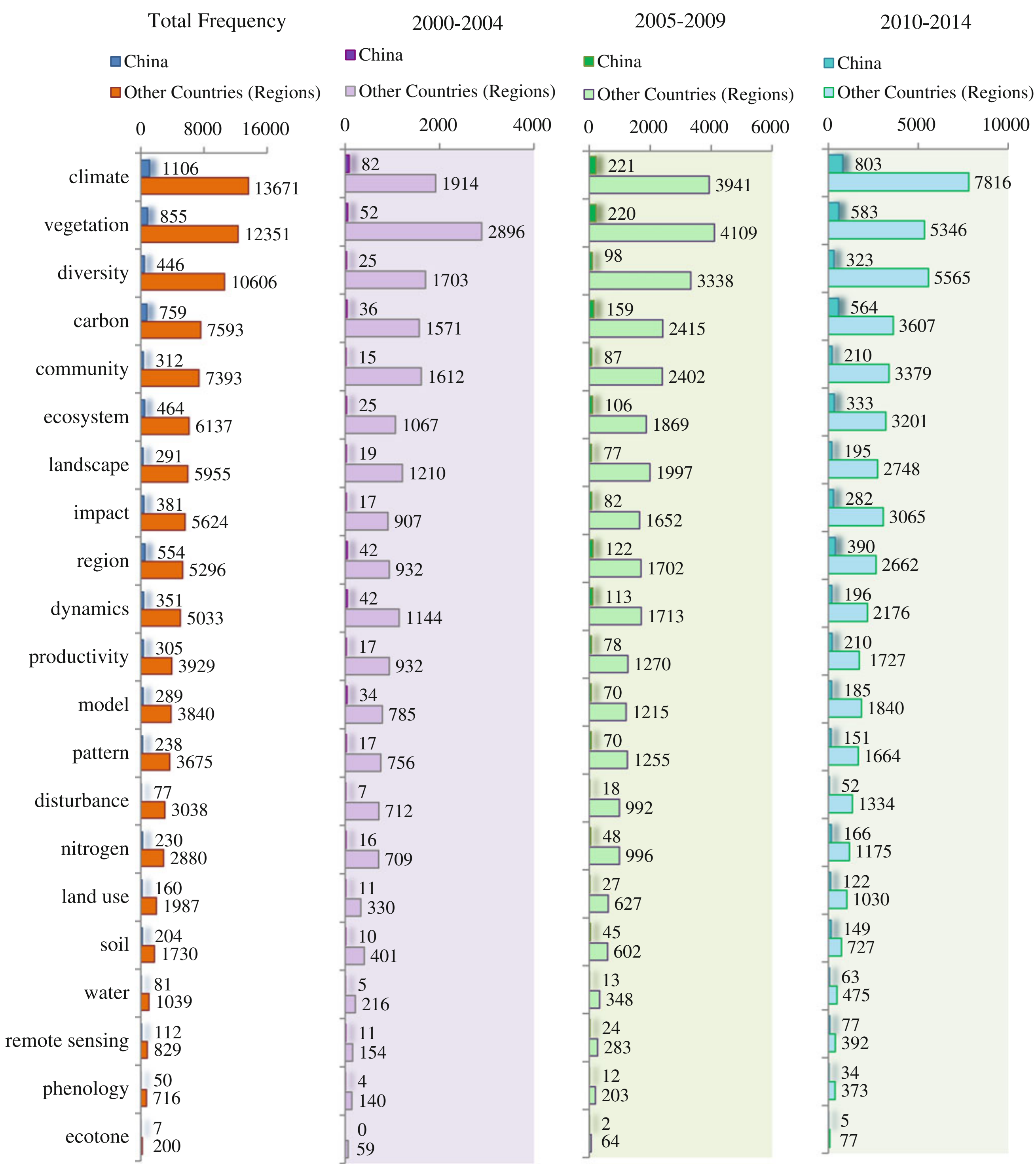


Fig. 8.2 Keyword temporal trajectory graph for SCI/SSCI-indexed articles on "Global Change and Terrestrial Ecosystems" during the period 2000–2014

7 % of the total, indicating that the response and feedback of the global ecosystem carbon cycle to climate change has become a key scientific issue in light of the need to mitigate the global temperature rise caused by human CO_2 emissions. The frequencies of keyword categories such as "community", "diversity", and "landscape" rank high, signifying that traditional research on community, biological diversity, and landscape ecology are still important foci and as such serve as avenues for the analysis of global change biology. In addition, the sharp increase in the number and overall proportion of the category "ecosystem" suggests that the responses and feedback mechanisms of different types of terrestrial ecosystems to global change have received widespread attention from the scientific community.

Among the driving factors of global change—climate change, change in atmospheric composition and land use change—the increase in the frequency and overall proportion of the keyword category "climate" is much greater than that of other categories during the period of 2000–2014. In addition, "climate" ranks first in terms of frequency over the past five years. This confirms the dominant role of climate change, including its relationship to terrestrial ecosystems, within this research field. Although the frequency of categories such as "land use" and "nitrogen" has increased substantially over the past decade, their rankings are still relatively low, suggesting that studies on changes in terrestrial ecosystems caused by land use changes and atmospheric nitrogen deposition need to be increased.

It is impossible to directly and comprehensively predict the impacts of global change on ecosystems by field control experiments at regional and global scales. Thus computer models have gradually assumed an important role in estimating the structures and functions of large-scale ecosystems. Although the construction, parameterization, and validation of the models encounter many difficulties and the outputs of the models are often questioned, they still play an irreplaceable role in the evaluation of biosphere dynamics, past and present, and as the source of predictions for the future. As is evident in Fig. 8.2, although the frequency of the keyword category "model" does not rank among the highest, it has grown rapidly since the turn of the century. It is expected to become an even more important direction for research on global change and terrestrial ecosystems in the near future. Over the past four decades, the development of remote sensing (RS) technology has provided strong technical support for the study of ecosystem change and greatly promoted the study of the influence of global change on terrestrial ecosystems. Through the use of remote sensing data, research on global change and terrestrial ecosystems has resulted in a breakthrough from discrete points to the entire geographic study areas. Nonetheless, the frequency of the keyword category "remote sensing" is still relatively low in comparison with the category "model".

At present, research on ecological transition zones is seriously insufficient and the keyword category "ecotone" occurs much less frequently than those of other major categories. In addition, phenology, as the most sensitive and easily observed "sensor" for climate change, has drawn very limited attention relative to other categories. Although the above two domains may constitute important research directions in future studies of global change and terrestrial ecosystems, the scientific community has not as yet attached enough importance to them.

In examining Chinese research trends on global change and terrestrial ecosystems in recent years, we can conclude that studies by Chinese researchers closely follow the international scientific mainstream. At the same time, there are certain differences in terms of the overall pattern of Chinese, as opposed to international studies. These differences provide an opportunity as well as a challenge for making breakthroughs and achieving the international academic high ground in research on global change and terrestrial ecosystems. In comparison with the international community, the temporal trajectory of keywords employed by Chinese researchers for studies on global change and terrestrial ecosystems displays several distinctive characteristics.

Firstly, China's research on the carbon cycle is in its infancy, although it is developing rapidly. Since 2006, in China the number and overall proportion of the keyword category "carbon" have been increasing rapidly, while from a global perspective its frequency has remained relatively stable and its proportion has changed little. Secondly, the study of nitrogen and phosphorus cycling in the geochemical cycle has drawn much attention in China. For Chinese researchers the keyword category "nitrogen" accounts for a large and stable proportion among all categories, whereas its proportion in the world is small and has decreased since the turn of the century. Thirdly, in China research on soils shows sustained development. Whereas in China the proportional occurrence of the keyword category "soil" has increased over the last decade, it has declined considerably around the globe.

While Chinese researchers should continue to build on their established progress, they also cannot ignore the challenges confronting them as well. In terms of research scale, the keyword category "region" accounts for a larger proportion in China than in the world, indicating that Chinese research on global change and terrestrial ecosystems concentrates on the regional scale and is lacking at a global scale. In terms of research achievement, the proportioin of China's high-quality research results is lower than that of the international community, indicating that China has not as yet reached the frontier of research on important and prominent issues in the world. Compared to the United States and other top research countries, China does not occupy the leading position in the field. Thus there is a need to increase the scientific research output, strengthen international cooperation, and in the process enhance the country's international status in this research domain.

8.1.4 The Role of NSFC in Supporting the Research on Global Change and Terrestrial Ecosystems

Since 2000, the number of projects sponsored by the National Natural Science Foundation of China (NSFC) geographical science department in each subfield of "global change and terrestrial ecosystems" has significantly increased. The number of projects on the carbon cycle has grown the fastest among all the subfields. During the period of 2000–2004, the subfields with the largest number of projects sponsored by NSFC were vegetation dynamics, geographical information technology and science, environmental evolution, and the carbon cycle. However, the latter had the largest number of projects sponsored by NSFC from 2010–2014, followed by vegetation dynamics, pattern and process, and climate change. This reflects the fact that geographical information science and technology is no longer a restraining factor for related research that it once was, enabling ecosystem pattern, process, function and dynamics to become more prominent foci of research (Fig. 8.3).

During the period of 2000–2014, NSFC geographic science department sponsored 320 projects in the field of global change and terrestrial ecosystems, with a total funding of 178,006 thousand yuan. It shows that 262 principal investigators from nearly 91 institutions in the country were funded (Table 8.2). The number of SCI/SSCI-indexed papers resulting from NSFC-sponsored projects has increased rapidly in recent years and exceeded that of non-NSFC-sponsored papers by a large margin. Between 2000 and 2004, 62 of the more than 210 SCI/SSCI-indexed papers published by Chinese researchers resulted from 28 projects sponsored by NSFC. From 2005–2009, this situation changed dramatically. Among the 600 SCI/SSCI-indexed papers published by Chinese researchers, 32 % were sponsored by NSFC and the number of NSFC-sponsored projects increased threefold. After that time, papers sponsored by NSFC assumed a dominant position in SCI/SSCI-indexed publications. Between 2010 and 2014, 75 % of the 1900 SCI/SSCI-indexed papers authored by Chinese researchers were funded by NSFC and the total number of NSFC-funded projects increased to 208 compared to 84 projects in the previous 5-year period. This reflects a more general increase in support by NSFC in recent years. From 2000–2004, NSFC funded 27 pricipal investigators from 19 institutions with a total funding of 11,890 thousand yuan. From 2010 to 2014, the total funding rose to 130,090 thousand yuan; the number of pricipal inverstigators (198) increased sevenfold; and the number of institutions (80) funded more than doubled. On an overall basis, it is clear that during the past 15 years the

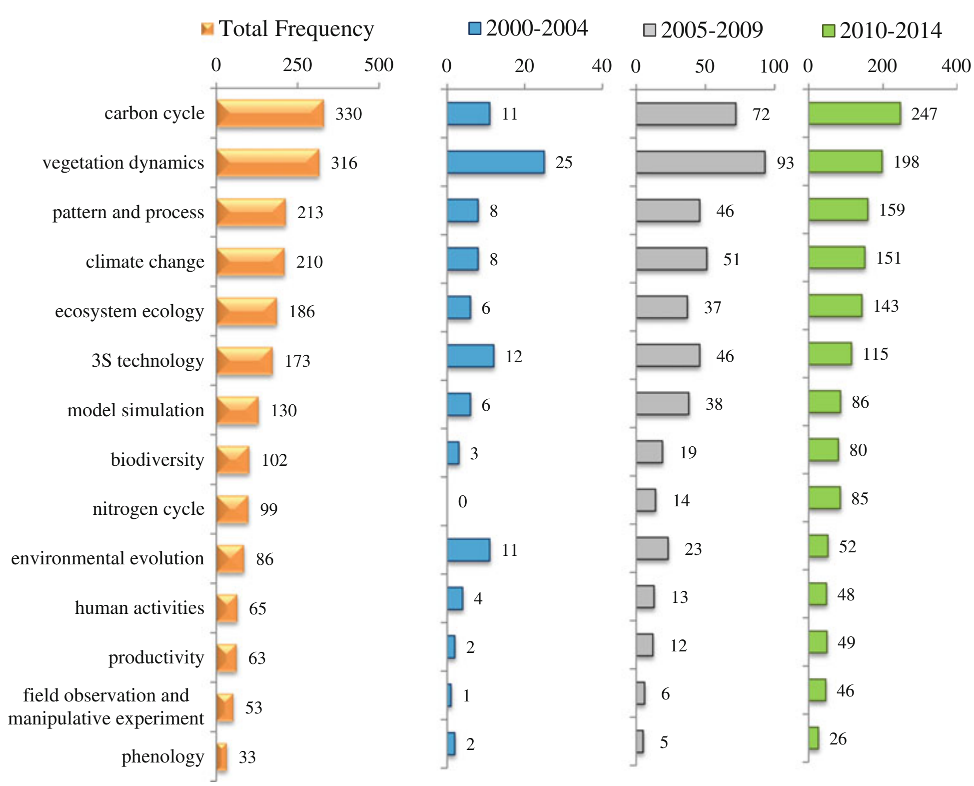


Fig. 8.3 Keyword temporal trajectory graph for NSFC-funded projects on "Global Change and Terrestrial Ecosystems" during the period 2000–2014

Table 8.2 NSFC-funded projects and SCI/SSCI-indexed articles on "Global Change and Terrestrial Ecosystems" during the period 2000–2014

SCI/SSCI-indexed articles					NSFC-funded projects			
Periods	Number of articles	% of articles by Chinese authors	% of articles with NSFC funding by Chinese authors	% of articles funded by MOST among those with NSFC funding	Number of projects	Funding (10,000 yuan)	Number of PIs	Number of institutions
2000–2004	7,397	2.9	28.9	0.0	28	1,189.0	27	19
2005–2009	12,360	4.9	31.8	33.9	84	3,602.6	77	33
2010–2014	20,327	9.5	74.5	47.3	208	13,009.0	198	80
2000–2014	40,084	6.9	61.6	44.0	320	17,800.6	262	91

geographical science department of NSFC has accorded much greater attention to research on global change and terrestrial ecosystems and gradually come to dominate the development of the field in China. Another positive trend is that the proportion of papers jointly supported by NSFC and the Ministry of Science and Technology (MOST) has gradually increased. From 2000–2004 there were no such papers, whereas this proportion rose to 33.9 % for the period of 2005–2009 and to 47.3 % from 2010–2014. This reflects a much stronger connection between NSFC-sponsored projects aiming at free scientific inquiries and MOST-funded projects orientend toward national strategies.

During the past 15 years, the projects funded by the geographical science department of NSFC have displayed the following characteristics. Firstly, the 320 funded projects represent a variety of types and different modes of NSFC-funded. The trade-off between on-site ecosystem projects and model simulations, especially such simulation research at regional and global scales, has been taken into consideration. Secondly, NSFC strongly encourages researchers to freely explore new domains in the area of global change and terrestrial ecosystems. Almost half of the 320 total projects were funded from General Programme (GP). Thirdly, NSFC has attached great importance to the start-up research of young researchers and the training of emerging talent. 96 Young Scientists Funds (YSF) were funded, accounting for 30 % of the total projects. Fourthly, NSFC has granted 35 projects of Fund for Less Developed Regions (LDR Fund) focusing on regional characteristics of global change, as well as one Joint Research Fund for Overseas Chinese Scholars and Scholars in Hong Kong and Macao, and one Joint Funds. These Fund for Less Developed Regions (LDR Fund) accounted for 10 % of all projects. Fifthly, NSFC has invested Key funds in specific areas, including 5 Major Research Plans (MRP), 12 Key Programme (KP), and 5 Special Grants, accounting overall for 7 % of the total funded projects. Finally, NSFC has devoted attention to the training of academic leaders in this research domain by sponsoring 3 National Science Fund for Distinguished Young Scholar (DYS Fund) and one Excellent Young Scientists Fund (EYS Fund).

The Key Programme (KP) and the Programmes for Talent Training by NSFC have effectively confirmed the organization's role in the fields of this discipline. Major/Key Programme (MP/KP) have focused on regions such as the Qinghai-Tibetan Plateau, the Loess Plateau, the northwest arid regions, and other key areas. Projects have examined the response of terrestrial ecosystems to global change, the formation and the maintenance mechanism of biodiversity, the environmental evolution in the past, and other foci consistent with international research. In particular, studies on the environmental evolution and the response to global change of terrestrial ecosystems in the Qinghai-Tibetan Plateau had distinct features and played a leading role for similar international studies. National Science Fund for Distinguished Young Scholar (DYS Fund) in the field encompassed discipline directions, such as ancient climate and ancient ecology, phytogeography, and vegetation and water relationships, and played a role in enhancing attention to these research areas.

8.2 Questions and Research Progress

8.2.1 How does Global Change Impact the Patterns and Processes of Terrestrial Ecosystems?

Pattern and process are the fundamental components at the core of studies of ecology and geography and the essence of geographical science (Fang 1980). For more than the past two decades, with the accumulation of long-term observational data and the technological progress in such fields as remote sensing, experimental simulation and geographical information systems, unprecedented achievements have been accomplished in research on the impact of global change upon ecosystem patterns and processes. The impact is primarily reflected in the structures and the functions of ecosystems. Concentrating on the above two aspects, this section will briefly examine the impact of global change on vegetation distribution, biodiversity and the carbon cycle of ecosystems at regional and global scales over the past 15 years; the major research advances in the above three fields; and the advantages and potential academic status of China in the future.

Effects of Global Change on Vegetation Distribution

Bibliometric Analysis of Contemporary Research

According to the statistics from the literature, 37,237 papers on global change and terrestrial ecosystems have been published worldwide since 2000 (excluding China). Among these, 12,351 contain the keyword "vegetation" accounting for 33.1 % of all papers and ranking second only to the 13,671 papers containing the keyword "climate." Although climate is the main driving factor of vegetation patterns and dynamics, other factors such as soil (1730 papers), water (1039 papers), and land use (1987 papers) have also received a lot of attention. Among all the papers, the number containing the keyword "dynamics" is 5033, which accounts for 40.7 % of the all papers containing the keyword of "vegetation" and indicates that most of the research on vegetation is concerned with its dynamics in the field of global change and terrestrial ecosystems. The research on the climate-vegetation relationship is an important aspect in the study of vegetation dynamics and the basis of the study of the influence of global change on vegetation distribution. Over the past 15 years, the research papers that contain the keyword of "ecotone", the sensitive area of climate change, have significantly increased. However, the total number of published papers is only 200, indicating that it is still a new field. Among all the vegetation types, forests receive the most attention. The research papers that contain the keyword of "forest" account for 14.9 % of all papers containing the keyword "vegetation". In addition, papers containing the keywords of "tree", "rainforest" or "tropical forest" account for 11.5 % of all papers. The number of research papers on forests is much greater than those on grasslands (4.7 %), deserts (1.8 %), and woodlands (1.2 %).

Contemporary Research

On an overall basis, the international study on the impact of global change on vegetation distribution has made significant progress in three aspects, including vegetation-climate relationships, vegetation dynamics in ecotones, and vegetation change and ecosystem services, and has promoted the development of related research as well. (1) With respect to the **vegetation-climate relationship**, past research placed more emphasis on the relationship between the distribution of vegetation types and climate conditions, and the climate parameters are based primarily on average annual temperature and annual precipitation. However, climate change can result in not only the change of vegetation types, but also that of the vegetation cover. In addition, the climate factors that bring about the vegetation change may also include climate seasonality, water deficit, and others (Fang et al. 2002). In recent years, the development of geographic information science and technology has facilitated the establishment of a database of woody plant coverage in China (Fang et al. 2009). The sample database of global and regional plant communities, such as sPlot, is under construction (http://www.idiv-biodiversity.de/sdiv/workshops/workshops-2013/splot). Meanwhile, climate databases containing more and more parameters are also being constantly improved. With the establishment of large databases, research on the vegetation-climate relationship continues to develop and deepen, as exemplified by the research on the savanna woody plant coverage and its determinants (Sankaran et al. 2005). (2) Regarding the study of **the vegetation dynamics of ecotones**, the research on global ecotones (including timberline) has become a prominent area with the improvement of field accessibility and observational ability. The alpine timberlines of the Alps of Europe, the Rocky Mountains of North America, the Andes Mountains of South America, and the Himalaya Mountains of Asia are favored areas for the studies of the vegetation impacts of global change (Cui et al. 2005). In recent years, research on the Arctic timberline has also increased annually. In addition to alpine timberlines, alpine grass lines and the vegetation zones between the forest and grass lines have also received attention. For example, the Global Observation Research Initiative in Alpine Environments (GLORIA) launched by the Austrian Ministry of Education, Science and Culture in 1999 has produced several high-level papers in the last two years and found that the alpine grass line has risen significantly during the past decade in southern Europe, whereas the trend is not obvious in northern Europe (Pauli et al. 2012). Moreover, forest decline is a widespread phenomenon in forest-grassland ecotones since the middle of last century (Allen et al. 2010). It has become a prominent research area on global change and terrestrial ecosystems. (3) **The changes in ecosystem services caused by vegetation dynamics** in the context of global change are important topics with both theoretical and practical significance. In the past 15 years, research has focused on changes in the capacities of ecosystems for carbon sequestration and the feedbacks to climate changes resulting from reforestation and deforestation, climatic aridity, and desertification caused by overgrazing, etc. Among the various vegetation types, the dynamic changes of tropical rain forests, particularly the Amazon rain forest, have received the most attention, as exemplified in research by Hilker et al. (2014) on the vegetation dynamics of the Amazon rain forest and its sensitivity to precipitation, and the research by Engelbrecht et al. (2007) on the impact of droughts on the Panama rain forest. The Millennium Ecosystem Assessment has devoted close attention, including published monographs, to research on desertification. Reynolds et al. (2007) proposed the Drylands Development Paradigm (DDP), a research system for the study of desertification.

Bibliometric Analysis of Contemporary Research in China

According to SCI/SSCI statistics for the period of 2000–2014, the number of papers by Chinese researchers containing the keyword "vegetation" is 855, which accounts for 31.0 % of all Chinese papers on global change and terrestrial ecosystems and ranks second only to papers containing the keyword "climate" (1106 papers). This proportion is close to that around the world, indicating that Chinese researchers pay much attention to the research on vegetation. The numbers of the papers containing the keywords "dynamics" and "water" are 351 and 81, respectively, which account for 41.1 and 9.5 % of the Chinese papers on vegetation, respectively, and are close to the international proportions. It should be pointed out that the proportion of vegetation study focused on dynamics, pattern and interference is significantly less than that of international studies. Seven papers have been published by Chinese researchers on sensitive ecotones, which account for 0.8 % of Chinese papers on vegetation research and are lower than the international proportion. With respect to the research on different vegetation types, Chinese researchers have placed more emphasis on forests (15.4 %), grasslands (8.1 %), and deserts (4.7 %), which is similar to research worldwide. It should be noted that Chinese researchers have also conducted studies on vegetation types which do not exist in China, such as tropical savanna grasslands and tall grass prairie in North America, reflecting the increasing degree of international cooperation.

Contemporary Research in China

From 2000–2014, Chinese researchers have made outstanding contributions in the following three areas. (1) **The expansion of the vegetation-climate relationship**. As early as the end of the last century, Chinese researchers systematically studied the vegetation-climate relationship in China (Fang et al. 2002). Zhang (1993) proposed a vegetation-climate classification system for studying global change. Fang et al. (2002) proposed the existence of the moisture gradient in addition to the temperature gradient in eastern China. It is the moisture gradient rather than the temperature gradient that determines the vegetation differentiation between the warm-temperate regions and the subtropical regions of China. These studies have laid a foundation for clarifying the difference of the vegetation distribution and the spatial differentiation of the impact of future climate change between the East Asian continental and oceanic climate zones. (2) **Timberline dynamics and its response to climate change**. Chinese researchers have conducted extensive research on this topic, such as the research on the alpine (upper) timberline and the study of the lower timberline (forest-grassland ecotones) (Li et al. 1983; Liu et al. 2013a, 2014a; Cui et al. 2005; Liang et al. 2011). The research on the dynamics of the alpine forest line of the Tibetan Plateau by Liang et al. (2011) is particularly distinctive. They found that the timberline of the Sygera Mountains of the Tibetan Plateau has not risen over the past century (Liang et al. 2011). Using datasets on the pollen, tree rings, and remotely sensed data, Liu et al. (2013a, 2014a) conducted a comprehensive study on the dynamics of the forest lines in the arid region of northern China and proposed various modes for forest-grass vegetation changes resulting from climatic aridity. (3) **The geographical patterns of the vegetation process**. In addition to the attention paid to the spatial patterns and impact factors of the vegetation types, in recent years Chinese researchers have begun further studies on the geographical patterns of vegetation processes (e.g., growth, death and regeneration) through sample-total sampling of tree rings and field investigations of plant communities. For example, through sample-total sampling of tree rings and field investigation of plant communities in the Asian continental regions, Liu et al. (2012) found that the growth rate of forests had significantly slowed in the semi-arid regions since 1994, whereas the growth rate had not shown obvious changes in the semi-humid regions. Correspondingly, forest die-off has mainly occurred in the semi-arid region of the Asian inland area (Liu et al. 2012).

Contributions by Chinese Scholars and Subsequent Problems

The advantages of the research on vegetation distribution and global change in China lie in two aspects. Firstly, China has a wide variety of types of ecosystems. From the south to the north in eastern China, there are tropical rain forests, subtropical evergreen broadleaved forests, warm temperate deciduous broadleaved forests, northern coniferous forests, and other forest ecosystems. In northern China, there is a climatic sequence of humid, semi-humid, semi-arid, and arid regions from the east to the west and a corresponding sequence of ecosystems of forest, forest-grassland,

grassland, and desert in the same direction (Fang et al. 2002). In addition, China has immense mountainous areas, and those of high altitude such as Mount Everest have a rich vertical zonation of ecosystems. Secondly, as one of the regions of the most drastic global changes, China has experienced a significant climate change. In the last three decades, the rapid expansion of urbanization, overgrazing, and other human activities have been extraordinarily prominent in China, and the land use/land cover has also changed substantially. The above two advantages provide excellent and unique conditions for research on the changes in vegetation distribution under the impact of global change. The work of Chinese researchers fully reflects these two advantages and has contributed to the study of the vegetation-climate relationship, vegetation dynamics in ecotones, and other areas.

At the same time, relative to international studies, the work of Chinese researchers still has the following issues. Firstly, it is focused mainly on vegetation types in China and is less concerned with vegetation worldwide. Secondly, large-scale investigations began relatively late in China, resulting in the lack of materials and long-term databases, in turn making it difficult to investigate the ways in which vegetation distribution has responded to climate change in China over the past few decades. Thirdly, there are still no effective monitoring networks on vegetation response to climate change in sensitive regions.

Future Research

Based on the latest research at home and abroad, the studies of the impact of global change on vegetation distribution show the following two trends–the combination of different research methods and the deepening of the theories of vegetation dynamics. (1) **Combination of different research methods**. Past studies have mostly relied on statistical relationships to predict the future vegetation distribution and have difficulty in revealing the response mechanisms of vegetation distribution to climate change. Therefore, future research needs to develop and use such means as long-term and large-scale vegetation surveys, position monitoring of the forest line, and satellite-derived observations of long sequence and high resolution. (2) **Deepening of the theories of vegetation dynamics**. Current vegetation distribution forecasting is built on the assumption that vegetation and climate are in a state of equilibrium without considering the hysteresis effect or the dynamic processes of vegetation and environment. Thus what such forecasting models predict are only potential changes. At centennial to millennial temporal scales, the hypothesis of the equilibrium between vegetation type and climate type is well founded. However, at the temporal scale of current climate change, the hypothesis may not be true. It should be pointed out that the vegetation-climate relationship often tends to deviate from the equilibrium state due to the interaction among various environmental factors and the adaptation of vegetation to global change. Therefore, future studies need to quantitatively evaluate the sensitivity, vulnerability, and adaptive capacity of different vegetation types to global changes in order to improve our understanding of the response mechanisms of vegetation to global change. It can be predicted that uncertainty regarding future vegetation distribution changes will gradually lessen with the development of the research methodology and the deepening of theories.

The Impact of Global Change on Biodiversity

Bibliometric Analysis of Contemporary Research

Among the 219 keywords in international journals concerning this strategic question during the period of 2000–2014, 21 keywords belong to the word group (i.e., keyword category) "diversity" (including diversity, biodiversity, species richness, functional diversity, species composition) and another eight keywords—i.e., biological invasion, conservation, evolution, extinction, island biogeography, and phylogeography—are related to "biodiversity". The "biodiversity" keyword group constitutes the second largest keyword group, ranking second only behind the "carbon" keyword group. In addition, the keyword groups belonging to the categories vegetation (20 keywords), community (16), landscape (9), and pattern (3), are also related to "biodiversity" in terms of research content. Thus the occurrence frequency of papers whose topics are related to biodiversity would have been underestimated if it were evaluated based only on the keywords in the literature. In terms of the proportion of the total keywords, the occurrence frequency of the keyword category of "diversity" in the literature is 10.2 %, ranking the third among all keyword groups. In terms of the change in the occurrence frequencies over different periods, the occurrence frequency of the word group "diversity" has risen from 8.4 % during the period of 2000–2004 to 11.1 % from 2010–2014. It is evident that the importance of research on the theme of "the impacts of global change on biodiversity" has been improving within the domain of "the impacts of global change on ecosystems".

Contemporary Research

Over the past 15 years, international geographical studies on the "impacts of global change on biodiversity" have made extraordinary progress in four main subject areas—the patterns and causes of biodiversity; the impact of climate change on species diversity; the geography of ecological functional traits and phylogeography; and models of species distribution and their applications. (1) **The macro patterns and maintenance mechanisms of biodiversity**. With the accumulation and integration of information on the global distribution of biodiversity, research on the large-scale patterns of biodiversity and the impacts of climate change have made important progress over the last two decades. Comprehensive discussions have been carried out regarding the distribution patterns of the species of various taxonomic assemblages along macro environmental gradients such as latitude, altitude, drought, and ocean depth; and various distribution modes have been proposed. Dozens of hypotheses have been issued on the causes of the macro-scale patterns of biodiversity (Rohde 1992). Among them, the hypotheses that are related to climate include those concerning ambient energy (Turner 2004), low temperature restriction (Currie et al. 2004), and water-heat dynamics or productivity (Brown 1981; O'Brien 1993). There have also been studies on the relationship of regional differences to historical environmental processes (Ricklefs 1987). These process-based studies have proposed important revisions and extensions to the field of island biogeography, the classic theoretical framework for biodiversity patterns (Simberloff 2001; Whittaker 2008; Lomolino et al. 2010). (2) **The impact of global climate change on biodiversity**. Based on long-term monitoring data of species composition change in different ecotones—e.g., alpine treelines and forest-grassland ecotones (Gamache and Payette 2004); forest fire frequency and plant community dynamics (Bekker and Taylor 2010); and the distribution and migration of invasive or endangered species (Occhipinti-Ambrogi and Galil 2010)—European and American researchers have conducted quantitative evaluations of the impacts of climate change on biodiversity. They have found that recent global warming has already significantly affected movement of the distribution boundaries of different species (Pauli et al. 2012). In addition, the impacts of temperature and precipitation changes on species diversity have revealed significant regional differences. Such changes create a stronger threat to endemic species with narrow ranges and to species groups with poor dispersal capacity while facilitating the diffusion of invasive species on a global scale (Fridley 2012). (3) Research on biodiversity has extended beyond the traditional analytical approach based on species number and formed **a novel macro-ecological approach based on the ecological traits and phylogeny of species** (Blackburn and Gaston 2002), which provides functional and evolutionary interpretations for species diversity patterns and climate change effects (Reich et al. 2007). Phylogeography focuses on the populations of specific taxonomic units (generally species and genus). This method investigates the formation and evolution of regional biodiversity under the integrated impact of global climate change and geological history, shedding new light on the driving mechanisms of biodiversity in such regions as the Tibetan Plateau, the Andes Mountains, and the Hawaiian Islands (Baker et al. 2014; Munoz-Ortiz et al. 2015). (4) **The species distribution model (SDM)** is a statistical tool for biodiversity analysis developed in the last two decades (Elith and Leathwick 2009). It has produced a variety of models such as MaxEnt (Phillips and Dudík 2008) and developed rapidly through its integration with remote sensing, GIS and spatial databases. It has been widely applied to the exploration of prominent biodiversity regions (Wulff et al. 2013), the evaluation of the impact of climate change on biodiversity and specific species (Pearson and Dawson 2003), and the planning of nature reserve systems. SDM has become an effective tool for testing biodiversity theories.

Bibliometric Analysis of Contemporary Research in China

Although the occurrence frequency of the "diversity" word group ranks the third among all papers written by non-Chinese researchers, its occurrence in papers authored by Chinese researchers is only 6.1 %, which is about the half of the international proportion and ranks sixth among papers by Chinese researchers after such word groups as "climate", "vegetation", "carbon", "region", and "ecosystem". Among papers sponsored by NSFC, those with the theme "biodiversity" rank only eighth and account for 5 % of all themes. These statistics indicate that geographical science in China has paid relatively less attention to the relationship between global change and biodiversity than to other research foci. Papers with the specific theme "biodiversity" published by Chinese researchers account for 4 % of the papers on this theme, much less than proportions of the other themes (the average is about 7 %). It is worth noting that the occurrence frequency of the "biodiversity" word group in papers by Chinese researchers has risen from 5.1 % during the period of 2000–2004 to 6.3 % from 2010–2014. The proportion of the papers sponsored by NSFC geographical sciences has also increased from 3 to 5.4 % across the two periods. This does suggest that the geographical sciences in China have begun to attach more importance to research on biodiversity.

Contemporary Research in China

China is an important country in terms of research on global biodiversity. Although having begun rather late in this field, China has already provided valuable input with respect to research on biodiversity and the impact of global change thereon and played an important role in various international scientific research plans and initiatives. From an overall perspective, Chinese researchers have made significant contributions in the following areas: (1) **The construction of comprehensive data sets for species distribution and the macro-scale patterns and causes of species diversity**. Over the last two decades Chinese researchers have established databases of high-resolution geographical distribution patterns for various taxonomic assemblages in China, including woody plants (Fang et al. 2009), endemic seed plants (Huang et al. 2015), birds (Zheng 2011), and mammals (Jiang et al. 2015). Based on these databases, Chinese researchers have conducted fruitful studies on biodiversity patterns and mechanisms, filled a void in the data on global biodiversity, and proposed important validations of and complements to existing theories (Wang et al. 2011). (2) **Regional inventory of plant communities**. Chinese researchers have studied the large-scale patterns and the causes of plant diversity for more than 60 mountains in China (Fang et al. 2012; Shen et al. 2012; Tang et al. 2012). Meanwhile, through the construction of large permanent sampling plots for the major zonal vegetation types of China, researchers have conducted experiments and monitoring using unified methods; studied the mechanisms affecting the composition and animal-plant relationships of local communities; and scaled up the results through network cooperation in order to examine the macro laws for the maintenance of biodiversity. These extraordinary efforts have produced some significant achievements (Shen et al. 2009; Ma et al. 2011; Mi et al. 2012; Du et al. 2015). (3) Based on the extensive biodiversity resource in China, researchers have carried out phylogeographical studies on vascular plants, fish, amphibians, reptiles, and birds, focusing on the **biogeographical effects of the uplift of the Tibetan Plateau and the fluctuations of the monsoon climate in eastern Asia** (especially the glacial-interglacial cycle of the Pleistocene glaciation) (Yan and Chen 2009; Kang et al. 2014; Wang and Ran 2014). The studies suggest that the uplift of the Tibetan Plateau and the rapid erosion in the surrounding mountain areas, in conjunction with the glacial-interglacial climate cycle since the Pleistocene, have provided a unique "cradle" of global scales for the widespread and rapid speciation process (Yu and Zhang 2013). (4) Research on **biological invasions** under the impact of climate change and human activities has evolved rapidly over the last decade. Since China possesses such rich biodiversity resources and suffers greatly from biological invasions, Chinese researchers have conducted national monitoring and formulated research plans for the monitoring, evaluation, and control of biological invasions in agriculture and forestry, with important achievements in the exploration of underlying processes (Liu et al. 2007; Liao et al. 2008; Shen et al. 2011; Wan and Yang 2016). Meanwhile, research on the protection of key species has also yielded significant results (Lei et al. 2014; Li et al. 2013; Hu et al. 2013; Bai et al. 2014).

Contributions by Chinese Scholars and Subsequent Problems

With its extensive biodiversity resources China's physical geography affords it a unique advantage for conducting studies of global change and biodiversity. In particular, the history of environmental changes centering around the uplift of the Tibetan Plateau and the glacial-interglacial cycles in the Pleistocene has exerted a profound effect on the origin and evolution of the biodiversity in east Asia and beyond. After accumulation of studies in the relevant fields for nearly a century, China has cultivated a clear understanding of its biodiversity resources in terms of species inventory, flora, and fauna at both species and community levels. This has led to global contributions in such fields as the biogeography of vertebrates, floristic geography, as well as the study of large-scale plant diversity patterns, mechanisms for maintaining species diversity, and regional differences in forest communities. Chinese researchers have played important roles in international plans and initiatives for biodiversity research and conservation, such as DIVERSITAS and Global Mountain Biodiversity Assessment (GMBA). Meanwhile China has established several basic research platforms and communication networks, such as Chinese Forest Biodiversity Monitoring Network (CForBio); accumulated a number of important biodiversity databases at multiple spatiotemporal scales; and trained a large number of young, active and competent researchers. However, there are still shortcomings in this area of geographic research in China, which consist mainly of the following three aspects. Firstly, given the relatively recent origin of related research, the basis for data accumulation is still weak. Secondly, attention paid by Chinese geographers to biodiversity is inadequate and the link between geospatial thinking and biological technology needs to be strengthened. Thirdly, research on the processes and dynamics of biodiversity is relatively insufficient and long-term monitoring and multi-scale studies need to be augmented.

Future Research

Currently, the research on the "impact of global change on biodiversity" is providing an unprecedented opportunity for solving the global biodiversity crisis and testing the fundamental theory of biodiversity. Facilitated by the information technology, as exemplified by remote sensing, GIS and the Internet, the accumulation and processing efficiency of biodiversity information have changed rapidly. Using multi-site unified techniques and standards to construct experiment and monitoring networks, processes for obtaining information on biodiversity and environmental change at regional and global scales have gradually matured. Networks for monitoring biodiversity include DIVERSITAS and Global Observation Research Initiative in Alpine Environments (GLORIA), national station networks such as National Ecological Observatory Network (NEON) and Chinese Ecological Research Network (CERN), and experimental monitoring networks for specific ecosystems such as Center for Tropical Forest Science (CTFS). These scientific networks have evolved rapidly and represent the mainstream direction of the research platforms for the evaluation and verification of the impact of climate change on biodiversity. In terms of biodiversity information processing and integration, the rapid integration of remote sensing/GIS/GPS, network databases and TDWG (Biodiversity Information Standards) technologies has forged a technological system for the collection, mining, and integration of biodiversity information, such as GBIF (Global Biodiversity Information Facility). The capacity of tools for evaluating and predicting the impact of global change on biodiversity will depend mainly on the integration of species distribution models (SDM), phenology models, and dynamic global vegetation models (DGVM). The feedback of changes in biodiversity distribution to global change will significantly alter the nature and provision of ecological system services. Within this context and inspired by the IPCC, the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) was created, and its observation network Group on Earth Observations Biodiversity Observation Networks (GEOBON) will rely on the global network monitoring and evaluation cooperation of Essential Biodiversity variables (EBVs), in order to predict the impact of global change on biodiversity and the functions and services of ecosystems.

The Impacts of Global Change on the Carbon Cycle

Bibliometric Analysis of Contemporary Research

Since 2000, 7593 papers with the keyword "carbon" have been published around the world (excluding China), which account for 20.4 % of all papers on global change and terrestrial ecosystems. The proportion is much higher than that of the papers with other keywords such as nitrogen (2880 papers) and water (1039). This indicates that the carbon cycle is a major international focus related to global change relative to biogeochemical cycles of other elements. From the period of 2000–2004 to that of 2010–2014, the number of papers with the keyword "carbon" rose from 1571 to 3607, while its percentage in all published papers did not change significantly. This confirms that research on the ecosystem carbon cycle has received continuous attention in the context of global change. Among all published papers, the number of papers with the keyword "productivity" is 3929, which is twice as large as that of the keyword "soil" (1730), suggesting that research on the soil carbon cycle is less than that on vegetation and needs to be strengthened.

Contemporary Research

From 2000 to 2014, international research on the "impacts of global change on ecosystem carbon cycle" has made significant progress in the following three aspects—the responses of vegetation productivity to global change; assessments of global and regional carbon budgets and the ecosystem carbon sink/source; and responses of the ecosystem carbon cycle to global change and their underlying mechanisms. (1) With respect to **the responses of vegetation productivity to global change**, Net Primary Productivity (NPP) that underlies the material and energy for the biosphere has been a longstanding subject in global change and terrestrial ecosystem research. With the accumulation of long-term remote sensing data, over the past 15 years the research focus has shifted from the assessment of global or regional productivity to productivity dynamics and its forecasting. Representative studies include Zhou et al. (2001) and Nemani et al. (2003). Although results may differ among various studies, the trends in vegetation productivity are basically the same. Global change has resulted in an increase in global terrestrial ecosystem productivity over the past 30 years and this increase has diminished or stagnated for the last decade (Zhao and Running 2010). Currently, exploring the driving factors for the stagnant trend of global vegetation productivity over the last decade has become a prominent research focus. (2) **In terms of global and regional carbon budgets**, **the estimation of global ecosystem carbon sink/source areas and their distributions** constitutes an important part of the scientific input to climate change negotiations aimed at reducing carbon emissions and plays an essential role in constructing a fair and reasonable international carbon emission reduction program. In recent years, increasing attention has been paid to the study of global and regional carbon budgets. Many countries have initiated a series of large scientific research programs on the carbon cycle, such as the CarboEurope launched by the European Union that focuses on carbon storage/flux in the European terrestrial ecosystem and the Regional Carbon Cycle Assessment and Processes Program recently organized by the Global Carbon Project that estimates the carbon balance in various regions (Canadell et al. 2011). In terms of ecosystem carbon sink/source research, the analysis of observed atmospheric CO_2 concentrations shows a significant increase in the global carbon sink over the last half century (IPCC 2013), but its spatial pattern is still poorly understood. The question arises as to whether in light of global climate change the ecosystem carbon sink will be sustained in the future. This issue has attracted widespread attention from the entire scientific community. A large quantity of carbon is stored in high-latitude permafrost and tropical rainforests. Dynamic changes in the carbon stocks in these regions have become important focuses of research. Representative studies include Zimov et al. (2006), Phillips et al. (2009), Lewis et al. (2009), Koven et al. (2011), and Schuur et al. (2015). (3) Regarding **the processes underlying the response of the ecosystem carbon cycle to global change**, climate warming, elevated atmospheric CO_2 concentration, increased atmospheric nitrogen deposition, forest restoration, and the increases in the establishment of tree plantations are generally considered to be the main mechanisms responsible for the global carbon sink (Norby et al. 2005; Wan et al. 2005; Magnani et al. 2007; Knapp et al. 2008; da Costa et al. 2010; Janssens et al. 2010). Although the above-mentioned four mechanisms have been proposed, their relative roles in determining the C sink is still quite uncertain and results differ among various studies. In addition, in the context of global change, the occurrence of extreme climate events becomes more and more frequent and the response of the carbon cycle to these extreme events is different from that of long-term gradual climate change. Thus study on the response of the carbon cycle to extreme climate and its recovery process has become another important focus of carbon cycle research (Ciais et al. 2005; Phillips et al. 2009).

Bibliometric Analysis of Contemporary Research in China

Over the past 15 years, among all papers published by Chinese scholars (2757 papers) in the field of "global change and terrestrial ecosystems", there are 759 papers with the keyword "carbon", which account for 27.5 % of all the papers and is higher than the international proportion. This indicates that the Chinese scientific community attaches more importance to research on the carbon cycle for global change and terrestrial ecosystems than the international scientific community. From the period of 2000–2004 to that of 2010–2014, the proportion of Chinese papers with the keyword "carbon" rose from 16.5 to 29.1 %, reflecting increased attention to the carbon cycle by Chinese scholars. Among all the papers, there are 305 papers having the keyword "productivity", accounting for 40.2 % of papers with the keyword "carbon". This is slightly lower than the international proportion (51.7 %). There are 204 papers with the keyword "soil", accounting for 26.9 % of all papers with the keyword "carbon." This is slightly higher than the international proportion (22.8 %).

Contemporary Research in China

On the whole, Chinese scholars have made significant contributions in the following two areas related to the carbon cycle. **The first is the regional carbon budget**. Through comprehensive study over the past two decades, Chinese scholars have quantified the carbon budget in many Chinese ecosystems, which significantly reduces uncertainty related to the global carbon budget. For example, Fang et al. (2001) used forest inventory data to estimate biomass change in Chinese forest vegetation over the past three decades, and Zhou et al. (2006) found that old subtropical forest soils were still functioning as a strong carbon sink. Recently, Yu et al. (2014a) used continuous CO_2 flux observations to estimate Net Ecosystem Production (NEP) of Chinese subtropical forest ecosystems, which confirmed that Chinese subtropical forests acted as a carbon sink. Piao et al. (2009) used top-down and bottom-up approaches to estimate the size and uncertainty of the Chinese terrestrial carbon sink, finding that China's terrestrial ecosystems absorbed 28–37 % of its accumulated fossil carbon emissions during the 1980s and 1990s. **The second significant contribution concerns the responses of the carbon cycle to global change**. Through controlled field experiments Chinese scholars have systematically explored responses of the typical ecosystem carbon cycle to temperature change (Wan et al. 2009), moisture change (Liu et al. 2009) and nitrogen addition (Mo et al. 2007). In addition, Yu et al. (2014b) used observations of ecosystem carbon flux based on China FLUX to systematically clarify key processes and control mechanisms of the carbon cycle of China's typical ecosystem. In recent years, Chinese scientists have also begun to explore responses of the carbon cycle of global and other regional ecosystems to climate change. For example, the team led by Shilong Piao in Peking University has made important progress in quantifying the impacts of daytime and nighttime warming on the terrestrial carbon cycle in the Northern Hemisphere and the changes in the temperature sensitivity of tropical ecosystems. Some of these results were published in *Nature* (Peng et al. 2013; Wang et al. 2014). The aforementioned work provides an important theoretical basis for improving existing ecosystem carbon cycle models and Earth System Models, and enhances both understanding of and capacities to predict the responses and feedback processes of terrestrial ecosystem carbon sink/sources to climate change.

Contributions by Chinese Scholars and Subsequent Problems

China is the largest emitter of CO_2 in the world, and quantification of the size of the carbon sink of Chinese terrestrial ecosystems receives widespread attention from both Chinese and foreign scientists in the international community. In recent years, Chinese scholars have conducted a great deal of research on the capacity for carbon sequestration of Chinese terrestrial ecosystems and have basically quantified the size and the strength of the carbon sinks of these ecosystems at the country level. This bridges an important gap in the global carbon balance and reduces the uncertainty in estimating global carbon sink/sources, in effect representing an outstanding contribution to the accurate assessment of the global carbon balance. In addition, utilizing China's unique geographical resources, Chinese scientists have conducted a large number of field control experiments on different types of ecosystems; systematically clarified the responses of ecosystem carbon cycles to simulated changes in hydrothermal and nutrient status; deepened the understanding of response mechanisms of the ecosystem carbon cycle to global change in the northern hemisphere (especially in such unique natural geographical units as the Tibetan Plateau); and enriched the knowledge system of global change ecology. At the same time, Chinese scholars have focused mainly on the impacts of climate change on terrestrial ecosystem carbon cycles at regional scales, but fewer studies have been conducted regarding the responses and feedback mechanisms of the global carbon cycle to global change. In addition, in terms of the impacts of global change on the carbon cycle, most domestic research in China is still follow-up studies that lack originality. For example, China still lacks ecosystem models that incorporate independent property rights as well as original research findings on ecosystem carbon cycling processes and their underlying mechanisms.

Future Research

Given the recent status at home and abroad with respect to the impacts of global change on terrestrial carbon cycles, future research needs to focus on the following three areas. **The first is on reducing the uncertainty of carbon budgets at regional scales**. Currently, there is substantial uncertainty regarding estimates of carbon sinks/sources at national and regional scales. In the future studies of the carbon cycle, it becomes a major challenge to find an effective way to accurately estimate the carbon budget at national or regional scales in order to meet greenhouse gas emission reduction targets established in international negotiations. This requires cross-scale observations and model ensemble simulations on terrestrial ecosystem carbon cycles. In addition, vegetation and soils are two main carbon stocks in terrestrial ecosystems. The size of vegetation carbon sinks has been somewhat clarified, but the estimation of soil carbon sink/sources remains most uncertain. It is therefore necessary to conduct long-term monitoring of soil carbon storage and its temporal change in different regions. **The second focal area concerns deepening our understanding of coupled carbon-nitrogen-water dynamics and their underlying mechanisms**. In future studies, we should not only study the impacts of global change on carbon cycles but also pay attention to the interaction and coupling of the carbon cycle with other cycles such as those of nitrogen and water. In addition, under natural conditions, different environmental factors (such as elevated CO_2 concentration, global warming, altered precipitation patterns, and increased nitrogen deposition) often co-vary and the individual contribution of these driving factors to each carbon cycle component cannot be simply added together to yield an end result. It can be very difficult to generalize single-factor experimental results to the actual responses of the whole ecosystem to global change. Therefore, the latest research trend is to progress from short-term single-factor control experiments to long-term multi-factor experiments. In addition, the scientific foci also shift from understanding the impacts of changes in single-factors (e.g., temperature, CO_2 concentration, precipitation, atmospheric nitrogen deposition) to studying the synergistic effect of different environmental factors on ecosystem processes. **The third focal area for future research is on strengthening observational studies of the carbon cycle in key areas**. Most of the previous observation studies on ecosystem carbon cycles have focused on the temperate regions, while those on ecosystems such as tropical rain forests and alpine ecosystems are much fewer. This significantly limits our understanding of the responses of the carbon cycle to global change and their underlying mechanisms. For example, we still cannot quantify how much C can be released from permafrost in the Tibetan Plateau and pan-arctic region in response to future global warming. How large will the feedback of C released from the permafrost to future global warming be? These issues will receive continuing attention in global studies on the carbon cycle.

8.2.2 How can the Impacts of Global Change on Terrestrial Ecosystems at Different Spatiotemporal Scales be Effectively Observed and Simulated?

Impacts of global change on ecosystems are multi-scaled and multi-layered. How to timely and effectively observe and evaluate ecosystem responses to global change poses a challenge to the development of the geographical sciences. Meeting this challenge calls for the application of a variety of observational methods and technical means to carry out systematic and comprehensive research. Current research methods mainly include ground-based observations and surveys, manipulative experiments, and remote sensing and model simulations; and continued refinements in these methods have directly enhanced the knowledge base regarding the impacts of global change on ecosystems. At this point in time, some large monitoring networks have been constructed and are in place for specific regions or ecosystem types. Some regional networks have also been established to comprehensively study various surface phenomena. These observation and monitoring networks allow for direct descriptions of relevant phenomena for research on global change and terrestrial ecosystems. The objectives of manipulative experiments are to simulate the impacts of various global change phenomena on terrestrial ecosystems, understand ecosystem response processes, and provide parameter tests and a theoretical basis for ecosystem forecasting and simulation. Remote sensing technologies provide spatially explicit data, reflect continuous ecosystem changes at global and regional scales, and can be used to summarize the laws underlying spatial patterns that govern ecosystem responses to global change. Model simulations are effective means for forecasting global change and related impacts on terrestrial ecosystems.

Bibliometric Analysis of Contemporary Research

A summary of the literature revealed that from 2000–2014, there have been 37,237 papers published in the field of global change and terrestrial ecosystems by the international community (excluding China). Among these, 3840 papers utilized the keyword "model" and 829 employed the keyword "remote sensing". They account for 10.3 and 2.2 % of the total papers, respectively. The low proportion for remote sensing suggests that traditional ground-based observation is still a major research tool for research on global change and terrestrial ecosystems. After 2000, the number of papers with the keywords "model" and "remote sensing" have increased substantially, whereas the weight they carry for the field of global change and terrestrial ecosystems has not undergone any obvious changes.

Contemporary Research

Over the last 15 years, the international research community has achieved significant progress in observing and simulating impacts of global change on terrestrial ecosystems. (1) With respect to **ground observations and surveys**, many positioning observations have been automated. The observed spatiotemporal range, observation frequency, and accuracies have all increased significantly. At present, establishing regional positioning observation networks has become a key goal of major observation programs for global change and ecosystems. For example, in conjunction with the "BigFoot" program of the National Ecological Observatory Network (NEON, http://www.neoninc.org/) and the National Aeronautics and Space Administration (NASA), joint observational and comparative studies can be conducted for ecosystems across different scales in order to comprehensively analyze the driving mechanisms underlying ecosystem change. To accurately monitor ecosystem carbon cycling, the international community has established nine regional carbon flux observation networks, including AmeriFLUX in the United States, CarboEurope in Europe, ChinaFLUX in China, and others (Baldocchi et al. 2005; Baldocchi 2008). (2) In terms of **manipulative experiments**, the international community has carried out a large number of such experiments related global change via such manipulations as enriched CO_2 (Schlesinger and Lichter 2001; Norby et al. 2005), elevated temperature (Luo et al. 2001; Melillo et al. 2002), modified precipitation (Knapp et al. 2002; Xu et al. 2013), and enhanced atmospheric nitrogen deposition (Bai et al. 2010; Niu et al. 2010). On the basis of hundreds of such experimental platforms around the world, a research network focusing on terrestrial ecosystem responses to atmosphere and climate change was established (i.e., An Integrated Network for Terrestrial Ecosystem Research on Feedbacks to the Atmosphere and Climate, INTERFACE, http://www.bio.purdue.edu/INTERFACE/index.php). Its aim is to uncover universal laws governing the mechanisms of terrestrial ecosystem responses to global change at regional and global scales through analysis of integrated findings from different locations and ecosystems. (3) The rapid development of **remote sensing technology** has made it possible to conduct direct observations at regional and global scales; facilitate the progression from point to surface, qualitative to quantitative analysis, and from individual to comprehensive themes for research on global change and terrestrial ecosystems. Thus for example, on the basis of development over several decades, optical remote sensing technology has accumulated a large number of Normalized Difference Vegetation Index (NDVI) data gathered by National Oceanic and Atmospheric Administration/Advanced Very High Resolution Radiometer (NOAA/AVHRR). These data series have made it possible to carry out previously difficult research on vegetation coverage and productivity at large spatial and long-term temporal scales (Zhou et al. 2001). The subsequent development of laser radar technology has also made possible the more accurate estimation of tree height, canopy density, and above-groud biomass (Lefsky et al. 2005; Baccini et al. 2008;

Mitchard et al. 2013). (4) With respect to **model simulation**, over the past three decades ecosystem models have evolved from simple statistical programs to sophisticated models for vegetation dynamics. At present, dynamic vegetation models such as LPJ (Sitch et al. 2003) and ORCHIDEE (Krinner et al. 2005) have been widely applied in studies of global change and terrestrial ecosystems. These models can simulate not only impacts of global change on carbon cycling, but also the responses of ecosystem structure to fire, deforestation and other disturbances.

Bibliometric Analysis of Contemporary Research in China

Since 2000, Chinese scholars have published 2757 papers on global change and terrestrial ecosystems. Among these, 289 papers utilize the keyword "model". They account for 10.5 % of the total number of papers, a proportion which mirrors that of the international community. 112 papers by Chinese researchers have employed the keyword "remote sensing". They account for 4.1 % of the total, which is higher than the percentage (2.2 %) of the international community. From the periods of 2000–2004 to 2010–2014, the number of papers with the keyword "model" has increased from 34 to 185, whereas the proportion of the total has fallen from 15.6 to 9.6 %. The number of papers with the keyword "remote sensing" has increased from 11 to 77, whereas its proportion has fallen from 5.0 to 4.0 % during the same periods.

Contemporary Research in China

China has made concrete and significant progresses in three areas—ground-based observations and surveys, manipulative experiments, and remote sensing. (1) Regarding the first of these areas, in initiating scientific research on global change China has achieved rapid development in the use of positioning observations, ground-based surveys, and research networking establishments. In 1988, China set up the Chinese Ecosystem Research Network (CERN, http://www.cern.ac.cn) that focused on a variety of ecosystem types including forests, grasslands, deserts, swamps, lakes, ocean, and urban environments. China subsequently established the Chinese National Ecosystem Research Network (CNERN). Led by Ma Keping of the Institute of Botany, the Chinese monitoring network of forest biological diversity (http://www.cfbiodiv.org/) employed permanent large sample plots (>10 hm^2) to monitor biodiversity change and conduct interaction experiments between community and environmental processes. The permanent plot studies elevated the study of plant community ecology in China to the international frontier in this field of research (Shen et al. 2009; Ma et al. 2011; Mi et al. 2012; Du et al. 2015). (2) With respect to manipulative experiments, Chinese scientists began conducting field manipulative experiments on natural ecosystems at a relatively late date. However, they still accomplished some remarkable achievements. To date, there are nearly 100 global change manipulative experiments on natural ecosystems underway in China, including 19 warming simulation experiments, 19 modified precipitation simulation experiments, 39 nitrogen deposition simulation experiments, and 17 manipulative experiments on other factors (such as CO_2, phosphorus addition, etc.). For example, since 2005, Wan Shiqiang of Henan University supervised the design and implementation of China's first large-scale (an area of 5.3 ha) and multi-factor (mowing, nutrient addition, precipitation increase and warming) manipulative global change experiments in the Innner Mongolia Steppe ecosystem (Wan et al. 2009; Niu et al. 2010). (3) With regard to remote sensing technology, China's satellite positioning system and remote sensing applications of multiple sensors and multiple platforms have advanced to a position on the global frontier. For example, under the auspices of National High Technology Research and Development Program of China, the National Administration of Surveying, Mapping and Geoinformation, in cooperation with 17 ministerial institutions and enterprises, developed the "global land cover data of 30 m". Liang et al. (2011) created a series of radiative transfer models of soil-vegetation-atmosphere systems, developed a series of inversion algorithms of surface parameters based on satellite remote sensing, and developed global leaf area index (LAI) products over the past 30 years.

Contributions by Chinese Scholars and Subsequent Problems

Chinese developments in the area of ground-based observations and surveys, manipulative experiments, and remote sensing technology have made significant contributions to research on the impact of global change on terrestrial ecosystems. The ecosystem research network and the various flux observation networks established by China serve as long-term scientific observation and experiment platforms for studying global change and terrestrial ecosystems. These platforms can facilitate long-term and large-scale process studies, improve our capability to resolve the questions arising from individual sites, and speed up the modernization of the observation instruments and technical means for the study of ecosystem ecology (Sun 2006; Sun et al. 2014). The Chinese forest biodiversity monitoring network is the world's largest (in terms of scale) and most systematic monitoring and research network of its kind. It is comprised of large plots situated in most ecosystems around the world, with the exception of tropical areas. It constitutes a research platform capable of integrating studies of the impacts of climate change on biodiversity across scales and disciplines. The various field manipulative experiments in China have generally enriched the scientific community's knowledge of the impacts of global change on Chinese terrestrial ecosystems and provided necessary and crucial means for parameter estimation, model verification, and calibration for model simulation and forecasting. China's rapid development of remote sensing technology constitutes a strong base of technical support and a significant growth opportunity for studying global change and terrestrial ecosystems using remote sensing. With respect to simulation modeling, the vegetation dynamics model has become an important tool for addressing the impacts on terrestrial ecosystems. At the same time, however, China still lacks a dynamic vegetation model with independent intellectual property rights and consequently China's capability to predict terrestrial ecosystem responses to future global change is undermined.

Future Research

Propelled by the rapid development of the various research tools and methods such as remote sensing technology, manipulative experiments, simulation models, and long-term network data accumulation, the study of the impacts of global change on terrestrial ecosystems is developing at an unprecedented pace. However, there is still much to achieve. Chinese scholars can play an increasingly important role in the development of research tools. Currently, ground-based observations and surveys, as well as the global field observation network, are mostly concentrated in the temperate regions. The related observation sites are still inadequate in some critical zones such as the Tibetan Plateau. Constructing China's surface process and environmental monitoring network (http://www.horn.ac.cn) in alpine regions could provide a timely remedy to this shortcoming while enhancing current understanding of the response of the Tibetan Plateau ecosystem to global change. With respect to manipulative experiments, China has recently established the world's first field warming experiment targeting the sub-tropical forest ecosystem, as well as the first canopy nitrogen deposition experiment. These manipulative experiments will advance our understanding of the mechanisms underlying ecosystem responses to global change. However, it should be noted that, although a great number of manipulative experiments have been established around the world, their findings are not readily comparable and difficult to cross-validate, with occasional results that are even contradictory. This is due primarily to the fact that a standardized design among all experiments is lacking. Establishing coordinated network experiments is critical for conducting ecosystem research in the next generation (Vicca et al. 2012; Fraser et al. 2012). For remote sensing technology, the long-term accumulation of remote sensing data by the Fengyun series of satellites will greatly facilitate the study of terrestrial ecosystem dynamics. China's first CO_2 monitoring satellites will be launched, which will fill in technology gaps involving greenhouse gas monitoring in China, aid China to better understand the laws underlying global warming and the global spatial patterns of carbon emissions and provide strong technical support for solving issues related to global climate change (Liu et al. 2013b; Zhang et al. 2014). With respect to simulation models, the current vegetation dynamic models are still in a developmental stage, particularly for carbon cycling simulation of permafrost and the interactions among carbon, nitrogen, and water cycles. China Meteorological Administration, Peking University, Tsinghua University, Beijing Normal University, and other institutions are developing Earth System Models, which will provide opportunities for developing a new generation of vegetation dynamics models for which China has independent intellectual rights.

8.2.3 How may Terrestrial Ecosystems be Sustainably Managed in the Context of Global Change?

The sustainable management of ecosystems has always been an important goal of studies on global change and terrestrial ecosystems. Human activity is an important cause of global change. Nowadays nearly one half of the global land surface has been transformed by human activities and the concept of human-dominated ecosystems has been widely recognized. In the context of the huge impact of human activities on ecological structures and functions, the fundamental way to avoid excessive consumption of ecosystems and prevent threats to human well-being (Western 2001) is to establish a framework of sustainable management for the protection of natural ecosystems. Through a comparison of 34 global governmental decisions, the benefits of adaptive management have been widely confirmed and have been recognized to yield three biological effects: strengthening the delivery of ecosystem services, ensuring sustainable utilization of natural resources, and maintaining the stability of biodiversity (Kenward et al. 2011). However, ecosystem changes often occur at a pace faster than the accumulation of human knowledge, and predictive models are associated with a large degree of uncertainty, which makes it difficult to develop effective and sustainable management policies. Thus more attention should be paid to the heterogeneity, optimization, simulation, and evaluation of policies, as well as to the flexibility and responsiveness of management (Schindler and Hilborn 2015). In addressing these complex challenges, the perspective of sustainable ecosystem management embodies the features of comprehensiveness, territoriality, openness and practicality of the geographical sciences, and is an important guide for research on global change and terrestrial ecosystems on the pathway from theory to practice.

Bibliometric Analysis of Contemporary Research

According to the statistics in the literature, 1229 international papers have been published on the subject of sustainable ecosystem management since 2000, mainly in terms of three themes: ecosystem management (179 papers), ecosystem services (891), and ecosystem sustainability (159). Papers on global change and sustainable ecosystem management are relatively few, largely due to the fact that this is still a new international subject. Approximately 40 % of papers on ecosystem management discuss appropriate policies in this area, and 10.6 % of the papers clearly distinguish different ecosystem management scenarios. For the theme of ecosystem services, the proportion of paper dealing with valuation of these services is the highest (24.1 %), followed by ecosystem service mapping (8.6 %) and trade-offs (8.3 %). The subject of ecosystem service compensation accounts only for 2.8 % of these papers, but it has attracted increasing attention as an emerging research direction. For ecosystem sustainability, which is the goal of the sustainable management of ecosystems, only 11.3 % of the papers have clearly identified this as their primary focus.

Contemporary Research

On an overall basis, international studies have made significant progress in the field of sustainable ecosystem management in the context of global change in the following three areas. **The first** is management scenario analysis of particular types of ecosystems. To develop targeted and adaptive plans for specific ecosystem types such as forest, grassland, freshwater, and agriculture has become a prominent focus of research. Human adaptation to climate change through such actions as the sustainable management of grazing land in arid regions (Raven 2002), the improvement of water productivity in freshwater ecosystems (Grant et al. 2012), and the reduction of runoff from human residential areas in order to maintain healthy aquatic ecosystems (Sabo et al. 2010), have become important study foci.

The second major area is the shift from the structural and functional analysis of ecosystems to the evaluation and management of ecosystem processes and services. Ecosystem services and the mapping of its monetary values provide a clear guideline for the spatial decisions in ecosystem management (Naidoo et al. 2008). In terms of ecosystem services trade-offs, the necessity of adding social elements to the analysis of ecosystem change has been recognized (Carpenter et al. 2009). The payment (i.e., compensation) for ecosystem services and its marketization are regarded as an important economic tool for ecosystem management (Kinzig et al. 2011). However, large-scale payments for ecosystem services are not fully marketable and often require governmental promotions at all levels (Muradian et al. 2010). Through the comparison of 34 ecosystem services projects and 26 biodiversity conservation projects in the world, it has been found that ecosystem services projects are able to prevent the degradation of protected areas, attract more conservation funds, and expand the opportunity of landscape protection (Goldman et al. 2008).

The third area in which international research has effectively addressed sustainable ecosystem management in the context of global change is in comprehensive risk assessment of the coupled system of humans and land and its adaptation. The vulnerability analysis of this social-ecological system and the determination of its ability to respond to risks has become an important step in sustainable management decisions (Turner et al. 2003). Close attention is now being paid to the combination of vulnerability study and landscape planning (Cumming et al. 2013), social surveys (Alberini et al. 2006), and systematic theory (Salvati and Zitti 2009). Moreover, the landscape scale is now considered optimal for the analysis and management of trade-offs among ecosystem services, biodiversity conservation, and natural resource utilization (Nelson et al. 2009; Wu 2013).

Bibliometric Analysis of Contemporary Research in China

The studies by Chinese researchers on sustainable ecosystem management in the context of global change still lack an acceptable degree of international influence. According to the literature, the papers with the theme of ecosystem management published by Chinese researchers account for 7.8 % of the total number of the papers with this theme worldwide. Regarding the theme of ecosystem services, publications by Chinese researchers account for 4.2 % of all the papers on this subject and focus primarily on the estimation of ecosystem service values. Chinese researchers have just begun to focus on ecosystem sustainability in the context of global change, with less than 10 papers having been published to date.

Contemporary Research in China

The regional human-land system remains a vigorous focus of Chinese geographers (Wu 1991). Sustainable ecosystem management and associated ecosystem services and ecological risk are also research priorities for ecosystem studies in China (Fu 2010). (1) **Elucidation of the conceptual framework and research topics of ecosystem**

management (Yu et al. 2001, 2002): Work on the concepts and theoretical underpinnings of ecosystem management have laid a solid theoretical and methodological foundation for research on sustainable ecosystem management in China. Important studies include those on the basic elements of ecosystem management (Ren et al. 2000); the content and methods of the comprehensive evaluation of ecosystems (Fu et al. 2001), the theoretical basis of regional ecological security patterns (Ma et al. 2004), the principle of landscape management (Xiao et al. 2004), and regional ecosystem health (Peng et al. 2007). (2) **Spatial data analysis and quantification**. Research on land use change in China and its driving mechanisms has yielded good spatial databases and algorithmic models for the sustainable management of terrestrial ecosystem (Liu and Deng 2009) and effective support for the construction of the national ecological security pattern (Yu et al. 2009). It has also contributed to the valuation and spatial mapping of terrestrial ecosystem services (Ouyang et al. 1999; Xie et al. 2003, 2008). (3) **The clarification of critical issues of terrestrial ecosystem services and the research orientation of ecological compensation** (Fu et al. 2009; Li et al. 2011). The study of mechanisms for ecological compensation in China based on the concept of ecosystem services payment is providing theoretical guidance for trade-offs between regional economic development and ecological protection. The geographical implications of ecological compensation have been clarified (Li and Liu 2010; Ouyang et al. 2013; Liu et al. 2014b). (4) The improvement of models and methods for the sustainable evaluation of ecosystems: Chinese researchers have developed new quantitative approaches for ecosystem management based on a variety of perspectives such as ecological capacity evaluation (Yang et al. 2007), the improvement of ecological footprint analysis (Xu et al. 2000; Peng et al. 2006), and the mapping of landscape ecological risk (Peng et al. 2014, 2015).

Contributions by Chinese Scholars and Subsequent Problems

Based on an understanding of the relationships within the coupled system of humans and land, effective ecosystem management emphasizes system spillovers, subsystem feedbacks, and the integration of spatiotemporal scales in order to guide policy formulation and the development of practical guidelines grounded in sound scientific research (Liu et al. 2015). The rapid urbanization and large-scale rural-urban migration in China have resulted in severe disturbances to terrestrial ecosystems and fostered strong motivation for research on ecosystem management in China. The work of Chinese researchers on the responses of ecosystems to changes in urban landscapes, developing measures of regional ecological risk and ecosystem health, and the construction of regional ecological security patterns have been at the forefront of international research for some time. Performance evaluations of China's large-scale ecological projects including the Three-Gorges project, the South-to-North Water Diversion project, the Green for Grain Project, and the Three-North Shelter Forest Program, have had great international influence. However, Chinese governments at all levels are still in the exploratory stage of developing ecosystem management strategies. There are lessons to be learned from experiences in accomplishing such large-scale ecological projects. The ecological compensation plans could not meet all the needs of stakeholders. It was difficult to directly apply the international advanced ecosystem management theory to specific practices in China because of different national conditions. Therefore, the ecosystem management approach in China is still relatively simple compared to those of foreign countries. The mutual feedback of social-ecological systems at multi-spatiotemporal scales needs to be clarified and the ecosystem management policies and decisions need to be further adapted to China's national conditions.

Future Research

Addressing the demands of sustainable development and management, the geographical sciences must move towards a more panoptic approach, carry out comprehensive studies in the context of global change, and progress from general descriptions to deeper revelations of ecosystem processes and mechanisms. In so doing, research on sustainable ecosystem management needs to focus on determining the impact of human activities on terrestrial ecosystem processes, exploring the response and adaptation of social-ecological systems to global change, and analyzing ecosystem service flows and ecological compensation mechanisms (Cai et al. 2009). (**1**) **Determine the responses of social-ecological systems to major ecological engineering projects and traditional and modern farming activities**. The Natural Forest Protection Program and the Green for Grain Program of China are the largest ecological projects in the world (Liu et al. 2008). In addition, the Chinese traditional rice-fish system dating from 1200 years ago is a representative mode of sustainable agro-ecosystem management (Xie et al. 2011). The experiences and lessons of Chinese historical and current ecosystem management activities could be used as a direct reference for global terrestrial ecosystem research. (2) **The sustainable use of land resources within a framework of adaptive management.** Research on the comprehensive physical and human dimensions of land change has always been an area of strength in Chinese geographical studies. Continuing exploration of sustainable land use topics and issues provides direct support for the sustainable management of terrestrial ecosystems (Xu et al. 2009). The targeted and adaptive plans for specific ecosystems such as forests, grasslands, freshwater, and agriculture depend on the modes of utilization of corresponding land types. The unified national management of the land resources of “mountain, water, forest, field, and lake” has become the strategic requirement for ensuring the sustainability of Chinese terrestrial ecosystems. (3) **Refinement of ecological compensation mechanisms based on ecosystem services**. As exemplified in several major ecological projects, there are already some practical cases of Chinese ecosystem services payments, i.e., ecological compensation (Zheng et al. 2013). However, there are not many buyers and demanders for the ecosystem services payment in China. This mechanism relies primarily on the special funds of the central government and has difficulties in guaranteeing the long-term livelihood of farmers. Further explorations are required for the establishment of the market mechanisms for ecosystem services payments and the development of diverse modes of payment. More attention should also be given to the dynamic monitoring of ecosystem services flows and the performance evaluation of ecological compensation projects.

8.3 Roadmap for Further Research

China has a variety of complex and diverse terrestrial ecosystems, providing excellent opportunities for conducting studies on the responses of these ecosystems to global change. Based on international research in related fields, such studies have been at the forefront of international research. However, related research in China is still in its infancy, which greatly limits the accuracy of forecasts of the status of terrestrial ecosystems in the context of future global change. In September, 2015, the State Forestry Administration of the People’s Republic of China issued the Plan Outline of Promoting Ecological Civilization, which proposed concrete measures for the ecological construction of major natural ecosystems like forests, grasslands, wetlands, and urban ecosystems in China. There is no doubt that global changes will pose challenges to the success of ecological construction efforts in China. Driven by both advances in science and national needs, studies on global change and terrestrial ecosystems in China will usher in a new era of development opportunities. Several key directions are highlighted below.

(1) **Strengthen Research on the Feedback Processes of Ecosystems to Climate Change Based on the Comprehensive Study of Physical Geography**

Global changes have greatly impacted the structures and functions of ecosystems at different temporal and spatial scales. In the past few decades, much research has been conducted on the impacts of global change on terrestrial ecosystems and has yielded fruitful achievements. However, it is worth noting that different elements of physical geography, particularly the interactions between climate and land surface vegetation, form an inseparable whole. Research on global change and terrestrial ecosystems needs not only to study the impacts and results of global changes on terrestrial ecosystems, but also pay attention to how terrestrial ecosystems respond to and in so doing influence the actual processes of global change. At present, research on the feedback of terrestrial ecosystems to global change is still in its infancy. The varieties of feedback mechanisms are unclear and their intensities clouded with uncertainty. With the development of the comprehensive study of physical geography, land surface has become an important component of the climate system and the feedback of terrestrial ecosystems to global change will become a major focus of research on global change and terrestrial ecosystems.

(2) **Strengthen Research on the Observation and Methodology of Global Change and Terrestrial Ecosystems**

How to accurately understand the responses and feedback of terrestrial ecosystems to global change using innovative methodology is a great challenge. Within the framework of geography, future studies on global change and terrestrial ecosystems need to take into account the interconnections, influences, and restrictions of various elements of the Earth system; understand and describe the operating mechanisms and synergies of terrestrial ecosystems within the Earth system; improve forecasting capabilities for global change; and provide a scientific basis for macro decision-making. The efficient cross-penetration and methodological integration of environment science, atmospheric science, ecological science, and Earth information science will best enable the comprehensive consideration of the influences and feedbacks of natural and human factors on terrestrial ecosystems. Previous studies have enhanced understanding of small-scale and isolated scientific phenomena and change processes. Future studies will reflect the overlapping of disciplines and incorporate a combination of micro-level and macro-level technologies as well as the integration of long-term field observations at fixed locations, models that simulate temporal ecosystem processes, and multi-source remotely sensed data. To improve research on the relationships between global change and terrestrial ecosystems at different temporal and spatial scales, there is a need to combine various technical resources, including interconnected observations at fixed locations, control experiments, remote sensing, geographic information systems, and simulation models. In the meantime, key parameters and process data that describe ecosystems should be shared efficiently. With the building of large datasets, the development of supercomputers, and the continued refinement of forecasting techniques and models for simulating climate change scenarios, integrated research will provide strong support for the study of land surface processes at regional and global scales.

(3) **Promote the Formulation of an Evaluation Index System for the Impacts of Global Change on Terrestrial Ecosystems**

At present, identifying the most vulnerable regions in terms of the responses of terrestrial ecosystems to global change remains a difficult challenge. This requires researchers to formulate an evaluation system for system vulnerability and adaptive capacity and quantitatively assess the sensitivity, vulnerability, and adaptive capacity of natural and human systems to global change. The interconnections among three key attributes of ecosystems—exposure, sensitivity, and resilience—introduce different frameworks for evaluation and management concepts and call for the integrated management of global change—ecosystem interactions from the perspective of sustainable development. The quantitative and qualitative research on the vulnerability of terrestrial ecosystems is the prerequisite to the fully integrated management of terrestrial ecosystems in the context of global change. Identifying regions whose terrestrial ecosystems are sensitive to global change not only has theoretical significance, but also important real-world consequences for transforming nature while adapting to local conditions and the rational allocation of the development of industrial and agricultural production. It also provides a scientific basis for the formulation of policies for the comprehensive improvement of the ecological environment. With respect to identification of sensitive or vulnerable ecological areas, more research is needed for the selection of sensitive elements, determination of key thresholds, and characteristic scale construction, etc. To be specific, further research is required to uncover the reasons underlying the formulation and evolution of the vulnerability, construct targeted judgement criteria, assess the degree of ecological vulnerability of different types of terrestrial ecosystems, and determine the spatial distribution of ecological vulnerability. For different types of vulnerable regions, it is necessary to pay continuing attention to the monitoring and evaluation of ecosystem health and the measurement of ecosystem services. That is to say, it is necessary to not only ensure the stability of ecosystems, but also to place more emphasis on the sustainability of ecosystem functions, quantify and forecast the dynamic responses of specific ecological processes to global changes, and address the processes underlying the formulation and evolution of ecosystem vulnerability.

(4) **Strengthen Research on the Adaption and Management Responses to Global Change**

The ultimate goal for carrying out comprehensive ecosystem management in the face of global change is to enhance the adaptive capacity of ecosystems through appropriate management methods. On the one hand, the management and control of ecosystems can reduce the disturbances emanating from multiple risk sources in ecologically vulnerable regions and promote the self-healing of ecosystems. To achieve this goal, close attention should be paid to deciding whether current measures can effectively reduce the disturbances based on observations across multiple scales, and to whether the reduction in ecologic risks can effectively promote the self-healing of ecosystems. When observation time at fixed locations is insufficient, ecosystem simulation models can be a good complement. Continued emphasis should be placed on the cross-validation of historical observation data and the results of ecological simulation models. Ecosystem health and service measures can be used to quantify these elements of ecosystem management. At the same time, economic resources can be applied to accelerate the restoration or artificial repair of ecosystems and facilitate their sustainable management. To decide whether the restoration of artificial ecosystems can withstand disturbances from risk sources and whether ecological restoration efforts can achieve expected goals, it is necessary to carry out multi-scenario simulation of ecosystems and to visualize the results of ecological restoration in different scenarios through the quantification of driving elements and processes. The restoration results can be used to judge whether economic investments in ecosystems can effectively ensure their sustainability. The optimal restoration method may then be selected and targeted to enhance the adaptive capacity of ecosystems in the face of global change.

8.4 Summary

Research on global change and terrestrial ecosystems is an integrated and multi-disciplinary field. Three key research directions over the past three decades include the impacts of global change on the patterns and processes of terrestrial ecosystems, observation methodology systems, and ecosystem management. Important progress has been made with respect to models for simulating vegetation dynamics, the macro mechanisms of biodiversity maintenance, and understanding the carbon cycle. The territorial differentiation theory in geography has promoted research on the patterns and processes of terrestrial ecosystems. Research on human-land relationships has deepened the study of the driving forces underlying the responses of terrestrial ecosystems to global change. Biogeography models and spatial analysis technology have promoted the dynamic forecasting of terrestrial ecosystems. In China, the number of published papers in this field has sharply increased and significant achievements have been made in work on carbon cycles. Much fundamental research has been carried out on the responses of vulnerable ecosystems, such as timberlines, to climate change and the patterns and dynamics of biodiversity. At the same time, the number of highly-cited papers still lags when compared with high-ranking countries such as the United States. Both the development of the discipline and national needs present new challenges to research in this field. Future research should focus on the system-dynamic mechanisms affecting the stability and sustainability of ecosystems; strengthen the study of macro-level patterns and processes of the Earth system through international cooperation; strive to achieve methodological breakthroughs; and better address the adaptation to management of global changes.

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Terrestrial Water Cycle and Water Resources

9

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Abstract

Driven by the need for water security in a changing environment, research on the water cycle and water resources has attracted intensive research in the last few decades. This chapter reviews the progresses in terrestrial water cycle and water resources research, including the state-of-art understanding of change in the water cycle, improvement of prediction capacities in hydrology and water resources, and achieving water security. The grand challenges and perspectives for the near future are discussed. In particular, we highlight the challenges to address interactions among multiple factors in the water system and to manage the water related risks.

Keywords

Water cycle • Water resources • Water security • Water system • Hydrological modeling

A total of 13,249 SCI/SSCI-indexed articles are analyzed in the research area of terrestrial water cycle and water resources. Articles were identified from 27 international journals from 2000 to 2014 (Appendix F). The title, keywords or abstract include one of the terms: "water resources", "water cycle", "water management", "hydrology", "hydrological", "hydrologic" in the title, key words or abstract, but do not contain the terms "water quality", "atmospheric", "atmosphere" or "pollution".

9.1 Overview

9.1.1 Development of Research Questions

Water is vital for all known forms of life and for the survival and development of human civilization. The water cycle links the atmospheric cycle, lithosphere and biosphere on the earth. Fresh water, which is an essential natural resource to human beings, is mainly stored in rivers and lakes and in underground aquifers. Due to large variability in climate and geographical conditions in different areas, the water cycle and water resources are highly variable on both temporal and spatial scales. More than two billion people in the world are now facing the risk of water shortage (Oki and Kanae 2006). Water shortage is becoming a serious issue which may limit the development of the economy and the society. Driven by the needs of our society, the water cycle and water resources have been important subjects of active research in geographic science.

Research on the water cycle and water resources traditionally assumes that processes in a water cycle in a given area are statistically stable. Along with the development of earth system science, it is recognized that the water cycle is one part of the complex earth system, which interacts intimately with atmospheric, landscape, ecosystem and human activities. Therefore, the water cycle should not be considered as a static and isolated system, ignoring the complex relationship with other factors in the earth system. Due to climate change and the rapid development of the social-economy, the terrestrial environment is undergoing significant changes, which have a great impact on water resources. In the changing environment, a current research trend is to consider all the terrestrial water components as an integrated process, namely, the water system, to study its properties and behaviors.

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Table 9.1 Top 20 countries (regions) with the number and citations of SCI/SSCI-indexed articles on "Terrestrial Water Cycle and Water Resources" during the period 2000–2014

	Number of articles						Cited frequency						Number of highly cited articles					
	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014
Rank	World	389	1,283	2,473	4,278	6,498	World	15,690	537	81,712	96,507	38,303	World	50	0	253	303	334
1	USA	160	297	863	1,275	1,569	USA	7,934	127	30,759	34,236	11,396	USA	28	0	101	113	106
2	China	3	135	54	202	638	China	38	54	1,386	4,064	2,937	China	0	0	4	11	25
3	Canada	36	72	181	304	394	UK	1,842	46	7,722	7,619	2,538	UK	5	0	23	30	23
4	UK	52	74	192	269	380	Canada	1,264	32	5,384	6,086	2,442	Australia	2	0	18	17	21
5	Australia	4	68	114	201	368	Australia	264	26	4,780	4,683	2,089	Canada	3	0	13	16	21
6	Italy	11	72	70	191	297	Germany	125	27	3,036	3,953	2,000	Germany	0	0	10	13	20
7	Germany	5	53	58	151	266	Italy	435	36	2,118	4,355	1,848	Italy	2	0	6	11	15
8	Netherlands	8	44	57	139	251	Netherlands	153	25	2,292	3,600	1,543	Switzerland	1	0	7	9	14
9	Spain	5	35	59	111	228	Switzerland	381	15	2,344	2,059	1,320	Netherlands	0	0	6	12	12
10	France	8	40	98	183	206	France	646	13	3,265	4,078	1,223	France	3	0	11	9	10
11	India	11	38	79	110	181	Spain	230	12	1,648	2,087	1,040	Iran	0	0	0	2	8
12	Switzerland	3	26	33	80	160	India	244	17	1,863	1,902	682	Sweden	0	0	4	6	7
13	Iran	0	25	7	35	121	Sweden	148	6	1,449	1,230	557	New Zealand	1	0	2	3	7
14	Japan	13	19	79	114	97	Austria	9	8	563	1,046	480	Spain	1	0	6	4	6
15	South Korea	1	22	12	40	88	Greece	64	4	684	1,086	362	Austria	0	0	2	5	6
16	Taiwan, China	4	16	38	83	85	Japan	253	10	1,611	2,184	359	Norway	0	0	1	3	4
17	Brazil	4	18	24	40	80	Belgium	58	9	835	1,167	322	Japan	0	0	5	7	2
18	Sweden	7	17	34	44	77	Taiwan, China	172	3	922	1,253	279	India	0	0	6	5	2
19	Turkey	3	16	20	64	73	Denmark	309	1	1,606	443	251	Denmark	1	0	8	0	2
20	Belgium	2	16	28	58	70	Turkey	43	2	339	1,037	240	Taiwan, China	1	0	3	4	1

Note Countries (Regions) ranked by the number of articles, cited frequency and number of highly cited articles during the period 2010–2014

9.1.2 Contributions by Scholars from Different Countries

Since the last decade, increasing attention has been paid to the water cycle and water resources in the context of global change. This resulted in an increasing number of papers and other research outcomes in this area. Quantitative analysis on published papers between 2000 and 2014 in 20 countries (see Table 9.1) shows that the number of SCI/SSCI papers in 2014 (1283 papers) was more than three times that in 2000 (389 papers) in the area of hydrology and water resources. American authors contributed around 28 % of the papers, making the United States the biggest contributor to publications. Chinese authors were second, contributing around 6.7 % of the papers. Many European countries contributed more than 3 % of the papers. The increasing rate of the number of Chinese SCI/SSCI papers exceeded the average rate in the world. In 2000, there were only 3 Chinese SCI/SSCI papers published, accounting for 0.8 % of all papers in the world, in comparison to 135 papers in 2014, contributing 10.5 % of all papers.

The United States held the first place for the number of paper citations (with 35 % citations in all citations), followed by the United Kingdom (8.3 %) and Canada (6.4 %). The number of citations of Chinese papers only accounted for 3.9 % of all citations, which was inconsistent with its second place for the number of published papers. An increasing trend was observed in the number of citations of Chinese papers between 2010 and 2014. Yet, the average number of citations of Chinese SCI/SSCI papers was 9.4 per paper, much lower than the average number of 16 per paper in the world.

The distribution of top cited papers (i.e., the 1 % most cited papers) in different countries was similar to that of the number of citations. The number of top cited Chinese papers (40 papers) was much less than American papers (320 papers) and papers form the United Kingdom (76 papers.) However, it is worth noting that the number of top cited Chinese papers was increasing. In 2010–2014, China got a second place for the number of the top cited papers (25 papers), next only to the United States (106 papers).

Above analysis shows that in the last decade, China has got remarkable achievement in the research area of water cycle and water resources. Though gaps still exist between China and the most advanced countries, the quantity and quality of Chinese SCI/SSCI papers have been rapidly improved. In general, the research level in water cycle and water resources in developing countries is much lower than that in developed Western Countries, and the gap tends to be even wider in the near future.

9.1.3 Key Research Topics

We divided research on the water cycle and water resources into three categories based on the Keywords Cluster graph for the period 2000–2014 (Fig. 9.1): (1) traditional hydrology studies focusing on the rainfall-runoff relationship and uncertainty in model parameters; (2) ecological hydrology focusing on micro-scale mechanism studies; (3) hydrological processes in watersheds considering the impacts of climate change, river channel change and human activities applying multi-disciplinary approaches. The third category contains the most co-occurrence words, revealing that the multi-disciplinary research aiming to address water resources security in the changing environment is an important topic of active research.

Figure 9.2 displays the evolution of the number of occurrences of different subjects in the SCI/SSCI papers in the area of the water cycle and water resources since 2000. We noted that increasing efforts have been put in this area. We divided the papers into 9 categories based on keywords, including: hydrological processes, model, human activity, uncertainty, ecohydrology, climate change, region, water disaster and others that are not easy to be categorized. These keywords cover almost all the main subjects in the research area. In the period of 2000–2014, the term that appears most frequently is hydrological processes (with 18 % of the occurrences in China and 19 % abroad), followed by uncertainty, human activity, ecohydrology and climate change. The total occurrences of human activity and climate change are around 20 % (22 % in China and 19 % abroad), indicating that much attention was paid to water issues in the changing environment. In addition, Fig. 9.2 also shows that the subjects being studied by Chinese and foreign researchers were mostly consistent. It is worth mentioning that the number of Chinese SCI/SSCI papers for different topics in all study periods increased 3–4 times, much faster than in other countries.

Above all, since 2000, Chinese researchers have captured important subjects in the area of water cycle and water resources. The production from Chinese researchers keeps increasing and more contributions can be expected from Chinese research. Models are an important tool to help understand different phenomena in water systems and predict the performance of water systems under various conditions. Water disaster is a key subject that combines the water resources research and the needs of our society. Therefore, research on these two subjects should be strengthened in China. Additionally, more attention has been paid in China on "region", possibly indicating a lack of global vision from Chinese researchers. In the global changing environment and the globalization context, climate change, multinational virtual water trade, etc. have made the safety of regional water cycle and water resources a global issue that relates to many countries and regions.

9.1.4 The Role of NSFC in Supporting the Research on Terrestrial Water Cycle and Water Resources

Increasing numbers of projects have been funded by NSFC since 2000. In particular, the number of funded projects in the last 5 years exceeded that of the 10 prior years (Fig. 9.3). Figure 9.3 shows that the research subjects covered in China were similar to those in other countries. In 2000–2004, research on hydrological models comprised a big proportion of funded projects by NSFC. From 2005, this subject was always a main one, but the number of funded projects was exceeded by research on hydrological processes. These two subjects, i.e., hydrological models and hydrological processes, had more projects funded than other subjects. In addition, the increasing rate of funded projects for these two subjects (over 400 %) was faster than the rate of others in the last 5 years. It indicates that the research on water cycle and water resources moves gradually from mathematical models characterizing the rainfall-runoff relation to models based on hydrological processes and mechanisms.

Between 2000 and 2014, NSFC funded 390 projects with a total budget of more than 300,000 thousand yuan, covering more than 300 researchers in around 100 institutions (Table 9.2). The number of NSFC-funded SCI/SSCI papers was increasing, which accounted for nearly 70 % of all papers. This indicates that NSFC plays a major role in research on the water cycle and water resources in China. Moreover, the increasing funding from NSFC also resulted in more outcomes in the research area. Data in the three periods (i.e., 2000–2004, 2005–2009, 2010–2014) in Table 9.2 show that, the number of funded projects was more than tripled and the amount of funding increased nearly 5 times. More specifically, the average funding per project increased from 350 thousand yuan in 2000–2004 to 930 thousand yuan in 2010–2014. The number of project principal investigators was ten times more in 2010–2014 in comparison to 2000–2004. There were 15 and 88 home institutions that participated in NSFC projects in 2000–2004 and 2010–2014, respectively. The percentage of SCI/SSCI papers based on NSFC-funded in all papers increased from 35 to 80 %.

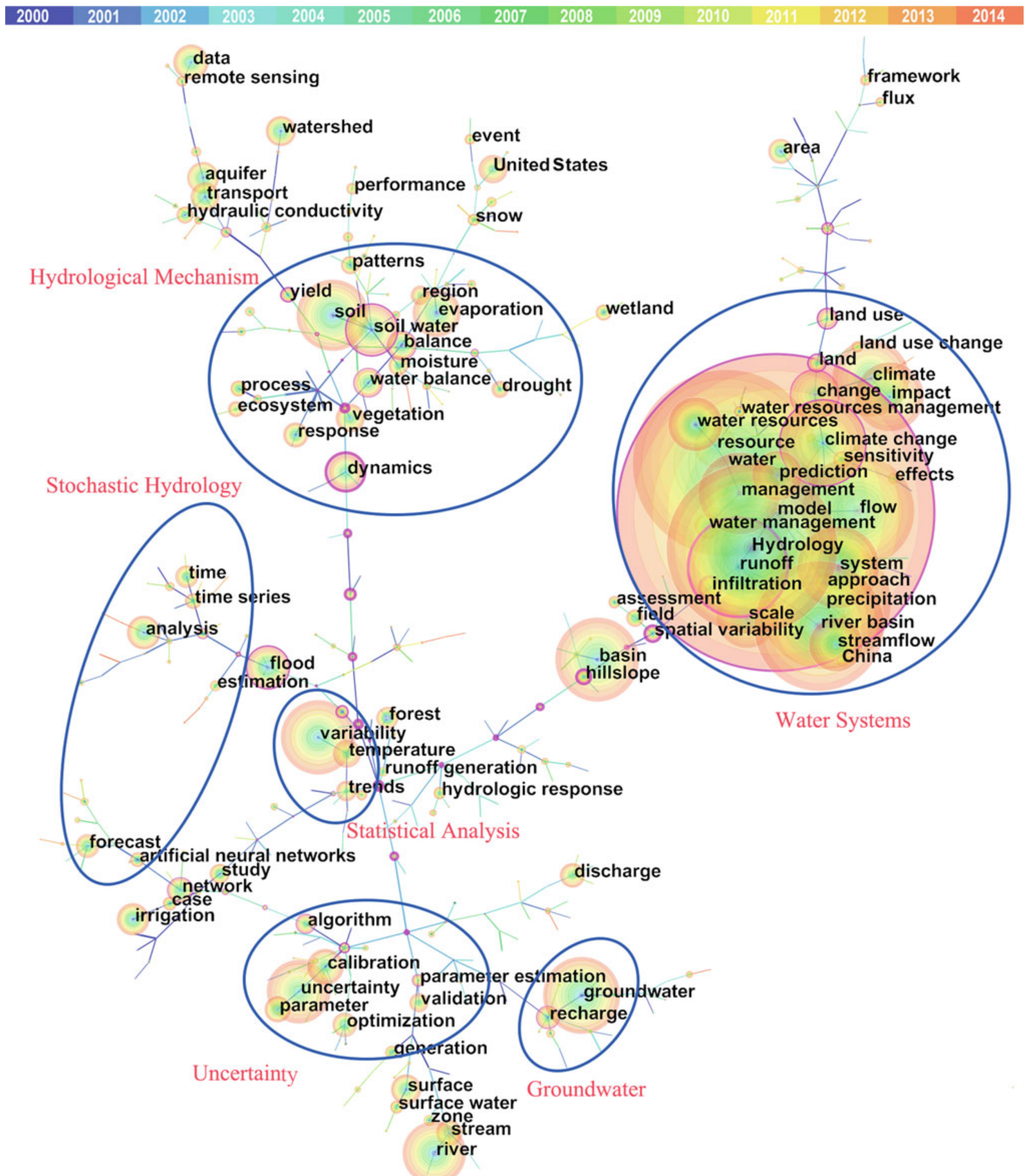

Fig. 9.1 Co-occurrence network of SCI/SSCI-indexed article keywords on "Terrestrial Water Cycle and Water Resources" during the period 2000–2014

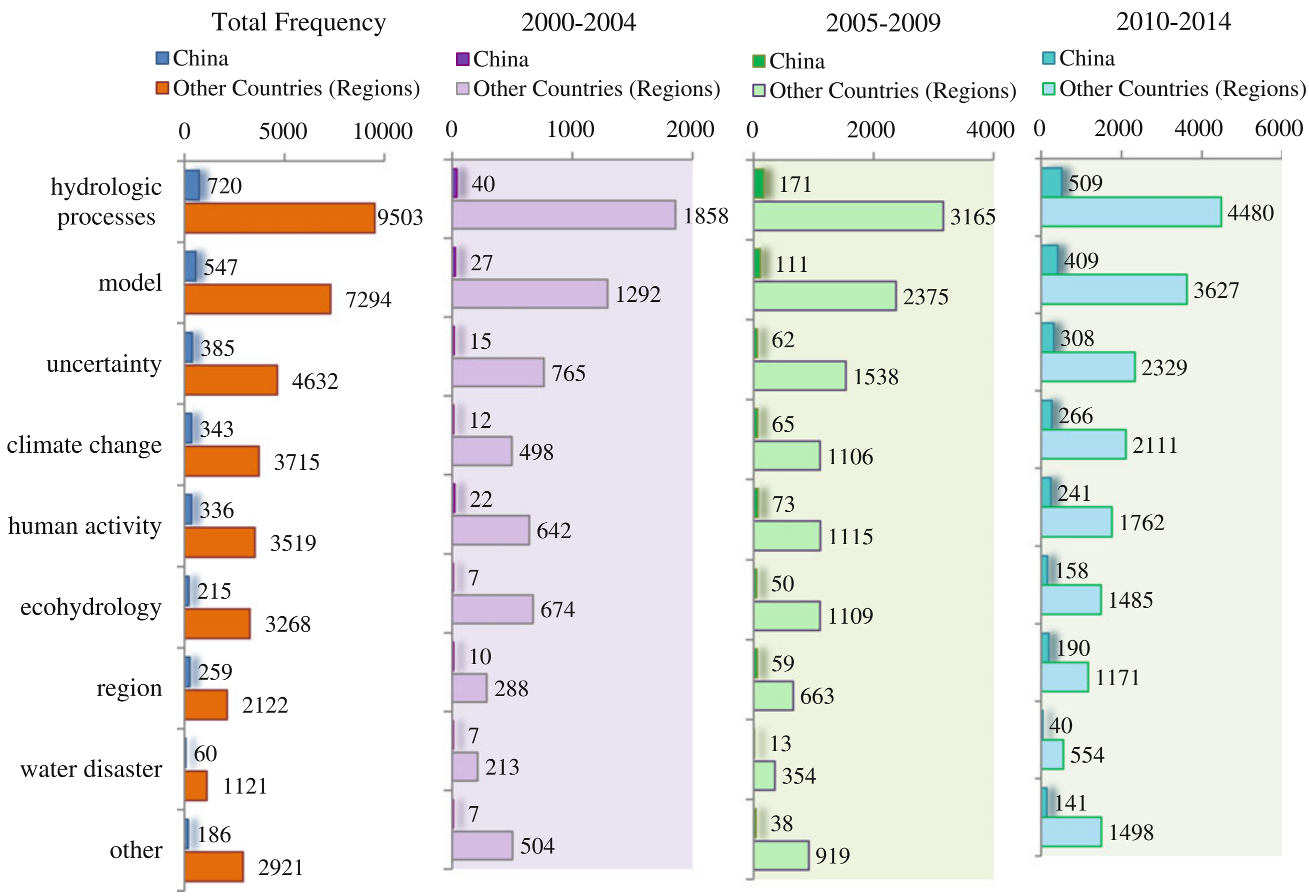

Fig. 9.2 Keyword temporal trajectory graph for SCI/SSCI-indexed articles on "Terrestrial Water Cycle and Water Resources" during the period 2000–2014

9.2 Questions and Research Progress

9.2.1 What Has Changed in the Water Cycle and What Changes Could Possibly Occur?

Our knowledge of the water cycle starts from the water balance. Previous research mostly focused on the water cycle and water balance on different temporal and spatial scales. In the last two to three decades, along with the progress in global change research, researchers started to investigate changes in the water cycle and water balance. As solar energy is the principal driver of the water cycle, recent interest has moved towards more comprehensive studies coupling water and energy cycles at diverse spatial scales as well as studies exploring the mechanisms and governing rules of the processes.

Bibliometric Analysis of Contemporary Research

Between 2010 and 2014, more than 10,000 papers on changes in the global water cycle were published, dealing with various sub-processes in the water cycle at different scales. Among these papers, around 3500 papers focused on precipitation or runoff; there were around 1500 papers related to evapotranspiration and 1500 papers on soil water; nearly 1/3 of the papers involved climate change. More than a half of the papers addressed catchment water cycles. More than 2600 papers contributed to groundwater research. Overall, the impact of climate change is an important subject in the research area of regional water cycle change.

Contemporary Research

Global warming is widely recognized (IPCC 2013), which may lead to changes in water cycles (Huntington 2006; Famiglietti and Rodell 2013). Based on the analysis of historical rainfall, evaporation and wet and dry patterns, many researchers attempted to investigate changes in the global water cycle in the last few decades.

Present research suggests that global terrestrial precipitation probably did not change significantly in the last few decades (Gu et al. 2007; Biemans et al. 2009). However, the results depended much on data. At the same time, some researchers believed that due to climate change, the wet

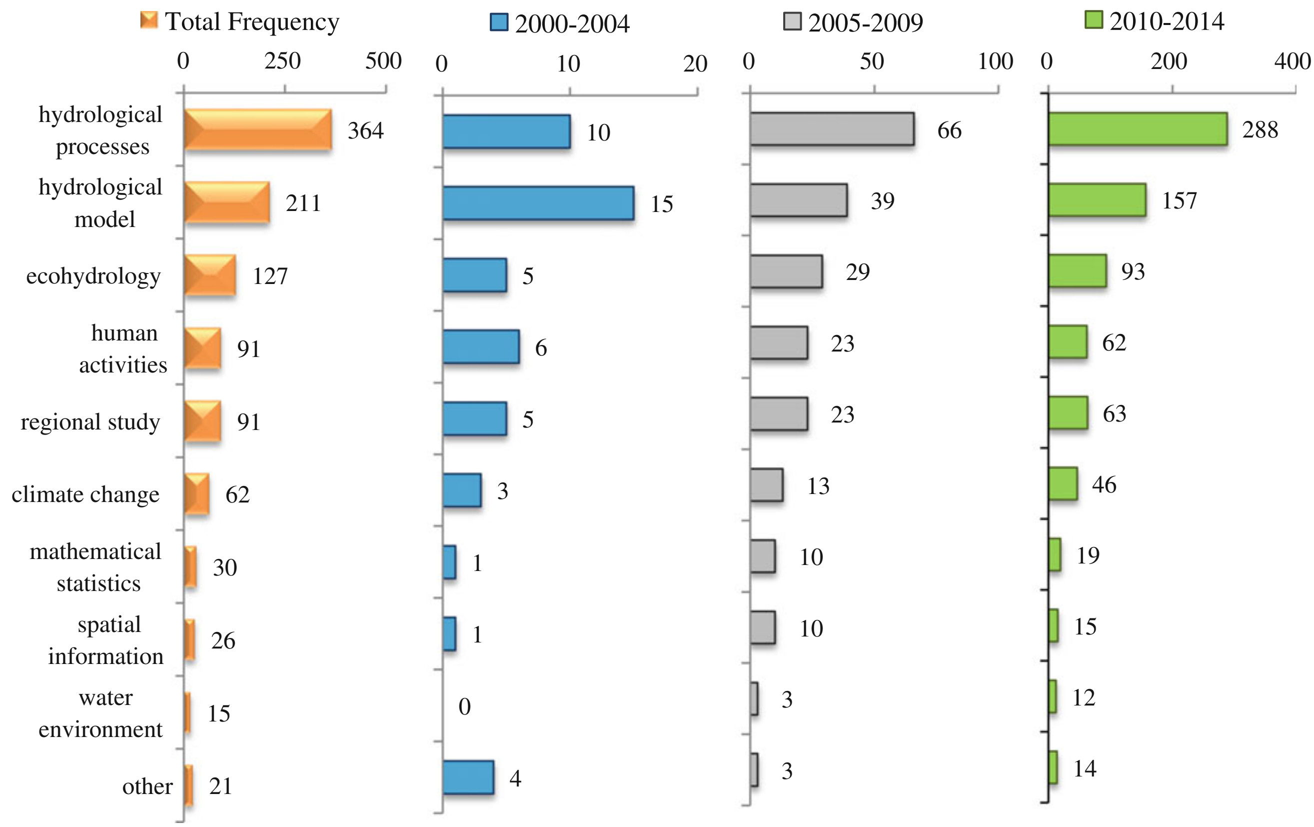

Fig. 9.3 Keyword temporal trajectory graph for NSFC-funded projects on "Terrestrial Water Cycle and Water Resources" during the period 2000–2014

Table 9.2 NSFC-funded projects and SCI/SSCI-indexed articles on "Terrestrial Water Cycle and Water Resources" during the period 2000–2014

SCI/SSCI-indexed articles					NSFC-funded projects			
Periods	Number of articles	% of articles by Chinese authors	% of articles with NSFC funding by Chinese authors	% of articles funded by MOST among those with NSFC funding	Number of projects	Funding (10,000 yuan)	Number of PIs	Number of institutions
2000–2004	2,473	2.2	35.2	0.0	25	887.0	24	15
2005–2009	4,278	4.7	48.0	26.8	94	5,067.0	85	29
2010–2014	6,498	9.8	78.1	48.4	271	25,272.3	255	88
2000–2014	13,249	6.7	68.7	43.5	390	31,226.3	318	97

areas were becoming even wetter and the dry areas even drier (Held and Soden 2006). Yet, until now, this statement mostly held in oceanic climate areas; there was not enough evidence to support this statement in continental areas (Roderick et al. 2012; Greve et al. 2014).

Some researchers used a combination of evaporation data from different sources in order to study possible trends in evaporation. The results were usually accompanied with large uncertainty as the time series was short (Jung et al. 2010). Another way to assess the change in actual evaporation was to use the relation between the actual and potential evaporation. In the last 50 years, observations indicated that the evaporation from evaporation pans presented a decreasing trend in many regions in the world (Peterson et al. 1995).

Variations in terrestrial wet and dry patterns are an important indicator for analyzing changes in a water cycle (Dai et al. 2004; Dai 2011). For the last few decades, the trend in global land surface runoff was still uncertain. The presence of a trend depended much upon selected data in a study (Labat et al. 2004; Milliman et al. 2008; Dai et al. 2009). No commonly agreed conclusion can be drawn on changes of dry areas in the world. Some researchers believed that globally the land surface became drier during the last few decades (Dai et al. 2009; Dai 2011), whereas some studies showed no significant change in global dry areas during the last 60 years (Sheffield et al. 2012).

The evaluation of the impact of climate change on hydrological processes and the assessment of possible changes in a terrestrial water cycle in the future are of great importance (Vörösmarty et al. 2000; Teng et al. 2012). Nowadays, the evaluation of the impact of climate change on the water cycle and water resources was mostly conducted using two approaches: (1) to use the output of the hydrological component in the general circulation model (GCM) under different climate scenarios (Milly et al. 2005); and (2) to couple the GCM and other hydrological models (Warszawski et al. 2014). Uncertainty in the evaluation on future changes in water cycles is still large. Particularly, outputs from hydrological models are even more uncertain than those from the GCMs (Schewe et al. 2014).

Bibliometric Analysis of Contemporary Research in China

Between 2000 and 2014, Chinese researchers published nearly 1000 papers on changes in the water cycle, including studies on various sub-processes in the water cycle at different scales (e.g, precipitation, evaporation, runoff, infiltration, snowmelt and soil water). Among these papers, there were more than 500 papers focusing on runoff and streamflow, and more than 500 papers dealing with precipitation. Around 300 papers dealt with evapotranspiration. More than 150 papers included studies on ground water. Among the studies on water cycle changes, climate change was one of the most important topics with nearly 300 published papers. Nearly half of the papers conducted their studies at the catchment scale.

Contemporary Research in China

There was probably no significant change in average precipitation in China. However, changes in regional precipitation patterns were significant, presenting large spatial variability (Piao et al. 2010). Much effort has been put to the analysis of spatial and temporal characteristics of regional precipitation and temperature (Liu et al. 2008; Xu et al. 2008). Northwest China was found to become wetter and warmer in the past few decades. During the same period, the area from the Southwest to Northeast China along the farmland-pastoral ecotones became dryer. In China, it was also found that the pan evaporation presented a decreasing trend in many regions, probably due to decreasing wind speed above the ground (Zheng et al. 2009; Shen et al. 2010; Liu et al. 2011). The complementary relation between the potential and actual evaporation was only effective in regions with limited water resources (Yang et al. 2006). Furthermore, some studies in China investigated the impact of climate change on water cycles. The results from the IPCC climate models showed that runoff changes linearly with the global mean temperature and that this relation is insensitive to the selected climate scenario and the increment of the global mean temperature (Tang and Lettenmaier 2012).

Contributions by Chinese Scholars and Subsequent Problems

Chinese researchers have been working on the assessment of changes in water cycles in different regions based on analysis of climatic and hydrological observations. Changes in statistical properties such as trend, period, distribution, and stationarity were extensively analyzed for many hydrological and climatic variables in different regions of China. Possible future changes in the water cycle over China were assessed based on the downscaled IPCC climate projections and the outputs were used to evaluate water management strategies. It is worth noting that Chinese research on changes in water cycles was mainly based on data from observation stations. Time series analysis focused mostly on one single hydroclimatic variables. Research on interactions between climate and the terrestrial water cycle was limited. Moreover, studies were usually performed on regional scales. Research with applications to other neighbouring countries and on the global scale were seldom conducted. In addition, discussion on uncertainty analysis of the results was limited. More attention needs to be paid to uncertainty issues in future research.

Future Research

Most of the current research believes that the global water cycle is speeding up under climate change. However, limited by the quantity and quality of observation data, the results of evaluations of changes in the terrestrial water cycle and water resources are uncertain. Different data and analysis usually lead to different trend analysis results for key hydrological parameters such as precipitation, runoff and dry areas. Therefore, it is important to improve the quality of climatic and hydrological observations. Consistent long-term water and energy flux data is useful for detecting changes in patterns in water cycles. In addition, evaluation of future changes in water cycles mainly relies on simulation results from models. Uncertainty in future trend evaluation results mainly originates from the global climate model and hydrological models. Uncertainty in hydrological models is even larger than that in the global climate model. Future studies should focus on uncertainty analysis in the evaluation results. The contributions of uncertainty from different sources can be estimated. Hydrological models should be improved in order to reduce uncertainty in simulation results.

9.2.2 How to Improve Simulation and Prediction Capacities in Hydrology and Water Resources?

Mathematical models are an important tool for simulating and predicting hydrological processes and water resources. These models are usually constructed based on physical facts and mechanics of hydrological processes. Temporal and spatial variations of hydrological fluxes and hydrological state variables are often helpful for understanding mechanics in hydrological processes (Maurer et al. 2001; Robock et al. 2003). Hydrological observation data helps not only to understand the mechanisms but also to calibrate and validate models.

Bibliometric Analysis of Contemporary Research

Since 2000, there were nearly 8000 papers published on modelling, which is an essential tool for simulation and prediction. Around 5000 papers included discussion of uncertainty, indicating that uncertainty is one of the key problems in current simulation and prediction research. Among 3000 papers on hydrological modelling, 1500 papers focused on calibration; 2400 papers were related to model parameters; 800 papers dealt with model optimization; and 2000 papers involved uncertainty. This implies that modeling and uncertainty analysis were the major tasks in hydrological simulation and prediction in this decade. In addition, more than 5000 papers addressed issues in rainfall-runoff models, among which, there were 1300 papers on vegetation and 1200 papers on forest. This indicates that eco-hydrological processes are an important research area in hydrological simulation and prediction.

Contemporary Research

Distributed models are able to characterize the spatial variability in the catchment surface and its impact on hydrological and surface processes. In distributed models, hydrological processes including canopy interception, evapotranspiration, infiltration, surface runoff, soil flow, underground flow and confluence are described based on physical mechanisms. The water and energy balance were used to describe the biophysical processes in order to include the influence of changes in environmental factors on the hydrological processes (Rui and Huang 2004). Coupling the hydrological model with vegetation growth processes was able to improve the simulation and prediction capacity of hydrological models (Yang et al. 2010, 2015). In comparison to hydrological models, land surface models can better simulate water and energy flux exchange processes (Pitman 2003). The carbon and nitrogen cycles were introduced in land surface models (Oleson et al. 2010), in order to study the impact of climate change on surface water and heat fluxes as well as carbon and nitrogen fluxes (Shi et al. 2013).

Human activities are one of the principal factors that affect terrestrial water cycles. Hence it is important to take into account human activities in hydrology and water cycle models in order to improve model performance. Previous research focused mostly on the indirect impact of greenhouse gas emissions on water cycles. Not enough attention has been paid to the impact of land-use and land-cover change (LUCC), agricultural, industrial and domestic water supply and reservoirs on the hydrological processes (Oki and Kanae 2006; Pitman et al. 2012). Water and land resource exploitation in wide areas has changed hydrological properties of catchment surfaces, and further changed the water and energy cycles (Vitousek et al. 1997; Bhaduri 1998; Vörösmarty and Sahagian 2000; Moussa et al. 2002). In recent years, some researchers have developed hydrological models considering human activities (e.g., Tang et al. 2006). In this type of model, the industrial, agricultural and household water demands were evaluated from data reflecting development level of the society such as irrigation area, population and gross domestic product (GDP) (Döll et al. 2003; Rost et al. 2008; Hanasaki et al. 2006).

Uncertainty in model parameters is one of the main factors that determine the simulation and prediction capacity of models (Duan et al. 1992). More and more attention has been paid to model parameter calibration, which usually employs a global optimization method. Uncertainty usually exists in model parameters due to the complexity of distributed model structures and limited quantity and quality of observation data used for calibration. Therefore, there is a trend to evaluate uncertainty in model parameters instead of searching only for optimal parameters in model calibration. Many model calibration methods have been developed in order to estimate parameter uncertainty, including GLUE (Generalized Likelihood Uncertainty Estimation) (Beven and Freer 2001) and Bayesian methods (Kavetski et al. 2006; Ajami et al. 2007).

With the development of observation means and technologies, more and more data are available with improved quality. However, data still suffer from many problems, which limit the use of models (Moradkhani and Sorooshian 2008). Data assimilation techniques offer the possibility to handle different sources of uncertainty explicitly in hydrological models and hence improve their predictive capabilities (Salamon and Feyen 2009). Global hydrological databases containing observation data on surface and remote sensing data are nowadays available. One example of these databases is WATCH (Water and Global Change) dataset, which is a global hydrological model driven database (Haddeland et al. 2011). Based on these databases, it is possible to build distributed models coupling land surface processes and hydrological processes over large areas up to the whole globe. These databases also provide data for validating model calibration methods.

Bibliometric Analysis of Contemporary Research in China

Since 2000, Chinese researchers have published more than 500 papers on hydrological simulation or prediction. Among these papers, around 40 % of the papers dealt with hydrological modeling; around 200 papers contributed to model calibration and optimization; and more than 100 papers addressed uncertainty. There were more than 140 papers on vegetation and 80 papers on forest, whereas fewers than 30 papers concerned rainfall-runoff models. The aforementioned analysis indicates that hydrological model and uncertainty are also important research subjects in hydrological simulation and prediction in China. In addition, eco-hydrological processes have received much attention in Chinese research.

Contemporary Research in China

Chinese researchers have been working on monitoring related land processes and hydrological processes in China. In the last few decades, a number of monitoring programs and research platforms have been established. Some examples include the research network of the Chinese ecological system, the observation and research platform for the Tibetan Plateau (Ma et al. 2008), the monitoring network for soil moisture and freeze-thaw on different scales in Tibet (Yang et al. 2013), the remote sensing experiments in the Heihe river catchment (Li et al. 2013). These monitoring networks provide long-term continuous observation data, which facilitates the development of hydrological models. In addition, knowing the importance of having consistent data of land surface water and heat fluxes in the country, Zhang et al. (2014) developed a database driven by the needs of hydrological models, which collected the last 60 years of data in China.

Contributions by Chinese Scholars and Subsequent Problems

Based on the research on water cycles in Chinese areas, Chinese researchers developed their own rainfall-runoff models. The Xinanjiang model (Zhao 1992), which produces runoff on recharge of storage in a basin, was extensively applied in China and some concepts of it were also borrowed by models abroad. In recent years, studies on water and energy exchanging processes have been carried out. Hydrological models considering the impact of human activities have been developed (Hu et al. 2004; Wang et al. 2006; Xia and Wang 2008; Jia et al. 2010; Lei et al. 2010; Xu and Li 2010). In addition, Chinese researchers were among the earliest to include the impact of human activities in water cycle simulations (e.g., dualistic water cycle theory). In China, the research in this area endeavors to understand the relation between ecology, hydrology and economy and estimate responses of water systems and land surface systems to the changing environment.

Hydrological models developed in China are often based on the water balance, within which the water demand is usually calculated by empirical parameters. Most studies by Chinese researchers focused on specific problems in China. The transferability of the model and the empirical parameters was not validated in other regions under different climates. Hence it is generally difficult to apply these models to regions abroad, especially to those without much observation data.

Future Research

The development in hydrological observation, experimental techniques and modelling tools helps improve our capacity of simulating and predicting the water cycle and water resources. However, uncertainty in observation data and models remains the main difficulty in the simulation and prediction of hydrology and water resources. Future research should focus on the integration of information from different sources including observation data and modeling results. The monitoring, simulation and prediction of the water cycle and water resources need to be improved.

9.2.3 How to Achieve Water Security in a Changing Environment?

Along with the progress in global change research, the research now focuses not only on the spatial and temporal distribution of water resources, but also on the water security issues. An important question in water security research is whether water resources are able to support the development of the economy and society. Water security is related to the security of the food, energy and ecological environments. In the changing environment, due to climate change and human activities, water security is such an important issue that relates to the maintenance of national security, which is also an important subject in water resources research.

Bibliometric Analysis of Contemporary Research

Between 2000 and 2014, nearly 5000 papers were published on water resources. Among these papers, 1/5 of the papers conducted studies on flood disasters due to extreme hydrological events; around 2/5 of the papers focused on water resources management; studies on agriculture and land use comprised 1/4 of all papers. Water resources management technology (e.g., information management) is an important topic in water security research with changing climate, with more than 2000 papers published. Water security studies were mostly performed at national or regional scales. There were nearly 1000 papers conducting studies in the United States. More than 200 papers performed analysis in each of other large countries including China, Canada and Australia.

Contemporary Research

Many studies have showed that climate change has a significant impact on water security. Climate change can possibly accelerate water circulation, which often leads to more concentrated precipitation and runoff in short periods. As a consequence, water resources in arid and semi-arid areas become more delicate under climate change. Furthermore, extreme precipitation events also result in flooding risks. Glacial recession due to climate change can further reduce runoff in dry seasons. Climatic warming leads to elevated evaporation, which results in increasing crop water demand. More irrigation water is likely to make water shortages even worse. In addition, sea level rise due to climate change possibly increases risks of land inundation, soil salinization and seawater intrusion (Ding 2008). In the meanwhile, with the growing global population, the pressure of meeting the water resource demand will continue to increase. Hence, water security is and will always be a challenging issue (Oki and Kanae 2006; Schewe et al. 2014).

The average per capita quantity of water is traditionally used as an indicator for water resources security (Falkenmark and Widstrand 1992). Water is considered abundant when the average per capita quantity of water resources is over 1700 m^3. When it is below 1700 m^3, stress on water resources appears. The limits for chronic water scarcity and severe water scarcity are respectively 1000 and 500 m^3. Another commonly used indicator for water resources security is the exploitation level of water resources, which is defined as the percentage of actual consumed water over all annual fresh water resources. This indicator is selected by many institutions in the United Nations (UN) to define the scarcity level of water resources (Engelman and LeRoy 1993; WWAP 2012). Different levels are empirically defined. One region is considered presenting low stress, mid-low stress, mid-high stress and high stress when the exploitation level is respectively below 10 %, between 10 and 20 %, between 20 and 40 %, and over 40 %. These two indicators are both able to indicate water security levels, but are not precise enough for water security management. Some researchers have proposed end-user oriented water security evaluation methods based on a number of water quantity and quality indicators, in order to support decision-making in water security (Norman et al. 2013).

Bibliometric Analysis of Contemporary Research in China

Since 2000, Chinese researchers have published around 500 papers on water resources security. Among these publications, more than 2/5 of the papers were related to human activities and over 3/5 of the papers contained the key word of water resources management. Much effort has been made to flooding research with more than 100 papers published, whereas drought has received less attention with 65 papers published. The case studies were mostly conducted in China. Around 60 papers included applications in the United States. Few papers dealt with applications from other countries.

Contemporary Research in China

Chinese researchers have pointed out that increasing evaporation due to elevated temperature will lead to higher irritation water demand, which will possibly result in water resource shortages (Ding 2008). In this context, many researchers have made evaluations of the vulnerability of water resources in regions in China and the regional water resources security in the changing environment (Xia et al. 2010; Jia 2014). In addition, Chinese researchers are among the earliest to study the influence of the social economy system on the exploitation of water resources and the impact of human activities on water cycles. The concept of the water cycle in the social economy system was developed (Jia et al. 2003). Research on water security in China often examines optimal allocation and efficient use of water resources based on the water resources system itself. The complex relationship between water, energy and food is not often considered. Therefore, it is important to include the interaction effects of the water system and the social economy system in water security research in order to achieve harmonious coexistence between humans and water. In recent years, social hydrology has become a new research subject in water resources and increasing attention has been paid to it. In comparison to traditional hydrology research, the key of social hydrology is to study the capacity of the water system to meet the society demands in the changing environment, in order to make decisions on water resources taking into account all relevant information.

Contributions by Chinese Scholars and Subsequent Problems

Chinese researchers proposed the theory and methodology for the assessment of water resources vulnerability and the development of adaptation measures under climate change. Research in this field should adopt "no regrets" adaptation measures in order to achieve sustainable development. Water resources management can also benefit from cost-benefit analysis and greater stakeholder involvement in information provision and decision making (Xia et al. 2015). Nevertheless, water resources vulnerability and adaptation under climate change needs more research in China. Current hydraulic engineering and water resources planning and management are mostly based on the assumption of stable hydrological random variables, that is, random variations in time series are analyzed based on historic climate data without considering a trend. The impacts of climate change, including possible changes in mean, variation and extreme events, were rarely considered, which may lead to grave hydraulic engineering accidents. Moreover, research on water security in China focuses mostly on optimal allocation and efficient use of water resources. Not enough attention has been paid to interdependent relations among water, food, and energy security, as well as ecological security. Models based on mechanisms for quantitative analysis are needed in order to support the planning and management of the system of water, food, energy, and ecological security.

Future Research

The relations among water resources, human activities and social development remain one of the difficulties in water security research. It is important to further develop social hydrology and to coordinate water, food, energy and ecological environment based on water system security. Great attention should be paid to impacts of components in social water cycles such as virtual water trade. Research on global strategies for national water security should be carried out, noting that the social water cycle may cross basin and national borders.

9.3 Roadmap for Further Research

At present, water has become a rigid constraint for the development of our economy and society. Water security needs to be improved in order to support the development of the economy and society. Internationally, efforts have been made to understand the processes and mechanisms of the evolution of the land surface water system. Researchers have been working on the development of risk management of the water system in order to provide scientific support for water security. Research in China follows the international state-of-the-art. In this context, future Chinese research on the water cycle and water resources needs to focus on quantitative characterization of water system evolution, mechanisms and risk management.

(1) Quantitative Characterization of Water System Evolution

In the last few decades, much research on the water cycle and water resources has been produced based on extensive field experiments and remote sensing observations. Nevertheless, the data were often limited to the description of one variable, one scale, and one process, resulting in incomplete information on the water cycle. To improve the quantification of the evolution of the water system, it is necessary to develop new methods and technologies for measuring the climatic and hydrological variables, and thus to construct the full image of the whole process of water movement and storage change. Therefore, hydrological database systems based on multiple sources are needed. Methods for the assessment and prediction of the evolution of the water system in regions with scarce data need to be developed. Platforms for data collection and sharing should be established with high-precision and multi-scale data characterizing hydrological processes in China and other regions.

(2) Evolution Mechanisms of the Water System under Many Influential Factors

Changes in the water cycle and water resources in the changing environment, which are a part of the changing regional environment, result from climate change, underlying surface change, river system regulation as well as the society's water intake. These changes have significant impacts on the formation, transfer and utilization of water resources. In order to address water security in the changing environment, mechanisms of water system evolution considering the influence of multiple factors need to be studied with more detail. Previous studies have worked on the impact of some of the factors on water system evolution. Future research needs to further study the mechanisms of changes in water cycles due to changes in land surface processes given the changing environment. It is necessary to quantify impacts of individual factors including changes in climate and underlying surface and human activities on water resources. The interaction between the water system and social needs to be evaluated in order to understand coordinated evolution rules between water and humans. Furthermore, models for evaluating regional water systems should be developed for predicting the evolution of water systems and renewable water resources.

(3) **Risk Management of Water Systems**

The main task of water security is to ensure that the water system is able to support the development of the economy and society and maintain the hydrological system. The operation and management of the water system must follow the evolution rules of the water system based on the process of the formation, transfer and utilization of water resources. In the past, water resources management lacked sufficient understanding of the complexity and severity of the water system. As a result, too much emphasis was usually put on one aspect of the problem, resulting in risks to other aspects. Future research on water security should develop integrated risk management of the water system. Based on the interaction effects of water, energy, food and ecology, the theory of integrated water system risk management including various factors can be established. Combining modern technologies such as remote sensing, ground observation, big data, cloud computing and internet of things, the monitoring system of the full water system processes and the water security risk evaluation system can be developed. A system to quantify risks in the water system needs to be provided. It is also necessary to develop methods for risk identification, early-warning, evaluation and emergency handling, and to establish decision-making platforms for risk management of the water system.

9.4 Summary

Research on the water cycle and water resources is driven by the need for water security, which is an important subject in geographic science. Research on the water cycle and water resources mainly includes the understanding of moving patterns of land surface water, the investigation of interactions between water and other factors on land surfaces and the exploration of approaches for sustainable utilization of water resources. The research on the water cycle and water resources has recently moved from description of isolated processes to characterization of the performance of the entire water system. At the same time, our understanding of mechanisms in water systems keeps improving by taking into account related land surface processes including the human, ecological and geomorphic processes. Traditionally, the objective of sustainable use of water resources is to meet the water demand; recently it has changed to addressing water security by coordinating the relation between human and water systems. Chinese research on the water cycle and water resources follows the international state-of-the-art in the research field. The traditional analysis of hydrological processes is evolving to integrate the interactions between the water cycle and related land surface processes. In the area of studying interactions between water and human processes, China is at the edge of international research. Based on practices of hydraulic engineering projects and inter-basin water allocations and water resources management, Chinese researchers have developed the theoretical framework of a dualistic nature-social water cycle, and have developed land surface hydrological models taking into account human activities. The spatiotemporal span of Chinese studies has been gradually expanded, which deepens the understanding of water scarcity risks under changing environmental conditions. Nevertheless, research in this area still needs to be strengthened in order to address interactions among multiple factors in the water system, and to manage the water related risks. Future research needs on water cycle and water resources are highlighted, including the needs to: (1) understand the interplay between hydrological and other land surface processes; (2) improve the simulation and prediction capacities of hydrology and water resources; and (3) develop the theory and methodology for risk management in order to achieve water security in a changing environment.

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Land Change

10

Huiyi Zhu and Wei Song

Abstract

We analyzed the progresses of land change research in the world with bibliometric method in this chapter. In the past 15 years, land change research worldwide mainly concerned the observation and monitoring, driving forces and causal mechanism, and environmental effect of land change. China produced many influential achievements in observation and monitoring based on remote sensing, influence of urbanization on land change and the impacts of land change on soil environment. NSFC tended to support the researches of urban land expansion, effects of urbanization and policy, and the impacts of land change on soil.

Keywords

Land use and land cover change • Observation and monitoring of land change • Causal mechanism of land change • Consequence of land change • Impact of land change on environment

A total of 32,876 SCI/SSCI-indexed articles are analyzed in the research area of land change. Articles were identified from 589 international journals from 2000 to 2014. The number of journals that have published more than 15 of the relevant articles is 340 (Appendix G). The search query is as follows: "land change" and "LUCC" (land use and land cover change) in literature titles, key words, and abstracts.

10.1 Overview

10.1.1 Development of Research Questions

Land change research began to arouse the interests of academia after the mid-twentieth century. The search results of papers in international journals show that it was not until the 1970s that the two concepts of "land use change" and "land cover change" appeared, and when global environmental change, especially climate change, attracted the attention of academics (Vitousek et al. 1997). The continuing deterioration of the global environment and the social need to address environmental change objectively require people to understand the changes of the earth system and the environmental and human driving forces behind them (Liu 2002; Rounsevell et al. 2012). Land change, as a constituent part of and an important reason underlying global change, is a key field at the frontier of global change research (Li 1996; Cai 2001).

The fact that land change attracted the attention of the public after the mid-twentieth century is closely related to the development of remote sensing technology (Zeimetz et al. 1976; Todd 1977; Byrne et al. 1980). It is also linked to the active promotion of such international programs as the International Geosphere-Biosphere Program (IGBP) and International Human Dimensions Program on Global Environmental Change (IHDP). To strengthen comprehensive research on the natural and human factors that affect land change, the IGBP organization [affiliated with the International Council of Scientific Unions (ICSU)] and the IHDP organization [affiliated with the International Social Science Council (ISSC)] jointly proposed and published the Land Use and Land Cover Change (LUCC) program in 1995 and further set up the Global Land Project (GLP) in 2005. After the launch of the two global projects, land change research quickly became a prominent issue in the natural and social

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sciences. The interdisciplinary study of global change science and sustainability science, that is, land change science, was thus born (Turner et al. 2007; Foley et al. 2011; Turner et al. 1994).

Land change includes land use change and land cover change (Turner et al. 1994; Cai 2001). Before the mid-1990s, LUCC, in the form of influencing factors of global change and major parameters for model evaluation, was beginning to catch the attention of academia. At that time, land change was mainly understood as forest conversion, and was considered to be a regional, continuous one-way process with a simple change trajectory. It was attributed primarily to the agricultural expansion caused by population growth. Research on the effects of land change focused mainly on carbon cycling (Lambin and Geist 2001). After the mid-1990s, people started to realize the dominant role of human activities in global change, and that LUCC are important modes of human activity. During this period, international land change research focused mainly on the driving factors of LUCC caused by human activity over the past three hundred years; the future scenarios of LUCC; and the sustainable use of land. Important research foci in this period included land use and land cover evaluation, modeling and prediction, the relationship between driving forces of LUCC at different scales, and data acquisition and processing. After 2005, IGBP and IHDP jointly initiated the Global Land Project (GLP). Changes of ecological systems and the terrestrial landscape due to human activity are recognized as the major source of changes to the surface of the earth. It is believed that changes in land use and management initially influence the status, characteristics, and functions of the ecological system and then its service functions and effects on human well-being. It is emphasized that land change should be understood from the perspective of a human–environment coupling system (Rounsevell et al. 2012). The driving mechanisms and results of land change, as well as integrated analyses and simulations of the sustainability of land systems, have become the key foci of research on land use in this period.

10.1.2 Contributions by Scholars from Different Countries

From 2000 to 2004, there were 5470 papers published on land change in total; from 2005–2009, the number reached 10,138; while from 2010–2014 it further increased to 17,268, showing a continuous rapid rise. The statistics of SCI/SSCI papers in this field reveal that 20 countries, including the US, China, the UK, Germany, Australia, and Canada (Table 10.1), have made significant contributions to land use research and become the major research centers in this field. The relevant SCI/SSCI papers published by these 20 countries over the last 15 years account for 86.6 % of the total papers published globally. The US ranks first in both the quantity and influence of papers.

During the 15 years between 2000 and 2014, China ranked second globally in the quantity of published papers. However, the growth rate of China's SCI/SSCI papers exceeded that of America's, with the number of papers increasing from 323 during 2000–2004 to 2449 from 2010–2014, and as a percentage of global publications rising from 5.9 to 14.2 % over this period. China ranked fifth in total citations between 2000 and 2014, surpassed only by the US, the UK, Germany, and Australia. The growth of total citations of Chinese SCI/SSCI papers is clearly evident. Its rank rose from eighth in 2000–2004 to third in 2010–2014, behind only the US and the UK, confirming that China is gradually increasing its academic impact in land change science. With respect to citations per paper, the average citation of papers published by China is only eight, lower than the world average citation of 20. From 2000–2004, 2005–2009, and 2010–2014, the average citation of papers published by China constituted 49, 53, and 55 % of the world average, respectively. Thus the gap with the international average has been continuously narrowing. Due to a growing the number of highly-cited papers, China moved from eighth in 2000–2004 to seventh in 2010–2014. China has leaped into the front ranks of the world both in terms of the scale of research and the quantity of papers in the field of land change. Although there is a certain gap between China and the US and the UK with respect to the international influence of papers and peer attention, China is witnessing a continuous increase in both the quantity and influence of papers. This indicates that China has great development potential in the field of land change research.

10.1.3 Key Research Topics

The clustering figure of co-occurring keywords (Fig. 10.1) shows that "land change" and "climate change" are the two keywords with the highest occurrence frequency in international journals. The "carbon" is the keyword with the highest co-occurrence frequency around "climate change", demonstrating that the influence of land change on climate change, especially with respect to carbon emissions, is a major focus of land change research. Other high-frequency keywords co-occurring with "land change" can be approximately divided into four categories: (1) keywords reflecting the type of and causal mechanisms for land change, including "forest", "land use", "land cover", "vegetation", and "landscape"; (2) keywords reflecting observation, monitoring and research methods of land change, including "remote sensing", "model", "pattern", "dynamics", "scale", and "classification"; (3) keywords reflecting the

Table 10.1 Top 20 countries (regions) with the number and citations of SCI/SSCI-indexed articles on "Land Change" during the period 2000–2014

	Number of articles						Cited frequency						Number of highly cited articles					
	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014
Rank	World	836	3,344	5,470	10,138	17,268	World	53,113	1,561	260,971	288,316	116,792	World	151	0	757	840	913
1	USA	299	813	1,936	3,105	4,277	USA	19,823	468	110,373	113,013	36,471	USA	70	0	370	374	338
2	China	22	571	323	938	2,449	UK	9,240	161	32,456	32,083	11,631	UK	24	0	86	111	98
3	UK	118	202	560	823	1,155	China	944	159	7,510	14,093	9,142	Germany	7	0	38	39	60
4	Germany	47	190	270	545	1,004	Germany	2,637	92	13,569	14,826	7,763	Australia	3	0	32	46	48
5	Australia	29	160	262	498	902	Australia	1,443	78	13,966	13,726	6,472	France	4	0	25	30	47
6	Canada	46	134	245	443	623	France	2,260	49	7,884	11,957	4,861	Netherlands	2	0	25	35	40
7	France	28	96	166	334	582	Canada	2,373	52	9,296	10,954	4,505	China	2	0	20	26	40
8	Spain	17	100	115	290	577	Netherlands	884	68	10,015	9,023	4,258	Canada	9	0	28	33	33
9	Italy	17	92	78	232	511	Spain	589	47	4,657	7,181	3,700	Spain	2	0	15	14	31
10	Netherlands	25	92	154	301	481	Italy	859	49	3,251	6,146	3,224	Switzerland	8	0	17	21	25
11	Japan	13	66	98	253	346	Switzerland	3,593	22	6,201	7,945	2,687	Italy	2	0	11	15	24
12	India	14	57	67	104	290	Sweden	483	19	4,254	4,456	1,949	Sweden	1	0	12	12	14
13	Switzerland	16	44	59	167	286	Japan	239	19	1,844	3,568	1,311	Denmark	1	0	6	9	12
14	Brazil	5	50	59	143	271	Denmark	345	27	2,633	2,549	1,261	New Zealand	1	0	8	9	9
15	Sweden	10	44	120	141	256	Belgium	835	14	5,739	4,170	1,234	Brazil	1	0	9	4	8
16	Belgium	11	26	74	165	180	New Zealand	327	13	2,892	3,369	1,162	Norway	3	0	4	2	8
17	New Zealand	11	31	75	108	170	Brazil	302	31	2,344	3,022	1,099	Belgium	4	0	16	10	7
18	Denmark	10	38	65	93	170	Norway	505	12	1,328	2,006	1,040	Austria	0	0	2	10	6
19	Finland	6	29	45	80	145	Austria	26	11	1,295	2,585	862	South Africa	1	0	5	3	6
20	Norway	7	26	38	91	142	Argentina	2,385	3	3,680	1,466	675	Finland	0	0	3	7	5

Note Countries (Regions) ranked by the number of articles, cited frequency and number of highly cited articles during the period 2010–2014

environmental effects of land change, including "water", "soil", "biodiversity", "conservation", "ecosystems", and "impacts"; and (4) keywords reflecting prominent topics or countries with respect to land change including "tropical", "China", and "United States". This indicates that the observation, monitoring, and simulation; causal mechanisms; and environmental effects of land change comprise the three major themes of international land change research. At the same time, distances between these keywords (Fig. 10.1) differ and they have evolved into many frontier research directions.

Keywords with similar connotations were combined and then sorted by word frequency. The results show that research on observation, monitoring, and pattern of land change focused mainly on "pattern", "dynamics", "scale", "remote sensing", "model", and so on; research on the causal mechanisms of land change concentrated primarily on "urbanization", "population", "response", "policy", "adaptation", etc.; and research on the environmental effects of land change centered mainly on "climate", "water", "soil", "diversity", "ecosystem", etc. With respect to observation, monitoring, and pattern of land change, "dynamics" and "model" always rank first and second in frequency (Fig. 10.2). This suggests that the quantitative description and prediction of dynamic changes of land use and land cover via the model method forms the core of international research after 2000. In terms of causal mechanisms for land change, "population" was the most prominent issue and its word frequency ranked first among the similar keywords prior to 2002. However, after 2003 "urbanization" quickly became the most prominent topic. With regard to environmental effects, "climate" is the most prominent topic with increasing concern being devoted to this subject. This demonstrates that atmospheric environmental effects have always been the key focus of research on the environmental effects of land change.

According to changes in the word frequency of keywords in literature published by Chinese authors, the ranking of the main keywords concerning observation, monitoring, and pattern of land change is similar to that of foreign countries. The frequency of "dynamics" and "model" has ranked first and second since 2007. This suggests that the quantitative description and prediction of LUCC dynamics via the model method also forms the core of research on observation, monitoring, and pattern of land change in China after 2000. In research on causal mechanisms for land change, the frequency of keywords in China differs from that of foreign literature. For example, "urbanization" has been the most prominent topic since 2000 and its word frequency has maintained this top ranking; "population" follows behind; and the word frequency of "policy" has been increasing rapidly, but has not exceeded that of "population." This shows that urbanization forms the core of research on the

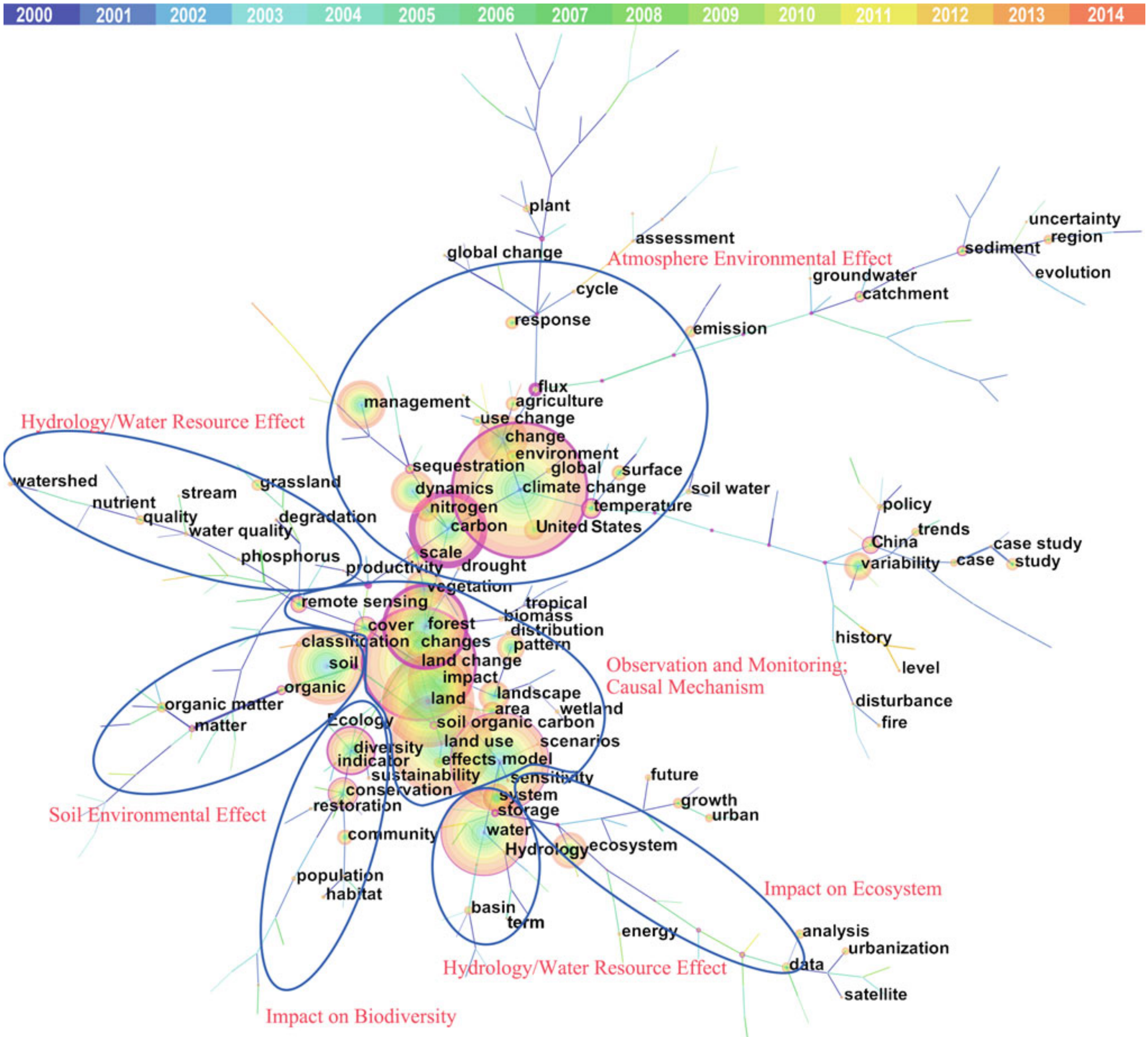

Fig. 10.1 Co-occurrence network of SCI/SSCI-indexed article keywords on "Land Change" during the period 2000–2014

driving forces of land change in China. With respect to environmental effects, "climate" is the most prominent topic with increasing concern in China, which is the same for other countries. However, in contrast to foreign countries, the word frequency of "soil" ranks second in China, higher than that of such words as "vegetation" and "water." This indicates that in their research on environmental effects, Chinese scholars strongly emphasize the impacts of land change on water and soil loss, land desertification, and water pollution. This is closely related to regional environmental problems in China such as water and soil loss, serious desertification, water shortages, and escalating water pollution.

10.1.4 The Role of NSFC in Supporting the Research on Land Change

The National Natural Science Foundation of China (NSFC) is one of the major funding sources of land change research in China. During the 15 years from 2000 to 2014, NSFC sponsored 716 relevant projects in total, with overall grants surpassing 383,364 thousand yuan. Table 10.2 shows the temporal change in the number of funded projects and the overall grants. NSFC only sponsored 83 projects related to land change research from 2000–2004 and the grants amounted to less than 34,894 thousand yuan. The projects sponsored by NSFC from 2005–2009 increased to 211 and

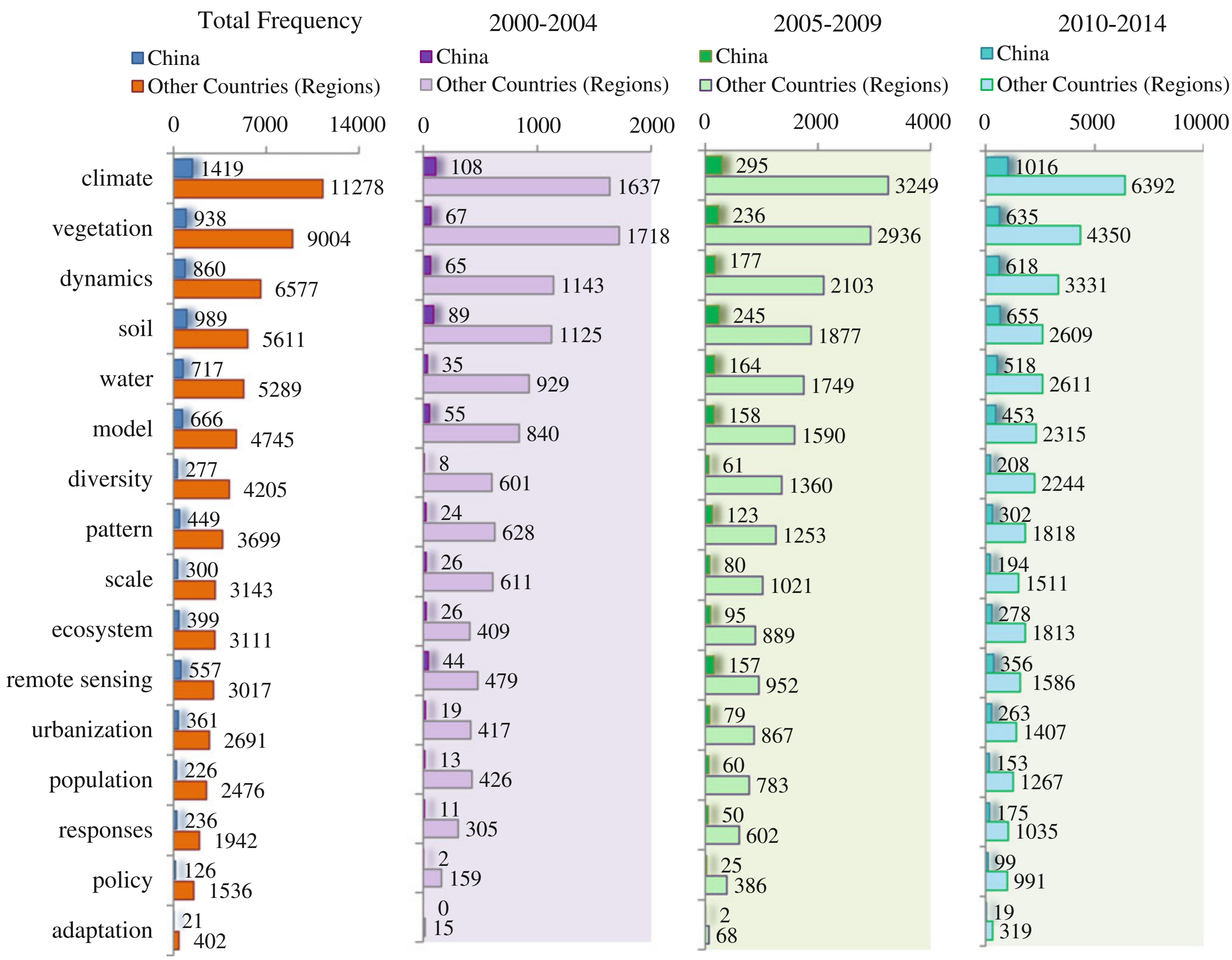

Fig. 10.2 Keyword temporal trajectory graph for SCI/SSCI-indexed articles on "Land Change" during the period 2000–2014

total grants exceeded 85,520 thousand yuan. Between 2010 and 2014, the number of funded projects further increased to 422 and grants reached 262,950 thousand yuan. The number of projects and grant amounts have clearly increased. The growth rate of the grants is much higher than that of the number of projects. The average grants of a project increased from 420 thousand yuan during 2000–2004 to 620 thousand yuan from 2010–2014. This indicates that NSFC has increased the grants of single projects while enlarging the number of funded projects, which is proof that NSFC has taken full account of the change in the costs of scientific research.

NSFC-funded projects cover many fields of land change research. The main directions of NSFC-funded research are also the key foci of international land change research, primarily related to observation and monitoring, driving mechanisms of land change, and especially environmental effects. Compared with the international land change research, NSFC-funded projects pay more attention to urban land than agricultural and forest land. Among the keywords of funded projects, the frequency of keywords including urban land increased from 4 in 2000–2004 to 14 in 2005–2009, and 27 in the period of 2010–2014. During these 15 years, NSFC funded at least 47 projects related to urban land research, much more than those related to agricultural land research (17 projects). With respect to driving mechanisms for land change, NSFC-funded projects concern urbanization and policy responses. The "urbanization" appeared 106 times in the key words of funded projects. This frequency showed a clear growth tendency, rising from seven in 2000–2004 to 36 in 2005–2009 and to 63 in 2010–2014. With regard to environmental effects, soil—especially soil erosion—has attracted the most attention, followed by climate change, ecosystem services, and hydrologic effects. By 2104 the overall frequency of keywords related to soil reached 262, while those related to atmosphere, hydrology

Table 10.2 NSFC-funded projects and SCI/SSCI-indexed articles on "Land Change" during the period 2000–2014

SCI/SSCI-indexed articles					NSFC-funded projects			
Periods	Number of articles	% of articles by Chinese authors	% of articles with NSFC funding by Chinese authors	% of articles funded by MOST among those with NSFC funding	Number of projects	Funding (10,000 yuan)	Number of PIs	Number of institutions
2000–2004	5,470	5.9	1.5	0.0	83	3,489.4	83	47
2005–2009	10,138	9.3	19.2	3.3	211	8,552.0	206	87
2010–2014	17,268	14.2	63.5	1.0	422	26,295.0	410	165
2000–2014	32,876	11.3	46.9	1.2	716	38,336.4	631	195

and water sources, and ecosystem services were only 149, 143, and 131, respectively. However, the growth rates of these latter three are higher than that of soil. The keywords related to hydrology and water resources displayed the greatest proportional increase, which indicates that the intensity of grants is increasing rapidly. NSFC-funded projects are mainly distributed in ecologically fragile regions such as the Loess Plateau, arid regions, the Sanjiang Plain, and agricultural and agro-pastoral ecotones (Fig. 10.3). The occurrence frequencies of keywords in funded projects for the above-mentioned regions are 56, 44, 20, and 14, respectively. This demonstrates that NSFC not only keeps pace with international frontiers in funding research on land change, but also strongly emphasizes the real needs and regional characteristics of China.

NSFC-funded projects include Key Programme (KP), General Programme (GP), Young Scientists Fund (YSF), and Fund for Less Developed Regions (LDR Fund). In addition, it has launched the National Science Fund for Distinguished Young Scholar (DYS Fund) and the Excellent Young Scientists Fund (EYS Fund) in recent years. These projects play a significant role in promoting team development and talent training for Chinese land change research, since they originate via a comprehensive selection process. From the total number of funded projects (Fig. 10.3), the 716 NFSC-funded projects have 631 project leaders. The number of newly supported project leaders continues to grow, from 83 in 2000–2004 to 206 in 2005–2009 and 410 in 2010–2014. Meanwhile, project-supporting organizations have also increased from 47 in 2000–2004 to 165 in 2010–2014, their total number reaching 195 within 15 years. These organizations support major scientific research institutions and colleges throughout the country. This indicates that NSFC has made important contributions to team development for land change research. In particular, the foundation provides young scientific talent and the scientific talent in western China with rare opportunities by launching regional projects and those for young scholars, thereby promoting the growth of these scientific talents.

NSFC has created an achievement evaluation system for its projects, which has stimulated productivity and research output. With respect to publication of SCI/SSCI papers, 46.9 % of papers published by Chinese scholars are funded by NSFC, equaling the sum of papers supported by other foundations (Fig. 10.3). Only 1.2 % of these papers are the result of the collaborative subsidy of NSFC and the Ministry of Science and Technology (MOST). This suggests that NSFC has made great contributions to the internalization of Chinese land change research. NSFC-funded SCI/SSCI papers comprised only 1.5 % of the total SCI/SSCI papers published by Chinese scholars in 2000–2004, rising to 19.2 % in 2005–2009, and to 62.5 % in 2010–2014. Thus during this 15-year period, the percentage has risen by 61 percentage points. In the meantime, the proportion of papers published by Chinese authors relative to the total number of international papers in this field has risen from 5.9 to 14.2 %, an increase of only 8.3 percentage points. This suggests that NSFC has played a significant role in promoting the transition of Chinese land change research from being a laggard to an equal participant with the international mainstream (Table 10.2).

10.2 Questions and Research Progress

10.2.1 What Changes in Land Use and Land Cover Have Occurred at Different Scales?

Bibliometric Analysis of Contemporary Research

Observing and monitoring the changes of land use and land cover is the starting point and basis of land change research. That is to say, the first research step is to ascertain when, where, and what land use and land cover changes have taken place and to clarify the pattern and process of land change. The literature search results show that among the 32,876 papers retrieved from (ISI) Web of Science, keywords containing "pattern" appear 4148 times, accounting for 13 %

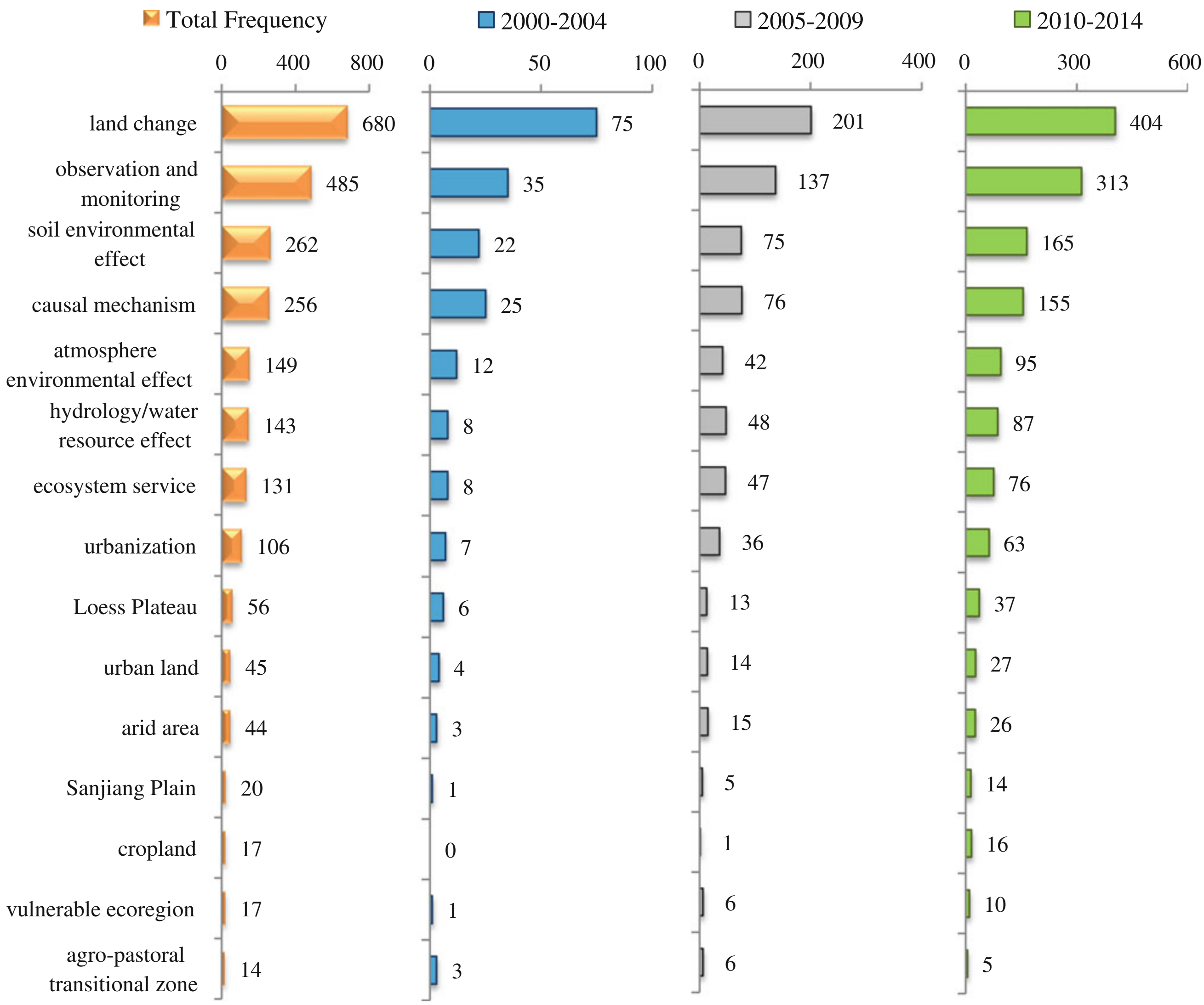

Fig. 10.3 Keyword temporal trajectory graph for NSFC-funded projects on "Land Change" during the period 2000–2014

of the total number of all keywords; keywords containing "scale" appear 3443 times, accounting for 10 %; those containing "remote sensing" appear 3574 times, accounting for 11 %; keywords containing "dynamics" appear 7393 times, accounting for 22 %; and those containing "model" appear 5411 times, accounting for 16 %. These results show that the observation and monitoring of pattern and process of land change with remote sensing and models occupy an important status in land change research. Given the high spatial-temporal heterogeneity of land change, research at a single scale cannot fully reflect the characteristics of land change at different spatial and temporal scales and research at local, regional, and global scales should be carried out. Thus the observation and monitoring of land change has obvious spatial-temporal characteristics.

Contemporary Research

Observation and monitoring of land change at a global scale is important for evaluating models of climate change and other global changes related to land cover. To evaluate the global changes of net primary productivity, carbon sources and sinks, and biodiversity, and to provide land cover parameters for the Osnabruck Biosphere Model (OBM), BIOME-Bio Geochemical Cycles (BIOME-BGC) and the IMAGE2 model, IGBP and other international programs have been engaged in the observation and monitoring of global land cover change since the 1990s and established a series of land cover datasets at a global scale. At present, the most widely used global datasets include the Global Land Cover Characterization Database (GLCC), the University of

Maryland land cover product (UMD), the Global Land Cover 2000 project data (GLC 2000), the Moderate Resolution Imaging Spectro-radiometer annual Land Cover product (MODIS LC), and the GlobCover land cover product (GLOBCOVER) (Loveland et al. 2000; Hansen et al. 2000; Bartholome and Belward 2005; Friedl et al. 2010). Although the observation and monitoring of regional land change focuses mainly on the process of modern-day land change, it has extended its time span. It has produced some regional historical data products. Representative products include: a Deforestation Dataset covering the past 300 years in Europe (Kaplan et al. 2009); a Cultivated Land Dataset covering the past 300 Years in North America (Ramankutty and Foley 1999); a Dataset of Cultivated Land, Forest Land, and Urban Construction Land covering the past 300 Years in China (Ge et al. 2008); a Dataset of Cultivated Land, Forest Land, Grassland, and Urban Construction Land covering the Past 130 years in India (Tian et al. 2014); and a Land Use Dataset covering the past 50 Years in Brazil (Leite et al. 2012). These datasets of regional historical land changes, similar to the global historical datasets, generally adopt population and historical documents and other proxy data (such as land suitability) to map historical land use on the basis of the modern land use/cover patterns.

Bibliometric Analysis of Contemporary Research in China

A statistical analysis has been conducted on the main keywords related to the observation and monitoring of land change from 2000 to 2014. The results show that the frequency of keywords containing "remote sensing" in papers published by Chinese scholars is equal to 15.6 % of the overall global frequency; and that keywords containing "dynamics" and "model" equal 11.6 and 12.3 % of overall global totals, respectively, both exceeding the proportion of SCI/SSCI papers (11.3 %). This suggests that Chinese scholars have carried out much fundamental work in applying remote sensing technology and model technology to observe and monitor the dynamics of land change; and half of the work is funded by NSFC. In addition, the frequency of words containing "pattern" accounts for 10.8 % of the overall global total, close to the proportion of SCI/SSCI papers. This indicates that Chinese scholars are basically keeping pace with international researchers in studies of land change pattern. However, there is a certain gap between Chinese and international research with respect to the aspect of "scale." The frequency with which this occurs in Chinese papers only constitutes 8.7 % of the overall global frequency, which is clearly lower than the proportion of SCI/SSCI papers. Forty-seven percentage of Chinese papers in which "scale" occurs are the result of NSFC's sponsorship.

Contemporary Research in China

China lacks global vision in the observation and monitoring of land change and still lags behind developed countries such as the United States in global land change observation and monitoring, although in 2014 it issued the "Globe Land Datasets" products with a resolution of 30 m for the years 2000 and 2010. Observation, monitoring, and patterns of land change research in China are mainly concentrated on domestic areas and have yielded substantial results. They primarily serve social and economic development and the solving of regional environmental problems, with a focus on land use in recent years.

Contributions by Chinese Scholars and Subsequent Problems

At the national scale, a series of land use and land change products have been produced by the Ministry of Land and Resources (Lin and Ho 2003). Land cover datasets for 1995, 2000, 2005, and 2010 with a 30 m spatial resolution were completed by the Chinese Academy of Sciences (Liu et al. 2014). There are also some historical data products, such as the land cover dataset of 18 provinces in mainland China over the past three centuries (Ge et al. 2008). At a regional scale, the Pearl River Delta, the Circum-Bohai Sea Region, the Qinghai-Tibet Plateau, the Loess Plateau, and the arid regions of northwest China are all key areas where observation and monitoring of land change has yielded impressive results. Results from observation and monitoring of urban expansion at the regional level (Weng 2001; Yang et al. 2003; Weng et al. 2004; Song 2005; Liu et al. 2005; Chen et al. 2006); cultivated land changes (Chen et al. 2001; Deng et al. 2006; Long et al. 2009); and land cover on the Qinghai-Tibet Plateau (Cui and Graf 2009; Zhang et al. 2013) have exerted far-reaching international influence.

Future Research

International observation and monitoring of land change has exhibited a tendency for continuous expansion of spatial-temporal scale, the continuing improvements in spatial-temporal resolution, the detailed sub-division of land change type, and the further integration of multi-source data (Verbesselt et al. 2010). China has made some achievements in remote sensing technology and has the independent intellectual property rights of the Beijing-1 Micro-Satellite, the China–Brazil Earth Resource Satellite, and other satellite data resources. Yet compared with developed countries it has no distinctions in earth observation technology. The potential advantages of China in observation, monitoring, and pattern of land change research lie mainly in the application field of remote sensing data. China is one of the regions with the most dramatic land changes in the world, including such phenomena as urban expansion, forest transition, grassland degeneration, wetland degeneration, and glacial shrinkage in the last three decades. In addition, the large national territorial area and the extremely significant differences in terrain between south and north China, and east and west China, provide favorable conditions for research on observation, monitoring, and pattern of land change. China also has a long history of agricultural development and utilization and rich historical documents, which provide great advantages for research on land change patterns and processes. Giving full play to these advantages, Chinese scholars will enjoy great opportunities to conduct studies of both historical and modern processes of land change and urban expansion.

10.2.2 What Kind of Natural and Human Factors Can Lead to Land Change?

Bibliometric Analysis of Contemporary Research

In addition to observing and monitoring when, where, and what land use/cover changes take place, land change research also needs to explore the kinds of natural and human factors that lead to these changes, in order to grasp the underlying rules governing the occurrence and development of land change as a basis for land use management and regulation. The literature search reveals that of the 32,876 papers retrieved from the (ISI) Web of Science, keywords containing "urbanization" appear 3052 times, accounting for 9 % of the total number of key words; those containing "population" appear 2702 times, accounting for 8 % of the total; those containing "response" appear 2178 times, accounting for 7 % of the total; those containing "policy" appear 1662 times, accounting for 5 % of the total; and those containing "adaptation" appear 423 times, accounting for 1 % of the total. These keywords, which are related to the driving forces of land change, have a high occurrence frequency, suggesting that research on the driving forces of land change remains at the heart of land change research (Lambin et al. 2001). As land use changes are mainly driven by human activities, the research on driving forces of land change concentrates primarily on human factors.

Contemporary Research

To understand land changes from the perspective of human factors at a global and long-term scale, people usually use the theoretical framework of IPAT (Holdren and Ehrlich 1974) with respect to empirical analyses. IPAT explains land change from the perspectives of population, affluence, and technology, but has difficulty in explaining the diversity and complexity of land change at a regional scale (Lambin et al. 2001; Andersen 1996). Through more detailed surveys, it has been found that land changes are driven by the synergistic effects of a number of underlying factors, among which economic factors, population growth, institutional and political factors, technical factors, and cultural factors play important roles (Geist and Lambin 2002). These factors appear in regional or local land changes in an interlocking or nested way. Their combination and interaction make land change an extremely complicated phenomenon (Turner et al. 2007). The driving forces of regional land change are usually studied through case analyses (Lambin et al. 2001). With the deepening of such research, case analyses will gradually touch on some unique land change processes. The most representative processes are forest transition and intensive agricultural land utilization (Mather 1992; Mather and Needle 1998). The driving mechanism behind this process should be explored from five perspectives: changes in demand for forest ecosystem products and functions; changes in forest and woodland utilization policies; cropland marginalization caused by urbanization; regional functional differentiation caused by globalization; and changes in small-scale farmers' land use behavior (DeFries et al. 2010). With the deepening and continuous enrichment of regional case studies, research on the driving forces of land change is also beginning to devote attention to land changes induced by biomass (Gelfand et al. 2013) and natural factors. The latter include suddenly occurring elements, such as climatic and geomorphic calamities, and gradually accumulating elements such as climate change and the shortage of fresh water resources.

Bibliometric Analysis of Contemporary Research in China

A statistical analysis has been conducted on the major keywords related to driving forces of land change from 2000 to 2014. The results show that the overall frequency of "urbanization" in papers published by Chinese scholars is equal to 11.8 % of its overall global frequency, while that of "responses" equals 10.8 %, close to or greater than the proportion of SCI/SSCI papers (11.3 %). In the relevant literature, the overall frequencies of "population", "policy", and "adaptation" are equal to just 8.4, 7.6, and 5.0 % of the overall global frequency, which is much lower than the proportion of SCI/SSCI papers (11.3 %). This may be because Chinese land change research places importance on national and regional scales, but ignores the global scale, and also due to its distinctive setting within the current stage of China's social and economic development (Liu et al. 2010).

Contemporary Research in China

Compared to relevant international research, Chinese research focuses on the response of urbanization and land change to market and policy changes, but ignores such factors as "population", "policy", and "adaptation." Over the past three decades, China has been experiencing massive urbanization, and the effects on land change of the population migrating from rural to urban areas have surpassed those of total population change. Hence urbanization attracts more attention than population growth. With respect to the factor of policy influence, Chinese scholars pay the most attention to the "Grain for Green" program (Cao et al. 2009) and the policy regarding protection of cultivated land that follows from that program (Lichtenberg and Ding 2008).

Contributions by Chinese Scholars and Subsequent Problems

It can be seen from the literature that Chinese scholars are more concerned about the changes of cultivated land and forest land resulting from the "Grain for Green" program (Xie et al. 2005; Cao et al. 2009); rapid urban expansion and the resulting conversion of cultivated land (Ma 2002; Liu et al. 2005; Long et al. 2007); and the changes of agricultural utilization triggered by climate change (Piao et al. 2010). They have completed many case studies on these topics, resulting in significant international influence in land change research.

Future Research

Research on the driving forces of land change reveals the following developmental trends: (1) emphasis on urbanization, globalization, and other important driving factors: attention to the scale effects of these factors and regional differences in their effects on land change; (2) emphasis on studies of such unique processes as forest transition and intensive agricultural land utilization: attention to the driving mechanisms of these processes and their interaction; and (3) emphasis on comprehensive research on human and natural factors and the establishment of the theoretical underpinnings of land change. China is now in a stage of rapid urbanization and expanding social economy. Various socioeconomic factors and global forces have had extremely strong impacts on land change, which in turn has created golden opportunities for the study of the mechanisms underlying the occurrence and development of land changes within the urbanization and globalization processes. In addition, Chinese political institutions and systems have some characteristics that are different from western countries, as reflected in the recently revealed government strategies for the New Urbanization, Ecological Civilization Construction, and "The Silk Road Economic Belt and the 21st century Maritime Silk Road." The current socioeconomic environment also provides a distinctive policy background for research on the driving forces of land change. By turning these opportunities into advantages, combined with detailed research on land change progress, the comparative study of regional differences, and comprehensive research on human and natural factors, Chinese scholars can overcome the deficiency in driving forces research on the way to establishing an important place in theoretical studies of land change.

10.2.3 What are the Negative Environmental Impacts of Land Change?

Bibliometric Analysis of Contemporary Research

The impacts of land change on global and regional natural environments are important reasons why people pay attention to land change. Identifying the environmental effects of land change, addressing the negative environmental impacts exerted by land change, and promoting the sustainability of social and economic development have always been the important propositions of land change research. In the 32,876 papers retrieved from the (ISI) Web of Science, keywords containing "climate" appear 12,697 times, accounting for 39 % of the total number of keywords; those containing "vegetation" appear 10,181 times, accounting for 31 %; those containing "soil" appear 6600 times and account for 20 %; those containing "water" appear 6006 times, accounting for 18 %; those containing "diversity" appear 4482 times, accounting for 14 %; and those containing "ecosystem" appear 3510 times, accounting for 11 %. These data highlight the important position of research on environmental effects in land change research.

Contemporary Research

Research on the environmental effects of land change should be carried out with a focus on atmospheric environment effects, regional climate influences, water resources and water environment effects, biodiversity, and land degradation. Research on atmospheric environment effects should stress the influence of land changes on atmosphere composition (CO, CO_2, CH_4, N_2O, SO_2, etc.) (Crutzen and Andreae 1990; Meyer and Turner 1994; Turner et al. 2007; Sillman and Samson 1995) and regional climate (temperature and precipitation) (Costa and Foley 2000; Foley et al. 2005). Research on water resources and water environment effects should emphasize the impacts of land change on the quantity and quality of water resources and water recycling

(Turner et al. 2007). With respect to biodiversity, the impacts of land change on animal habitats, as well as landscape fragmentation and forest edge effects resulting from land change are major issues (Saunders et al. 1991; Foley et al. 2011; Wolfe et al. 2004). The influence of land change on land degradation should place emphasis on soil erosion, desertification, and soil chemical degeneration (Peterjohn and Correll 1984). Research on the environmental effects of land change should be promoted toward a comprehensive research (Fu and Zhang 2014) and strengthening of the application of simulation models. A large number of such models related to the environmental effects of land change have been developed: CASA, IMAGE2.0, TEM, and the "bookkeeping" model are used for carbon cycling simulations; the Yamada–Mellor model is used for the simulation of the urban heat island effect; CCM3-IBIS is employed to evaluate the influence of global land cover change on climate; DOE-PCM and the regional climate model RegCM3 are used to predict the impacts of landscape pattern changes on climate; CENTURY can simulate the soil carbon effect; RUSLE and WEPP are used to evaluate soil erosion; CREAMS can simulate nutrient transportation; SHE, Tank, HEC, IHDM, and SWAT can simulate hydrologic processes; NPS, SWMM, and HYDROSCIENCE are used to determine pollutants; and the framework and computing methods for ecosystem service value (ESV) have also been developed. Although there are many uncertainties in these models, they have played an invaluable role in research on the environmental effects of land change.

Bibliometric Analysis of Contemporary Research in China

A statistical analysis has also been conducted on the major keywords related to environmental effects of land change from 2000 to 2014. The results show that the overall frequency of "soil" in papers published by Chinese scholars is equal to 15.0 % of its overall global frequency, and that of "water" and "ecosystem" are equal to 11.9 and 11.4 %, respectively, both higher than the proportion of SCI/SSCI papers (11.3 %). In papers published by Chinese scholars, the overall frequency of "climate" reaches 11.2 %, close to the proportion of SCI/SSCI papers (11.3 %), but "vegetation" and "diversity" have frequencies of just 9.3 and 6.2 %, respectively.

Contemporary Research in China

With respect to the environmental effects of land change, Chinese scholars have conducted extensive research on soil, water resources, and ecological systems, especially on soil environmental effects. This is closely related to an array of regional environmental problems in China, such as water and soil loss, serious desertification, shortages of water resources, and aggravated pollution.

Contributions by Chinese Scholars and Subsequent Problems

Chinese scholars have focused on the influence of land change on water and soil loss (Zheng 2006; Li et al. 2007; Zhang et al. 2006); land desertification (Bai et al. 2010; Ma et al. 2008; Wang et al. 2006); water pollution (Tong and Chen 2002); carbon emissions (Ni 2002; Wu et al. 2003; Luo et al. 2006); and the urban heat island effect (Ren et al. 2008); and have produced significant results in these areas. A gap does exist, however, between Chinese and foreign studies with respect to effects of land change on plant distribution and biodiversity.

Future Research

Research on environmental effects of land change is constantly promoted regarding such aspects as process mechanisms and model simulation, with more attention being paid to the mechanisms and uncertainties of model simulation. In the meantime, research on land change effects will continue to evolve from more basic studies to field monitoring and comprehensive evaluation of relevant environmental effects (de Bello et al. 2010). China has complex geographical conditions and diverse ecological systems. Unique natural geographical regions such as the Qinghai-Tibet Plateau, the Loess Plateau, and the deserts of northwest China are extensive, but their ecological systems are quite vulnerable and sensitive to climate change and human disturbances. Even from an international perspective, these regions are prominent foci for research on land change and its environmental effects. They certainly constitute favorable settings for Chinese research on the environmental effects of land change. In addition, a number of large-scale monitoring networks, such as the National Ecosystem Research Network of China (CNERN), the Chinese Terrestrial Ecosystem Flux Research Network (ChinaFlux), and the China Forest Biodiversity Monitoring Network, have been built in the last 30 years. These networks, together with the earlier large-scale station networks, such as the National Hydrological Observatory Network and the Meteorological Observation Network, lay a solid data foundation for research on the environmental impacts of land change. By giving full play to geographical conditions and data advantages and combining these with the development of experimental technologies and innovative model simulation technology, Chinese scholars can further improve their international status in research on the environmental effects of land change.

10.3 Roadmap for Further Research

After 15 years of rapid development, land change research has undoubtedly made important strides and played a significant role in understanding earth system changes and influencing the development of human society. However, the current observation and monitoring of land change cannot satisfy the needs of land management in terms of temporal and spatial resolution, as well as in the observation and effective monitoring of detrimental land changes such as those which might arise through ill-advised land management measures. Theoretical underpinning and predictive modeling beyond local and regional scales still need to be improved. Simulations of environmental effects must focus more closely on problems related to scale, the integration of human and natural factors, uncertainty, and mapping. In short, land change research is still confronted with a series of great challenges. Chinese land change research has rapidly evolved in terms of both scale and influence over the past 15 years, and transformed from following the international frontier to keeping pace with it. In general, however, China is still weak in research on the effects of and adaptations arising from land changes. To further improve the international status of Chinese land change research and meet the needs of continuing urbanization, ecological civil construction, and "the Belt and Road Initiative", future studies must devote more attention to the following areas.

(1) **Conducting More Detailed Observation and Monitoring of Land Change**

Observation and monitoring of land change is the basis for studying land change processes, mechanisms, and effects in a scientific way. The existing observation and monitoring of land change concentrates mainly on such primary land types as cultivated land, forest land, and construction land, and expands to global and long temporal scales with the purpose of providing data support to global change research. At present, the observation and monitoring of contemporary processes of land change is not elaborate enough and encounters difficulties in producing results that both address problems arising from the land change process and can be translated in ways that positively affect management decisions and policy formulation. Future observation and monitoring should not only improve time and spatial resolution, but also increase "type resolution." This requires observing and monitoring land change in continuous time series, land cover change caused by land change (forest thinning, soil loss, and bio-deterioration), as well as the changes in land management measures. In addition, it is necessary to conduct integrated research based on multi-source and multi-scale data, and to improve the spatial accuracy of detection protocols.

(2) **Promoting Research on Adaptations to Land Change**

Land change is not only an active selection process dominated by regional social and economic factors, but also an adaptation process under the influence of macro-factors such as global change, economic globalization, and national policy changes. The existing research on reasons for land change focuses mainly on the driving forces of regional social and economic activities, but ignores the adaptation of different regions to macro-factors, especially to global change. This restricts the development of basic theoretical research to some extent. Future research should stress the adaptations of land change in the context of global change and urbanization. In particular, the sensitivity, adaptability, and adaptive behavior to land change in densely populated areas, major grain producing areas, ecologically fragile regions, ecological shelter zones, and areas of key projects should be investigated, along with the resource and environmental effects of these land changes.

(3) **Promoting Comprehensive Research on Multi-scale Environmental Effects**

The effects of land change on the natural environment and resources obtained therefrom has been the focus of global change and sustainable development research. Research on simulation models has played an important role in evaluating the environmental effects of land changes and will play a greater role in the future. Existing studies of environmental effects place importance on the simulation and evaluation of the atmospheric environment, water environment, soil environment, biodiversity, and ecosystem functions, and are gradually evolving toward comprehensive frameworks for addressing these foci. However, simulation models of environmental effects are comparatively weak in multi-scale comprehensive evaluation. It has become an accepted goal of future research on environmental effects to promote comprehensive studies of multi-scale environmental influences, and to effectively resolve problems concerning scale, mapping, uncertainty, and the integration of human and natural factors.

10.4 Summary

Land change is a major manifestation of human activity, and research in this area reflects an important breakthrough regarding the human–land relationship, situated at the cutting-edge of global change science and sustainability science. With the rise of global change research and the advancement of remote sensing technology over the past 30 years, in addition to the impetus of LUCC and GLP, international land change research has centered on the in-depth observation and monitoring of change processes, the causal mechanisms for land change, and the environmental effects. Important progress has been made in these efforts. Spatial and temporal scales for observing and monitoring change processes continue to be enlarged; integration of natural and human factors continues to become more detailed; and evaluation of environmental effects more comprehensive. Chinese land change research, which follows international frontiers while closely mindful of national needs, has yielded results of international influence regarding domestic land change detection, the impact of urbanization on land change, and effects of environmental change on soils. This research field has gradually changed from pursuing international advanced research to moving forward with the momentum of effective research leaders and cooperative scientists. Future research on land change will continue to evolve in depth while keeping pace with the international scientific community. Considering the needs of guaranteeing water and soil resources and improving the ecological environment in the context of global change and urbanization, Chinese land change research should conduct more detailed observation and monitoring of land changes, intensify research on adaptations to land change, and develop a comprehensive research agenda on multi-scale environmental effects. By contributing to breakthroughs in these cutting-edge areas, China will enhance its international status in land change research.

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Global Cryosphere Evolution and Land Surface Processes on the Tibetan Plateau

11

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Abstract

Land surface process studies over the Tibetan Plateau had made large achievements in the last three decades, focus mainly on: (1) Multi-sphere interactions in the Tibetan Plateau and their impacts on regional climate, hydrology and ecosystem. (2) Mechanisms and impacts of cryospheric hazards, including cold regions engineering. (3) tempo-spatial patterns of paleoenvironment. Achievement was also made in the changes of polar cryosphere and their influences to high/middle latitudinal climate. Future expectation includes enhancing the modeling work on cryosphere research, multi-discipline research considering multi-sphere interaction, and the potential new directions linked to social activities.

Keywords

Cryosphere science • Tibetan Plateau • Polar climate • Land surface process • Cold regions hazards and engineering

A total of 35,683 SCI/SSCI-indexed articles are analyzed in the research area of global cryosphere evolution and land surface processes on the Tibetan Plateau. Articles were identified from 218 international journals from 2000 to 2014. The number of journals that have published more than 15 of the relevant articles is 148 (Appendix H). The search query is as follows: "glacier" OR "ice sheet" OR "ice core" OR "frozen ground" OR "permafrost" OR "snow cover" OR "antarctic" OR "arctic" OR "sea ice" OR "cryosphere" OR ("frozen ground" AND "engineer") OR ("permafrost" AND "engineering") OR ("cryosphere" AND "vulnerability") OR ("cryosphere" AND "sustainability") OR ("tibet" AND "hydrological cycle") OR ("tibet" AND "water cycle") OR (("climate change" OR "melt" OR "monsoon" OR "isotope" OR "temperature" OR "precipitation" OR "hydrology" OR "westerly" OR "water cycle" OR "climate" OR "record" OR "lake" OR "water resource" OR "oscillation" OR "black carbon" OR "remote sensing" OR "aerosol" OR "heavy metal" OR "trace metal") AND ("tibet" OR "tibetan" OR "tianshan" OR "tienshan" OR "arctic" OR "antarctic" OR "polar region" OR "qinghai-tibet" OR "qinghai-xizang" OR "greenland" OR "southern ocean")).

11.1 Overview

11.1.1 Development of Research Questions

No place is more extraordinary than the Tibetan Plateau in terms of areal coverage of the cryosphere in the middle and low latitudes. The total area of the glaciers on the plateau is 59,425 km^2, which accounts for approximately half of the total glacier area in the middle to low latitudes on Earth, and the average winter snow cover is 740×10^8 m^3 water equivalent (Qin et al. 2006a). The glacial areas of western China are the headwaters of more than 10 large rivers in Asia, such as the Yangtze, Tarim, Brahmaputra, Ganges, Indus, Nu-Salween, Mekong, Ili, Ergis and Yellow Rivers (e.g., Bolch et al. 2012; Immerzeel et al. 2010). The cryosphere on the Tibetan Plateau and surrounding mountains

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regulates the seasonal river discharge in central Asia via the freezing and melting of ice. Moreover, the cryosphere also supports ecosystem stability in the cold and arid regions of western China; thus policymakers and the public are aware that cryosphere changes and their effects are related to ecological security and socioeconomic sustainability in central Asia, including West China. Therefore, in addition to the fundamental scientific questions on the uplift history of the Tibetan Plateau and long-term cryosphere evolution, the Chinese government emphasizes scientific cryosphere research to better support socioeconomic sustainable development. This research includes: (1) enhancing the knowledge base of basic glacier inventory and potential volume of melting water; (2) the needs of mineral exploration and highway/railway and oil pipeline construction in cold regions; and (3) more effective prevention and reduction of disasters caused by snowdrifts and glacier-induced debris flows.

The themes and foci of geographical studies of the Tibetan Plateau have changed in the past half century. Beginning with several comprehensive field expeditions in the 1960s, research shifted to observations of key processes in the representative regions in the 1990s. At present, roughly four transitions in research have occurred (Yao 2014): (1) the transition from expeditionary investigations of the overall plateau to site-specific observational research; (2) the transition from qualitative descriptions to quantitative studies; (3) the transition from statistical to dynamic research, and (4) the transition from single subjects to comprehensive and integrated multi-disciplinary research.

According to the statistics, both articles published by Chinese scientists about the Tibetan Plateau and their total citations have risen to the most numerous in the world from their third-place position at the beginning of the 21st century (Zhang et al. 2011); and the focus of research on the Tibetan Plateau cryosphere and plateau-related land surface processes has changed from an earlier palaeoenvironmental emphasis to the integrated process-archive-model research of the present, making the plateau a prominent focus with respect to the study of regional responses to global climate change (Xiao et al. 2008). Prior to the 1990s, geophysical research on the Tibetan Plateau focused exclusively on regional differentiation of geophysical elements and most process studies looked mainly at natural archives and interpretations. However, since the 1990s studies have gradually paid more attention to processes, although most are still linked to natural archives. Since the turn of the century, however, with the progress of the process-archive-model integration, an important regional and sub-disciplinary field of research in the Tibetan Plateau has emerged within the framework of global change science.

The polar regions are one of the key areas for global change research. Developed countries began polar research quite early, from an era of adventure in the late 19th century to the polar science era marked by the "International Geophysical Year" in 1958. Polar regions significantly affect the global climate system, and it is essential to perform research at the poles to understand their role in the global climate. It was much later that China began polar research. In 1980, two Chinese scientists ventured to Antarctica. Glaciological study has been the primary focus of Chinese polar research, and in the past 20 years Chinese polar cryosphere research has developed and expanded, and now addresses foci at the international scientific frontier such as the polar ice sheets, sea ice, permafrost, snow cover and climate change, as well as multi-sphere interactions in the polar regions.

The cryosphere has changed significantly in the context of global warming. It is vital to global change science and has gradually become an independent research discipline. The cryosphere is considered to be a major component of the climate system, together with the atmosphere, hydrosphere, lithosphere and biosphere (IPCC 2014). The role of the cryosphere in the climate system is critical because of its high albedo effect, large latent heat during phase transition, isolation effect of snow cover and sea ice, soil moisture lag effect associated with melting during water-energy circulation, fresh water storage, effects on sea level (Jacob et al. 2012), the greenhouse effect of permafrost carbon, and many other aspects. In the year 2000, the World Climate Research Plan (WCRP) launched the "Climate and Cryosphere Plan (CliC)" with the goal of quantitatively evaluating the influence of climate change on each cryosphere component and the role of those components in the climate system. The International Council of Science Unions (ICSU) and World Meteorology Organization (WMO) subsequently launched the fourth "International Polar Year" (IPY 2007–2008), which emphasized international collaboration and interdisciplinary efforts to strengthen our knowledge of polar regions and the linkages between those regions and the rest of the planet. In 2007, the International Union of Geodesy and Geophysics (IUGG) established the International Association of Cryosphere Sciences (IACS) as its newest association (and the only one added in approximately the past 80 years). This evidence shows that international cryosphere research has evolved from an earlier dispersed field of single-component studies to a modern, systematic and interdisciplinary direction. Cryosphere research has now become a major topic in global change research, and since the turn of the century the number of published papers related to cryosphere in "Nature" and "Science" has already approached 300.

China is arguably the first country to establish a cryosphere science framework. The study of them emphasizes not only the cryosphere evolutionary process itself but also its interactions with other climate components, with a particular focus on cryosphere change and its socioeconomic

Table 11.1 Top 20 countries (regions) with the number and citations of SCI/SSCI-indexed articles on "Global Cryosphere Evolution and Land Surface Processes on the Tibetan Plateau" during the period 2000–2014

	Number of articles						Cited frequency						Number of highly cited articles					
	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014
Rank	World	1,386	2,787	8,450	11,607	15,626	World	71,711	1,291	350,514	311,459	114,445	World	234	0	1,017	957	845
1	USA	451	631	2,700	3,212	3,699	USA	30,334	365	144,244	116,531	35,958	USA	108	0	472	425	313
2	China	55	566	513	1,222	2,547	UK	11,029	141	42,612	35,428	12,809	UK	32	0	117	125	103
3	UK	161	214	824	1,186	1,365	China	2,237	167	11,514	20,062	11,225	China	5	0	26	50	67
4	Canada	133	210	726	1,150	1,309	Canada	5,019	97	26,398	27,425	9,129	Canada	9	0	71	80	63
5	Germany	121	168	640	756	1,022	Germany	5,092	85	27,712	18,961	7,956	Germany	17	0	74	40	59
6	France	51	89	344	462	632	France	3,267	45	15,263	13,708	5,511	France	10	0	43	37	42
7	Norway	35	87	257	371	466	Switzerland	2,153	50	9,879	10,760	4,320	Switzerland	11	0	39	30	29
8	Switzerland	43	76	206	328	431	Norway	1,502	46	9,211	9,009	3,258	Australia	10	0	29	24	23
9	Japan	45	57	322	395	410	Netherlands	954	36	4,741	6,807	3,123	Netherlands	5	0	19	21	23
10	Sweden	20	66	216	233	376	Australia	2,333	26	9,373	6,825	3,015	Denmark	2	0	12	29	23
11	Australia	43	70	217	273	352	Sweden	861	39	7,967	5,905	2,858	Norway	7	0	30	22	21
12	Italy	18	56	141	210	286	Japan	1,140	28	7,088	6,621	2,049	Sweden	5	0	25	18	21
13	Netherlands	23	48	153	175	270	Denmark	1,386	23	7,784	6,307	2,038	Italy	0	0	7	6	10
14	Russia	29	45	134	173	249	Italy	420	15	3,562	3,797	1,745	New Zealand	1	0	4	6	10
15	Denmark	40	29	204	178	214	New Zealand	608	11	2,054	2,928	1,307	Japan	2	0	9	10	8
16	Spain	10	30	64	117	202	Spain	334	5	2,265	2,674	1,303	Spain	1	0	8	3	6
17	India	11	38	43	74	193	Finland	586	18	3,886	2,308	974	Finland	1	0	6	7	6
18	Finland	14	42	126	122	189	Belgium	255	0	2,031	1,501	703	Belgium	1	0	6	2	4
19	New Zealand	13	24	70	117	188	Russia	448	5	2,131	1,980	484	Austria	1	0	3	3	0
20	Belgium	9	12	67	78	107	Austria	300	6	1,235	1,905	456	Russia	1	0	2	5	0

Note Countries (Regions) ranked by the number of articles, cited frequency and number of highly cited articles during the period 2010–2014

impacts. Methodologically, China has gradually established a complete system, including a cryosphere observation network, remote sensing, numerical simulations, and impact and adaptation studies. Not surprisingly, cryosphere science in China has engendered increasing international attention and influence in recent decades.

11.1.2 Contributions by Scholars from Different Countries

Table 11.1 displays a summary of the SCI/SSCI paper publications for different countries on the subject of "global cryosphere evolution and land surface processes on the Tibetan Plateau" from 2000–2014. The table shows that 35,683 papers have been published, increasing by approximately 27 % every 5 years, from 8450 in 2000–2004 to 15,626 in the most recent 5 years. The United States has contributed the largest number of publications (9611) over the past 15 years, with a slight but continuing increase every 5 years. China, the second largest contributor, has published 4282 papers (nearly half that of the United States) over the past 15 years, but China shows a remarkable rate of increase (doubling) every 5 years. The United Kingdom, Canada, Germany, France, Norway, Switzerland, Japan and Sweden are ranked from 3 to 10, respectively. Numbers of publications all steadily increase for these countries (but not as fast as that of China) every 5 years. Australia, Italy, Netherlands, Russia, Denmark, Spain, India, Finland, New Zealand and Belgium follow with ranks from 11 to 20, respectively.

The total number of citations is 776,418 for all the SCI/SSCI papers identified via the above process. The five most-cited nations are the United States (296,733), the United Kingdom (90,849), Canada (62,952), Germany (54,629) and China (42,801). In terms of the number of high-citation papers, China also ranks number 5 after the United States, the United Kingdom, Canada and Germany. From the analysis below, it will be seen that the Chinese publications on cryosphere research are mostly on the Tibetan Plateau, whereas Western countries focus mainly on the Antarctic and Arctic regions, a result of the history and geographical interests of the different countries. It is noteworthy that German scientists have published studies on both the polar (Antarctic and Arctic) and Tibetan cryospheres, unlike other western countries. Germany is also the Western country that has the most diverse and closest collaboration with China on Tibetan studies.

11.1.3 Key Research Topics

References were retrieved for articles on "Global Cryosphere Evolution and Land Surface Processes on the Tibetan Plateau" based on the following keywords in papers published after 2000: 'glaciers' OR 'ice sheet' OR 'ice core' OR 'frozen ground' OR 'permafrost' OR 'snow cover' OR 'antarctic' OR 'arctic' OR 'sea ice' OR 'cryosphere' OR '(tibet AND monsoon)' OR '(tibet AND isotope)' OR '(tibet AND westerly)' OR '(frozen AND ecology)' OR '(frozen ground AND ecosystem)' OR '(frozen ground AND engineer)' OR '(cryosphere AND vulnerability)' OR '(cryosphere AND sustainability)' OR '(tibet AND hydrological cycle)' OR '(tibet AND water cycle)'. These not only cover the key scientific problems but also indicate the frontiers of current research on "Global Cryosphere Evolution and Land Surface Processes on the Tibetan Plateau". Using bibliometrics and document clustering methods, it was revealed that studies on "Global Cryosphere Evolution and Land Surface Processes on the Tibetan Plateau" generally focus on two major topics: "climate change, greenhouse gas and ecosystem" and "cryospheric palaeoclimate reconstructions", and are supported by three other secondary independent fields—"Antarctic and Arctic oceans and their impacts", "ice sheet instabilities" and "Tibetan Plateau and ENSO/monsoon".

Permafrost plays a key role in the sources and sinks of greenhouse gasses. Since the permafrost in high latitudes of the Northern Hemisphere has a close relationship with that of Tibet and its ecosystem, it has been a major topic of studies in recent years (e.g., Cheng and Jin 2013; Cheng and Wu 2007). Other interesting fields are palaeoclimatic and palaeoenvironmental reconstructions based on ocean deposits, polar ice cores and lake cores, including the many publications on Antarctic and Greenland deep ice cores. The North Atlantic overturning circulation and bi-polar seesaw studies, which require knowledge of both the palaeoclimate and an Earth system model, are widely considered to be potential breakthroughs in our understanding of global climate change. The evolution of West Antarctic and Greenland ice sheets and the relationships among fast ice streams, ice shelf instabilities and sea level rise have also represented challenges for the polar sciences in recent years. The Southern Ocean and Arctic sea ice are essential elements in the cryosphere. Changes in sea ice greatly impact climate and marine biology. The terrestrial fresh water runoff in the Arctic is also a prominent topic due to its impacts on the Arctic Ocean. The Tibetan cryosphere and its surface processes—accessed with the keywords "ENSO" and "monsoon"—appear to be a major topic of regional studies (Zhao and Moore 2004; Qin et al. 2006b). The climatic linkages between the Tibetan Plateau and its peripheral regions (e.g., Bamzai and Shukla 1999; Barnett et al. 1988a, 1989), modelled via large-scale circulation models, is another innovative area in global cryosphere research.

The cryosphere exhibits a positive feedback and is the fastest changing variable in the climate system. Because polar regions and the Tibetan Plateau are covered with cryospheric elements, e.g., snow, ice and permafrost, they are the key regions for climate changes and variations in the recent decades of rapid warming, as shown for different regions in Fig. 11.1. Due to the significant multi-sphere interactions over the polar and Tibetan regions, the mechanisms of ocean-land-ice/snow-atmosphere interactions and their climatic effects must be investigated via numerical simulation approaches. Studies on Arctic and Tibetan pollution and polar atmosphere environment, another increasingly studied secondary topic, have also drawn the attention of geography researchers. During the past 20 years, atmospheric models, ocean models and cryosphere models have all improved, thus greatly enhancing present and prospective future understanding of global climate change and corresponding regional responses.

During the past 15 years, the polar regions have become established as a long-term focus of international research societies studying changes in the climate system (sea ice, ice sheet and sea level, ecosystem) (Fig. 11.2). Palaeoclimatic and ice core studies also represent a large number of paper publications and are continually increasing due to several large ongoing scientific programs—e.g., EPICA Dome C, North GRIP, NEEM (EPICA Community Members 2004, 2006; Alley 2000)—and the International Trans-Antarctic Scientific Expedition (ITASE) (Mayewski et al. 2009). From the paper distributions, we can clearly see the foci of international authors. For example, Chinese authors contribute nearly equally to every cryospheric element (glaciers, permafrost, snow, etc.) but emphasize climate change and ice core subjects to a slightly greater degree, including the Chinese studies of Tibetan and Antarctic shallow ice cores in this time period. It should be noted that since "cryosphere" is a quite new concept, having just come into use in the past 10 years, it is does not frequently appear in keyword retrievals, even though it is the precise topic of many published papers. However, it is clear that "cryosphere" will be widely used as the focal topic of many more high-quality publications, given that the concept is being continuously and deeply investigated.

11.1.4 The Role of NSFC in Supporting the Research on Global Cryosphere Evolution and Land Surface Processes on the Tibetan Plateau

The National Natural Science Foundation of China (NSFC) actively focuses on the surface processes of the Tibetan Plateau and cryosphere research, providing substantial funds to study their status in China. The progress of cryosphere science in China is closely related to the support provided by NSFC projects. Many projects, including frontier research, strategic priority research programs and key basic research projects, are derived from the support of NSFC (Leng and Ding 2010; Leng and Song 2010). The foundation has played a leading role in terms of supporting new research

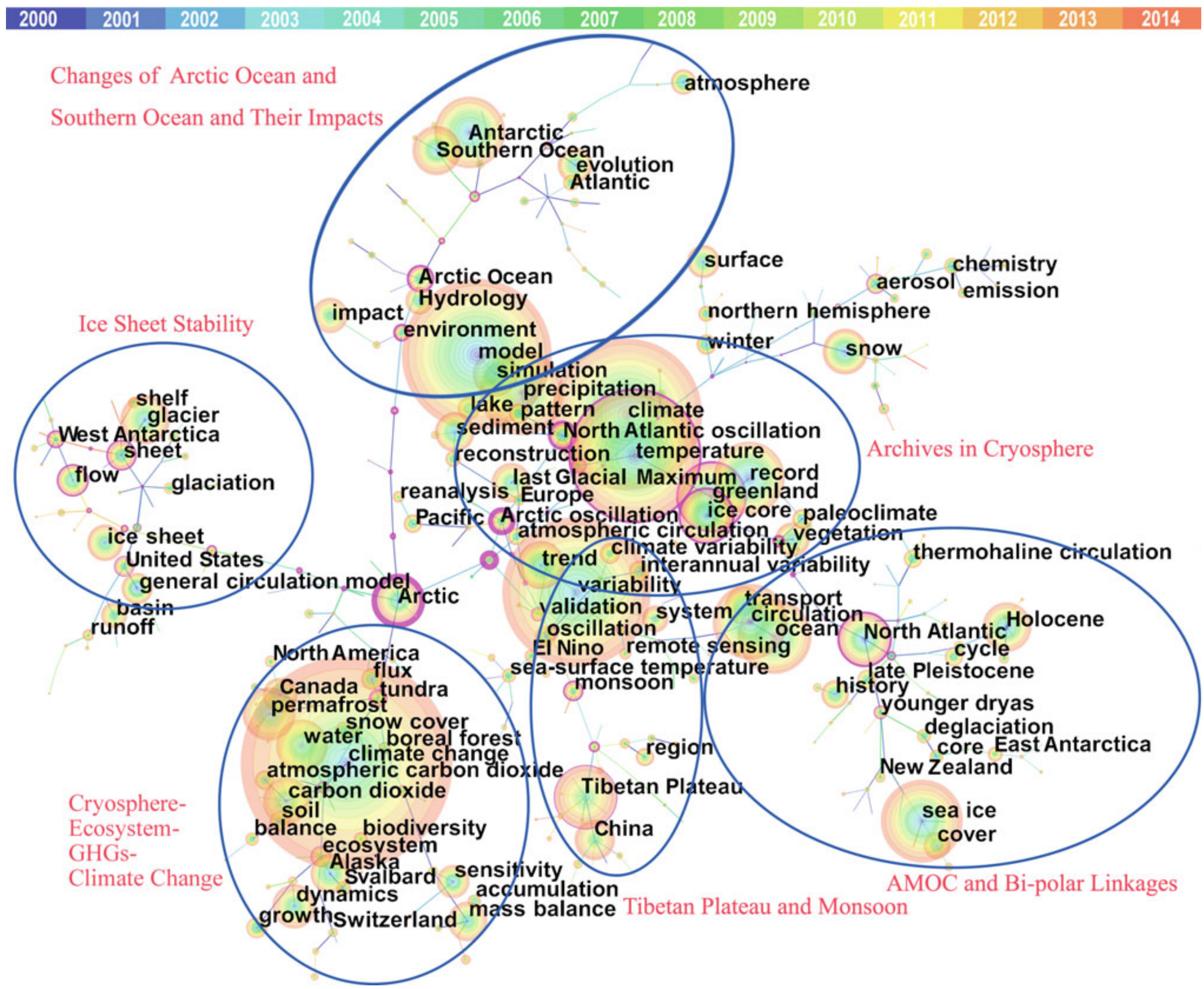

Fig. 11.1 Co-occurrence network of SCI/SSCI-indexed article keywords on "Global Cryosphere Evolution and Land Surface Processes on the Tibetan Plateau" during the period 2000–2014

fields and excellent young talent in cryosphere science. Currently, 13 scholars have been funded by the National Science Fund for Distinguished Young Scholars (DYS Fund). These measures have created a stable and innovative team of talented young and mid-career scientists in this field. Moreover, three research teams in the Science Fund for Creative Research Groups (CRG Fund) related to cryosphere science were supported by NSFC, further stabilizing the research community and individual teams. In 2008, according to the "11th Five-year Plan" discipline development investigation, NSFC revised the original discipline phrase "Snow and Ice, Geocryology" to "Cryosphere Geography" in the application system. This modification will support cryospheric science from a macroscopic and comprehensive perspective, subject cryosphere science to more systematization, and elaborate the discipline structure to a new level. Through NSFC and other funding sources, China promotes the development of cryosphere science in a planned way, with particular emphasis on cryospheric impacts on water resources, ecology, climate, and socioeconomic sustainability. These measures play a leading role in the discipline construction of cryosphere science. In the past 10 years, climate change, ecological surface processes, permafrost change, cryosphere simulation, and cold region hydrology have been the top five fields for projects most frequently funded by NSFC (Fig. 11.3). The statistical results show that "Tibetan Plateau" is the most frequent keyword in NSFC-funded projects, and the number of projects funded in this field was 68 from 2000–2004, increasing to 191 from 2005–2009 and to 401 from 2010–2014 (Table 11.2). Although the number of projects funded for "remote sensing monitoring" was only four from 2000–2004, it increased to 18 from 2005–2009 and to 69 from 2010–2014. Thus "remote sensing" is an increasing focal

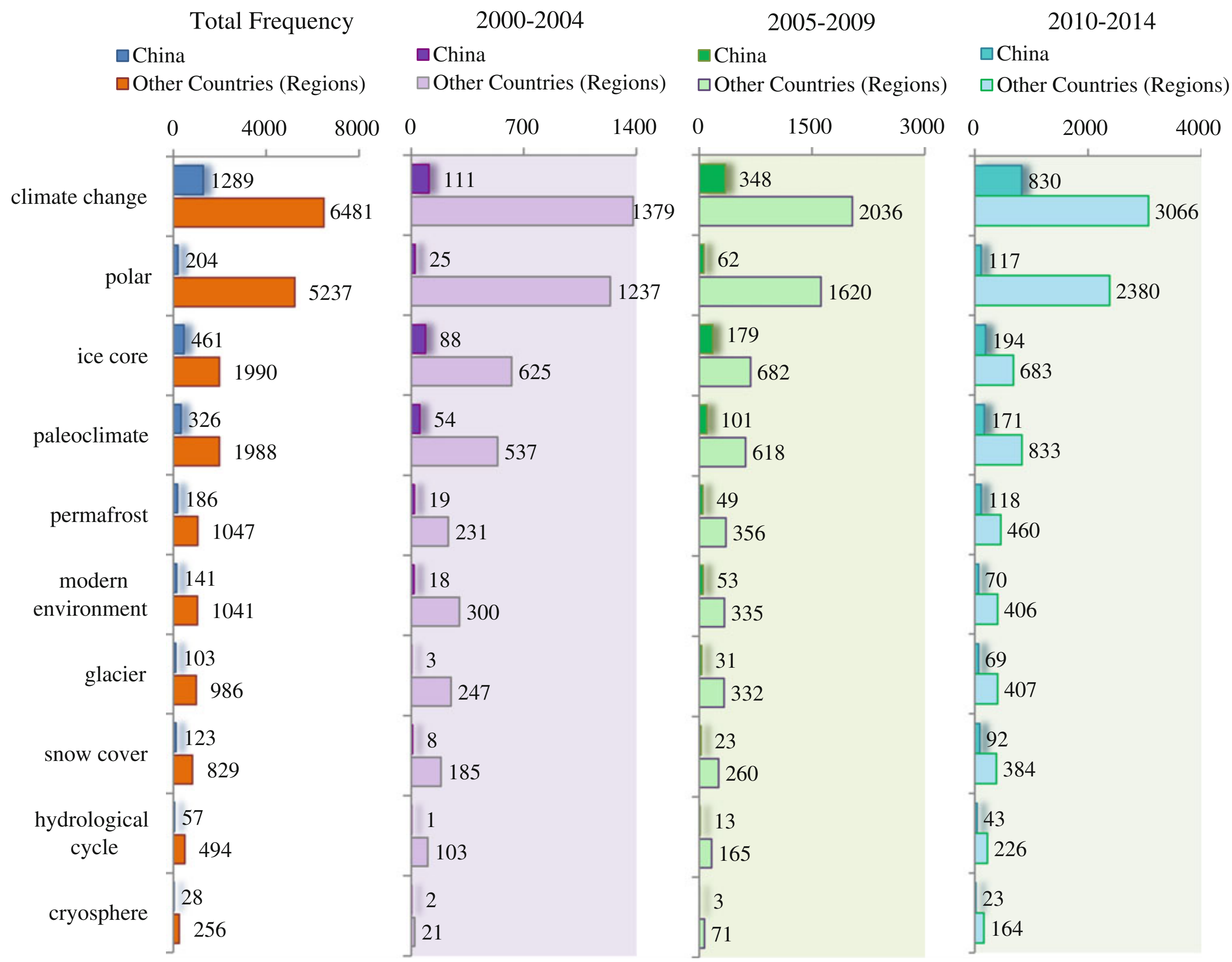

Fig. 11.2 Keyword temporal trajectory graph for SCI/SSCI-indexed articles on "Global Cryosphere Evolution and Land Surface Processes on the Tibetan Plateau" during the period 2000–2014

area of study for the Tibetan Plateau environment. In addition to in situ observations and remote sensing, simulation models have also been rapidly developed in recent years. The number of funded projects with the keywords "model simulation" was 19 from 2000–2004, rising to 90 from 2005–2009 and to 233 from 2010–2014. As noted above, the new technology significantly stimulated the development of cryospheric science research. Ice core studies were numerous in the early 1990s; however, likely due to the extensive melting of glaciers, it is very difficult to find ideal sites for drilling ice cores on the Tibetan Plateau. Moreover, the new proxy and absolute dating technology also limit the advances in ice core research. Therefore, it is important to identify new climatic and environmental proxies, and the innovative technology that could be applied in this field.

During 2000–2014, the number of worldwide published papers involving cryospheric science was 35,683 (Table 11.2), with a growth rate of approximately 30 % every five years; although for Chinese authors the growth rate was 5 % every five years. Approximately 64.1 % of papers by Chinese authors were funded by NSFC. The proportion of funded cryospheric science projects by NSFC was 24.6 % from 2000–2004, 42.2 % from 2005–2009 and 82.6 % from 2010–2014, corresponding to sixfold and fourfold increases in the number of funded scientists and scientific institutes, respectively. Among the papers that included funding agency information, the proportion of papers jointly funded by NSFC and the Ministry of Science and Technology (MOST) was 45.2 %. Notably, the average proportion of papers with a Chinese first author was only 12 % over the

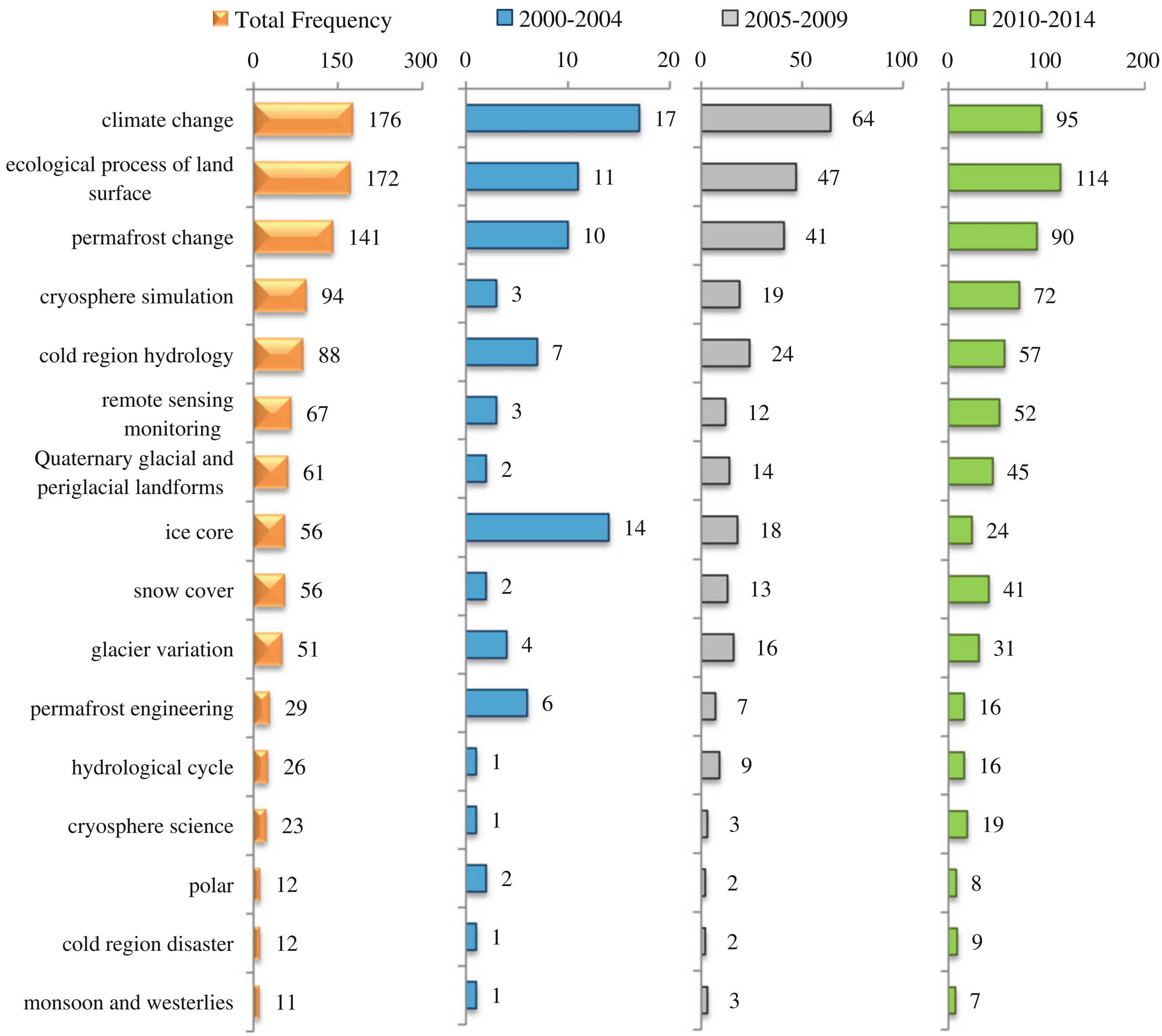

Fig. 11.3 Keyword temporal trajectory graph for NSFC-funded projects on "Global Cryosphere Evolution and Land Surface Processes on the Tibetan Plateau" during the period 2000–2014

Table 11.2 NSFC-funded projects and SCI/SSCI-indexed articles on "Global Cryosphere Evolution and Land Surface Processes on the Tibetan Plateau" during the period 2000–2014

SCI/SSCI-indexed articles					NSFC-funded projects			
Periods	Number of articles	% of articles by Chinese authors	% of articles with NSFC funding by Chinese authors	% of articles funded by MOST among those with NSFC funding	Number of projects	Funding (10,000 yuan)	Number of PIs	Number of institutions
2000–2004	8,450	6.1	24.6	0.0	68	3,244.7	61	23
2005–2009	11,607	10.5	42.2	30.4	191	9,816.1	162	47
2010–2014	15,626	16.3	82.6	51.5	401	32,847.0	363	93
2000–2014	35,683	12.0	64.1	45.2	660	45,907.8	483	108

past 15 years, showing that the study of cryospheric science and surface process of Tibetan Plateau has been conducted with substantial international cooperation.

11.2 Questions and Research Progress

11.2.1 How Has the Climate Changed in the Past on the Tibetan Plateau, and How is the Spatial Pattern Reconstructed from High-Precision Records?

The Tibetan Plateau is the highest plateau in the world and represents the majority of the "Third Pole". Scarcely disturbed by human activities, the plateau preserves continuous records on palaeoclimatic and palaeoenvironmental changes, including ancient glacial remains, lake sediment, ice cores, and tree rings. These archives bear long-term climate and environmental information on a scale of hundreds of thousands of years to several hundreds of years. These types of information can be reconstructed by collecting samples and analysing them in the laboratory, employing various dating approaches.

Bibliometric Analysis of Contemporary Research

According to a bibliometric analysis, 39,058 papers were published during the period of 2000–2014 on past climate and environmental records on the Tibetan Plateau. The most commonly used keyword was "record", which was used in 13,777 papers, approximately 35.3 % of the total papers published. The second most common keyword, "Holocene", appeared in 3652 papers, or 9.3 % of the total. "Ice core" appeared in 3078 papers, or 7.9 % of the total. Additionally, "glaciation" (2989), "quaternary" (2223), "Last Glacial Maximum" (2162), "ice age" (1646), and "deglaciation" (1582) were also frequently used keywords in the relevant set of papers. Most of these keywords are terms for specific periods in the past. Based on the temporal trends of these keywords, their number has been increasing with time, mostly at a steady rate. It was found that "stable isotope" is the keyword that increased the most among all keywords, indicating that stable isotopes play an important role in reconstructing the palaeoclimatic history. The "ice core" and "quaternary" are the keywords that increased the least during this period, due to the lack of new ice cores in the past 15 years and the relatively declining research interest in this topic.

Contemporary Research

International research has advantages in terms of its analysing techniques. Fontes and others (Fontes et al. 1996) developed a continuous Holocene climatic record from a 12.4-m core taken in Lake Bangong. Most of the lake sediment records from the Tibetan Plateau cover the Holocene, and the records are usually linked to the Indian monsoon and lake level changes. For research on glacial remains, international scientists have studied the advance of glaciers during the last glacial age using the new dating methods of cosmogenic nuclide exposure, thermoluminescence (TL) and optically stimulated luminescence (OSL) (Owen et al. 2008; Seong et al. 2009). The drivers of glacial advances through time are associated with precipitation changes due to shifts in the monsoon and the westerlies. A joint project between American and Chinese scientists performed an ice core study to focus on longer-term records. The Guliya ice core preserves a climate record back to the Last Interglacial Stage (Thompson et al. 1997), second only to Antarctic ice cores and older than Greenland ice cores. Integrated research work on ice core records from all the subtropical regions provide a broader information base on climate changes beyond the Tibetan Plateau (Thompson et al. 2003). Additionally, Chinese scientists have made advances in understanding recent environmental changes based on Tibetan ice cores drilled in different locations.

Bibliometric Analysis of Contemporary Research in China

According to the bibliometric analysis, 2288 papers on past climate and environment records on the Tibetan Plateau were published by Chinese scholars during the period of 2000–2014. The most commonly used keyword is "record" (appearing in 470 papers, or 20.5 % of the total number of published papers), followed by "ice core" (438 papers (19.1 %)), indicating that ice core research work represents a significant contribution to Tibetan Plateau palaeoclimatic reconstructions. "Holocene" appears in 230 papers (10 %); "Reconstruction" appears in 182 papers (8.0 %); "Stable isotope" appears in 176 papers (7.7 %); "Quaternary" appears in 169 papers (7.4 %); and "Ice age" appears in 152 papers (6.6 %). The distribution of keywords in publications by Chinese scholars is very similar to that of international scholars. However, "reconstruction" and "stable isotope" appeared more in publications by Chinese scholars, reflecting the emphasis of Chinese scientists on reconstruction of palaeoclimates and palaeoenvironments, as well as the stable isotope record and how it has changed under present conditions. From the temporal trend of these keywords, it was found that "reconstruction" and "stable isotope" display the greatest increases among all the keywords, reflecting the increasing focus on reconstruction of palaeoclimate information from ice cores, lake sediments, tree rings, and stable isotopes. The keyword with the least increase is "stratigraphy", followed by "ice core" and "Younger Dryas", due partly to the lack of new ice cores in recent years.

Contemporary Research in China

In the past three decades, the study of Quaternary glaciers changed from earlier qualitative estimates to the use of absolute dating methods (Owen et al. 2003; Yi et al. 2004). Chinese scientists have dated glacial remains in the middle and northern parts of the Tibetan Plateau, and a more detailed understanding of glacial extent has developed for different glacier stages. This work provided direct proof of the glacial extent during the Holocene. Additionally, much older glacial remains have been identified, potentially providing hints of the drivers of glacial advances in different parts of the plateau (Yi et al. 2008). In the ice core palaeoclimate reconstruction work on the Tibetan Plateau, Chinese scholars have found abrupt changes in climate, especially in the last ice age, and large climate fluctuations (Yao et al. 1997) in the stable isotope record from the Guliya ice core. Climate change over the past 2000 years has been reconstructed from the Guliya ice core and Dasuopu ice core. Important work on the recent climate and environmental changes has relied on Tibetan ice cores. Records of ions, black carbon, trace metals, and POPs were recovered from ice cores in different parts of the plateau, and both natural and anthropogenic impacts were found. Precipitation information for the past four centuries (Duan et al. 2006), as well as CH_4 records and black carbon records (Xu et al. 1999) from ice cores, are all specific contributions by Chinese scholars. Quite a few lake sediment records retrieved from the Tibetan Plateau cover the Holocene. Chinese scholars have focused on a key question: What is the driver for climate change in the Holocene? The Namco lake sediment record shows that climate change in the Holocene was influenced by the Indian monsoon (Zhu et al. 2008b). In contrast, lake sediment cores from the northern plateau show that climate change was influenced by the westerlies and are therefore different from the lacustrine records from the southern plateau (Zhao et al. 2007; Chen et al. 2008). Chinese scholars have made particularly noteworthy contributions using tree rings as a proxy in the reconstruction of past climate records. A few tree ring chronologies spanning multiple millennia were reconstructed from Qilian juniper in northeast Tibet. The longest ring-width chronology in China covers 3585 years and is composed of archaeological wood samples and living trees (Shao et al. 2010). The few 1000-year climate reconstructions with annual resolution available for the Tibetan Plateau based on Qilian juniper revealed a continuous climate trend, especially in the past 200 years (Zhu et al. 2008a). This work was cited by the 5th IPCC report. Additionally, the summer air temperature has been linked to volcanic eruptions and glacier movement by analysing the tree ring width and density at the upper forest limit in southeast Tibet (Liang et al. 2012).

Contributions by Chinese Scholars and Subsequent Problems

Although Chinese scholars have made obvious achievements in palaeoclimatic and palaeoenvironmental research, we must also bear in mind that challenges exist: (1) various archives are from different locations across the Tibetan Plateau, and the reconstructed climate and environmental records are from different proxies. This makes comparisons between different records difficult, and it is challenging to obtain a spatially consistent record from different records, e.g., ice cores, lacustrine records, and tree rings; (2) Chinese scholars have constructed a variety of historic records for the Tibetan Plateau, but the integration of these different records with respect to spatial and temporal variations, as well as answering key scientific questions that arise under these conditions, remains a problem; (3) there is usually a lag in dating methods and sophisticated laboratory analysis techniques between China and other international laboratories, which hinders innovative scientific findings; and 4) with the development of international geographic research, global-scale simulations have become the main research target and approach for understanding the geo-system. Chinese scientists focus more on the Tibetan Plateau and surrounding regions. Therefore, they should make an effort to link research work on the Tibetan Plateau to global scientific questions to provide a solution to global climate and environment questions.

Future Research

Several expectations for future climate change research on the Tibetan Plateau based on past accomplishments may be presented: (1) longer-term palaeoclimatic and palaeoenvironmental records, with more precise dating, are expected from ice cores, lake sediment and tree rings; (2) an improved understanding of various proxies preserved in these records and the processes and factors that influence these proxies is necessary. New and reliable proxies may be found which constrain the interpretation of palaeoclimatic and palaeoenvironmental records; (3) the palaeoclimate record can be embedded in the Global Climate Model and other models to simulate the drivers and processes of climate change and, theoretically, explain the mechanisms driving the frequent climate changes on the Tibetan Plateau; and (4) new dating methods will improve the ability to reconstruct palaeoclimatic records from various archives, e.g., the absolute dating of ice cores, especially for the bottoms parts of glaciers.

11.2.2 How Has the Cryosphere Changed on the Tibetan Plateau in Recent Years and How Have Such Changes Impacted the Ecosystem and Hydrologic Processes?

Global climate change significantly impacts the atmosphere, cryosphere, hydrosphere, lithosphere, and biosphere on the Tibetan Plateau. The cryosphere is the most significantly influenced realm, and glaciers, permafrost, and snow cover are declining in area in response to climate warming on the Tibetan Plateau. Consequently, the hydrosphere is impacted as well, especially the river runoff and lakes. This is significant because the Tibetan Plateau is the source region of several larger international and domestic rivers, and many lakes exist on the plateau. The surface temperature and moisture change will further modify the ecosystem and likely challenge the locally vulnerable ecological environment. Climate change will also result in changes in the hydrological cycle and energy balance, thereby affecting atmospheric conditions. Atmospheric circulation will transport this impact on the Tibetan Plateau further outward to the surrounding regions. The study of land surface processes is based on continuous field observations on the Tibetan Plateau, and in recent years a new technique has been used in studying these processes. Remote sensing is widely utilized to study changes in glaciers and snow cover. Numeric simulations are also employed in land surface process studies. New approaches, together with previous observation work, can expand the earlier research from site-specific studies to large areas and from qualitative estimates to research on process mechanisms.

Bibliometric Analysis of Contemporary Research

According to the bibliometric analysis, 79,236 papers were published during the period of 2000–2014 on cryosphere changes and their impact on the Tibetan Plateau. The most commonly used keyword is "temperature", which was employed in 14,536 papers, approximately 18.4 % of the total papers published in this research area. This keyword was followed closely by "snow/snow cover", which appeared in 11,276 papers, or 14.2 % of the total. "Glacier" appeared in 10,969 papers, (13.8 %); and "Climate change" appeared in 9474 papers (12.0 %). The four most frequently used keywords revealed that the key scientific topic in this research area is climate change, especially temperature. This is reflected primarily in glacial changes and "snow/snow cover" changes. The four keywords were used in 58.4 % of the total published papers, and they constitute the first class keywords. Other keywords are much less common. "Precipitation" appeared in 5513 papers, or 7.0 % of the total number of papers. "Soil" appeared in 5090 papers, or 10.0 % of the total. "Lake" appeared in 4644 papers (5.9 %); "Permafrost" appeared in 3164 (4.0 %); "Mass balance" appeared in 2064 papers (2.6 %); and "Hydrology" and "runoff" together appeared in 2951 papers (3.7 %). In atmospheric science, "monsoon" appeared in 1562 papers, and "atmospheric circulation" appeared in 1492 papers, and together they accounted for 3.85 % of the total number of papers. With respect to the temporal trend of these utilized keywords, we found that "climate change" and "ecosystem" are those which increased the most. "Persistent organic pollutants" also displayed one of the highest increases, but in fewer overall publications. In contrast, "aerosol" is the keyword which increased the least.

Contemporary Research

In recent years, there has been a growing interest in Tibetan glacial changes due to the recent warming trend and their effects on available water resources. Remote sensing work has shown that glaciers in the Himalayan region are rapidly retreating (Bolch et al. 2012), whereas glaciers in the Karakoram region are exhibiting a slight gain in glacial mass balance (Gardelle et al. 2012). The increase in glacial melting will affect water sources. Simulation study results have revealed that the meltwater is extremely important in the Indus and Brahmaputra basins and that these basins are the most susceptible to reductions in flow (Immerzeel et al. 2010). The significant increase in glacial melt water in these basins will not be able to compensate for the simulated decrease in the mean upstream water supply from the upper Indus and Brahmaputra. Simulations have shown that the amount of glacial melt water contributing to the total flow does not change substantially, at least until 2050, because the decrease in glacier area is compensated for by an increase in melt rate (Lutz et al. 2014). Results from a global, simultaneous inversion of monthly GRACE-derived satellite gravity fields have found that glaciers and ice caps, excluding the Greenland and Antarctic peripheral GICs, lost significant mass during 2003–2010 (Jacob et al. 2012). Based on elevation changes derived from ICESat, the total high mountain Asia (HMA) glacier mass budget was -29 ± 13 Gt year^{-1} during 2003–2009 (Gardner et al. 2013). Various researchers have studied the relationship between snow cover over Eurasia and atmospheric circulation. Satellite-derived snow cover data over Eurasia showed that the frequency of occurrence of snowfall is also correlated with the Indian summer monsoon rainfall (Bamzai and Shukla 1999). From a global perspective, snow cover over Eurasia exhibits a strong teleconnection to the atmospheric field over North America and ENSO phenomena (Barnett et al. 1988b).

Bibliometric Analysis of Contemporary Research in China

According to a bibliometric analysis, 6011 papers by Chinese scholars were published from 2000–2014 on cryosphere change and its impact on the Tibetan Plateau. The most commonly used keyword is 'snow/snow cover,' which appeared in 862 papers, or 14.3 % of the total number of published papers. This result reflects that the research work by Chinese scholars on snow cover has changed to study the effects of snow cover changes on hydrology by using remote sending and simulations approaches. In contrast to international publications, "precipitation" is more frequently used as a keyword (764 times, or 12.7 %) than "temperature" (295 times, or 4.9 %). Moreover, the numbers of papers with the keywords "monsoon" (655 times, or 10.9 %) and "glacier" (607 times, or 10.1 %) are substantially higher than the international bibliometric results, which is consistent with the particular contribution from Chinese scholars on Tibetan glacial changes and the influence of the Indian monsoon on the climate and environment of the Tibetan Plateau. Additionally, "permafrost" is also a commonly used keyword (398 times, or 6.6 % of the total publication number). This distribution of keywords from Chinese publications reflects the special interest in research on the Tibetan cryosphere and monsoon variations.

Contemporary Research in China

Chinese scientists have undertaken long-term observations of cryosphere changes on the Tibetan Plateau. There is an extended continuous observation record of glacier mass balance for selected glaciers. The use of remote sensing techniques has generated a large number of publications on glacier movement in recent decades. In recent years, glacier thickness change has been the trend of future research due to the interest in river water resources and lake level changes on the Tibetan Plateau. Chinese scientists finished the First Chinese Inventory of Glaciers based on expedition work from 1987 to 2004, and the Second Chinese Inventory of Glaciers was compiled in 2015 based primarily on remote sensing images (Liu et al. 2015). Combining field observation work and remote sensing data, the spatial inhomogeneous melting of glaciers in recent years has been studied, and the spatial glacier change has been linked to monsoon activity (Yao et al. 2012). Permafrost is also very sensitive to climate warming. Changes in permafrost will impact the water and energy exchange between the land surface and the atmosphere and will affect water resources, the water cycle, and carbon sinks. Chinese scientists have made long-term observations of active layer and borehole temperatures in the permafrost region and have found that the lower limit of permafrost on the plateau has risen over the past 30 years, the active layer thickness is increasing, and the borehole temperatures are increasing (Cheng and Jin 2013) in sequence with global warming (Zhao et al. 2010). There is a long time series of snow cover data since the 1950s collected by meteorological stations. There are no clear temporal changes in snow cover on the Tibetan Plateau, but large annual fluctuations have occurred (Che et al. 2008; Tang et al. 2013). Statistical analysis has shown that the annual fluctuations in snow cover respond to both snowfall and snow season temperature (Qin et al. 2006b). Climate warming also influences water resources and the water cycle. Studies have shown that most inland lakes expanded, especially during the period of 1990–2010 (Lei et al. 2013; Zhang et al. 2014). Tibetan ice cores have provided another means of understanding the recent climate change and its impact on the environment on the Tibetan Plateau. Emissions associated with human activities have resulted in increasing concentrations of ions and metals, such as SO_4^{2-}, NH_4^+, NO_3^-, POPs and Pb, in the Tibetan ice core record. Black carbon in ice core records reveals different source regions for the Tibetan Plateau (Xu et al. 2009). The spatial distribution of observed pollutants in the environment and ice core records reveal the strong influence of the interaction between the Indian monsoon and westerly winds.

Contributions by Chinese Scholars and Subsequent Problems

Although Chinese scholars have made achievements in the form of long-term field observations and much accumulated data, which is critical to the study of changes in the cryosphere on the Tibetan Plateau in response to global warming, there is a lag in conducting integrated research on the large spatial region, which limits the comprehensive understanding of continental as well as global scientific issues. The combination of observation data, remote sensing, and simulation approaches will be necessary to link the Tibetan Plateau with global climate and environmental changes. Chinese scientists have ready access to the Tibetan Plateau, and excellent work has been performed to better understand environmental changes in the past decades and the Indian monsoon transport to the Tibetan Plateau. But further steps are needed to simulate the global mass cycle in the atmosphere using the observed climate and environmental records on the plateau.

Future Research

Several expectations for future research on land surface processes on the Tibetan Plateau cryosphere may be offered: (1) high spatial resolution and high temporal resolution of remote sensing data, including laser radar data, will fundamentally change the nature of cryosphere observation work and significantly improve our understanding of precise changes in the cryosphere, thereby providing a more reliable estimate of future impacts on the environment; (2) future research should strive to provide more precise measurements of cryosphere changes, e.g., glacial ice volume changes, and more reliable estimates of how the cryosphere will affect water resources, the lake system, and the ecosystems on the Tibetan Plateau; (3) a multidisciplinary effort focused on the interaction of the Indian monsoon and westerlies with a multi-sphere perspective should be undertaken to understand the complicated atmospheric circulation system and its relationship to climate change; (4) an enhanced observation network at extremely high elevations will complement the lack of reliable meteorological and other data in these remote areas, thereby improving the representativeness of the spatial coverage of the available data.

11.2.3 How Has the Polar Cryosphere Changed and How do These Changes Influence the Planet?

Bibliometric Analysis of Contemporary Research

According to a bibliometric analysis of the polar cryosphere for the period 2000–2014, most research publications fit into six themes: "ice core records and palaeoclimate","Greenland ice sheet", "Antarctic ice sheet", "polar oceans and sea ice", "polar climate and atmospheric circulation" and" sea level change". The total number of publications with these themes during the 15-year period is 8429, 6596, 8112, 29,186, 5576 and 3298, respectively. The theme related to "polar oceans and sea ice" has the largest number of publications, with annual publications of more than 1000 articles, and ranging from 1114 in the year 2000 to 2115 in 2014. Polar ice sheets (including Greenland and Antarctica) is another major research topic, with more publications than the ocean and sea ice theme, reaching 14,708 articles during the 15-year period and ranging from 663 in the year 2000 to 1018 in 2014. Publications with other themes also show an overall increasing trend. For instance, the "ice core records and palaeoclimate" theme increased from approximately 363 publications in 2000 to 519 publications in 2014; the "polar climate and atmospheric circulation" theme increased from 205 publications in 2000 to 369 publications in 2014; and the "sea level change" theme increased from 135 in 2000 to 276 in 2014. In this light, the polar cryosphere has seen a burgeoning area of research over the past decades.

Contemporary Research

Polar regions are critical parts of the Earth system, and polar science is an essential and unique component of Earth science. Polar regions exert strong influences on the rest of the globe through positive and negative feedbacks. Relative to other regions, researchers understand polar regions poorly, and scientific studies on these regions are also the poorest. Approximately 90 % of global freshwater is frozen in Antarctica and Greenland. The polar cryosphere forms large reflective surfaces, thereby playing an important role in the global radiation balance. Polar ice sheets are potentially the largest and at the same time the most uncertain components in the process of sea level change. Ice cores from polar ice sheets have long been considered to be the best archives of palaeoclimate. In recent decades, changes in the polar cryosphere have been captured largely through remote sensing methods. These changes include ice sheet mass balance, sea ice extent and concentration, snow cover, river/lake ice durations, permafrost, and so on. The widespread decay of the polar cryosphere has provided direct evidence of global warming over at least the past three decades. Deep ice cores from EPICA Dome C (EDC) and Dome F in Antarctica and North GRIP and NEEM in Greenland provide robust evidence for climate change and greenhouse gases in the late Quaternary and Holocene (Masson et al. 2000). The International Trans-Antarctic Scientific Expedition (ITASE) has provided evidence for the most recent decadal-to-centennial-scale changes in Antarctic mass balance and climate change. The contribution of ice sheets to global sea level change is now better understood through utilization of altimetry, gravity and InSAR satellite data since the early 1990s (Rignot et al. 2008). Instability in both the West Antarctic ice sheet and Greenland ice sheet has been studied using observation data and multiple ice dynamic models. The role of the Arctic amplifier, largely due to cryopsheric change, is well studied via integrated observations and coupled global and regional climate models.

Bibliometric Analysis of Contemporary Research in China

Based on a bibliometric analysis of polar cryospheric research in China, the studies have themes similar to international publications. These themes are "ice core records and palaeoclimate","Greenland ice sheet", "Antarctic ice sheet", "polar oceans and sea ice", "polar climate and atmospheric circulation", and "sea level change". The numbers of publications by Chinese authors on the above themes from

2000–2014 are 944, 262, 357, 1082, 561 and 186, respectively, accounting for 11.8, 3.9, 4.4, 3.7, 10.0 and 5.6 %, respectively, of the total worldwide publications. Among these themes, "ice core records and palaeoclimate" has the most publications in China, followed by "polar oceans and sea ice." These studies are related to routine investigations of an inland traverse of Antarctica from Zhongshan Station to Dome Argus (Dome A) during the past 18 years, along with the drilling of a series of shallow ice cores, and subsequent discussions of these data. In addition, Xuelong has undertaken five voyages to the Arctic Ocean and 15 voyages through the Southern Ocean, providing abundant in situ data for publications. The number of publications from China also has a clear temporal trend over the past 15 years. For example, the "ice core records and palaeoclimate" theme increased from 18 papers in the year 2000 to 83 papers in 2014, with a steady rate of increase during this time. Papers concerning the Antarctic and Greenland ice sheets increased from 11 in the year 2000 to 75 in 2014; "polar oceans and sea ice" from 8 to 135, "polar climate and atmospheric circulation" from 2 to 81, and "sea level change" from 4 to 32. With the increasing investment of the Chinese government in polar science, China has produced an increasingly large contribution to polar research in recent decades.

Contemporary Research in China

The first investigation of polar research funded by the Chinese government did not occur until 1980, when two scientists (one geographer and one oceanographer) were sent to join an Australian Antarctic research team. During the 1980s, one of main research topics by Chinese scholars was glaciology. During the 1990s, research foci included most components of the cryosphere, such as ice sheets, glaciers, sea ice and permafrost. Over the past two decades, the principal studies have been ice core records and related physio-chemical processes; Arctic snow and sea ice changes and their impacts on climate; permafrost changes in the Northern Hemisphere; and influences on climate and hydrology. Many articles by Chinese scientists focus on the processes on the ice sheet surface, laying a solid foundation for interpreting ice core records. Qin and others (Qin et al. 1994) have systematically studied physical and chemical processes through large-scale in situ investigations, including inland traverses from Casey to Vostok direction and the International Trans-Antarctic Expedition in 1989/1990. Their improvement of the theory of snow densification and development of a database of water-stable isotopes and snow chemistry covering the most areas of the Antarctic ice sheet have been widely recognized. The study along Zhongshan to Dome A featured systematic glaciological investigations, including measurements of surface mass balance, ice dynamics, ice physics, chemistry, and shallow ice core records. The major outcomes of the traverse were: (1) identification of the main moisture sources of the Southern Ocean and deposition belts on the ice sheets using water stable isotopes, models, and chemical tracers; and (2) the establishment of ice core proxies for sea surface temperature (SST), sea level pressure (SLP), and sea ice extent (SIE) based on process studies along the traverse route. With these proxies, the researchers were able to interpret climate changes and atmospheric circulation patterns at decadal to centennial scales (e.g., Xiao et al. 2004, 2015). Through international cooperation, China was also involved in Greenland NEEM ice core studies, which reconstructed for the first time the details of the Eemian climate and ice sheet height and reassessed the contribution of the Greenland ice sheet to sea level changes (NEEM 2013). Zhang and others (Zhang et al. 2003) assessed the general changes in circum-Arctic permafrost in recent decades. Many studies have revealed strong linkages between the Arctic cryosphere (sea ice and snow cover) and climatic extremes in East Asia, especially climatic precipitation patterns in China, suggesting that the Arctic sea ice and Siberian snow cover are useful factors in weather and short-term climate prediction (Wu et al. 2009).

Contributions by Chinese Scholars and Subsequent Problems

China has been a member of the International Trans-Antarctic Scientific Expedition (ITASE) program for the past two decades. The findings of ice core studies over the Indian sector of the Antarctic ice sheet have contributed to the overall understanding of climate change in the high latitudes of the Southern Hemisphere. Surface mass balance studies using in situ measurements have established abundant ground-truth evidence for international programmes, such as Ice Sheet and Mass Balance (ISMASS) (ISMASS committee 2004). In addition, in situ chemical and isotope data from Antarctica is the most spatially and temporally continuous dataset at present. Process studies of ice core records contribute to the understanding of the mechanisms in these important archives. Observational studies of Arctic sea ice and black carbon and studies of permafrost and snow cover changes on the Eurasian continent also have contributed to the current understanding of the polar cryosphere and its role.

There are obviously many gaps in polar cryosphere research in China. The major gaps exist in the following areas: (1) remote sensing, including satellite altimetry, gravity and SAR measurements of ice sheets and glaciers; (2) dynamic models of ice sheets, glaciers and sea ice; (3) coupled climate models for polar regions; and (4) deep ice coring techniques and knowledge preservation.

Future Research

China should focus on both certain traditional areas and frontier polar science in the future. The important foci include: (1) deep ice coring at Dome A, seeking possible >1 Ma ice that may provide clues to the Mid-Pleistocene Transition (MPT) enigma; (2) mass balance of ice sheets and sea level change, of which key issues are the uncertainties in calculating ice sheet mass balance, including ice shelf-ocean interaction, surface mass balance, ice flow dynamics and subglacial processes; (3) mechanisms linking the polar cryosphere and high-/mid-latitude climates: This should particularly address Arctic amplification and the overflow effects of Arctic melting to climate extremes in the mid-latitudes; (4) study of the permafrost carbon pool in the high-latitude continents, including submarine permafrost: Chinese permafrost scientists should make an independent assessment of carbon storage and sink/source calculations; (5) new technologies of remote sensing for the polar cryosphere: China should help develop a new generation of altimetry, gravity and InSAR sensors for satellites to pursue higher accuracy monitoring of the polar cryosphere. In the long term, polar cryosphere research should follow the idea of the "future earth", combining the natural and socioeconomic sciences to explore sustainable pathways with respect to the polar environment and society.

11.3 Roadmap for Further Research

The cryosphere, atmosphere, hydrosphere, lithosphere and biosphere form the global climate system. The cryosphere plays an important role in this system, and it is the domain most sensitive to climate change. In recognition of the cryosphere's highly sensitive and important feedback effect on climate change, scientists have pursued cryospheric research in the context of global warming. With the development of cryosphere science, research on the cryosphere in China is facing new opportunities and challenges. Research is evolving from traditional geography to interdisciplinary research and the boundaries between different disciplines are becoming increasingly blurred. Research methods have shifted from long-term observation and data accumulation to the numerical simulation of interactions between multiple spheres. Spatially, cryospheric research is moving from local to global or continental scales and enhancing its potential to provide solutions to major scientific problems. New methods and technologies in different disciplines continue to emerge, providing new opportunities for addressing major scientific problems in cryosphere science. From a focus on natural science to equally addressing social and economic aspects, cryosphere science is constantly cultivating new topics. In the future, scientific research in cryosphere science needs to continue to make progress in the following areas:

(1) **Improving the Simulation of the Cryospheric System and Enhancing the Ability for Cryosphere Science to Solve Global Problems**

In the past few decades, cryospheric research has made the leap from qualitative to quantitative and from static to dynamic. With the development of international geographic research, global-scale simulation studies are the leading direction in the future of geographic science. Solving key scientific problems at large spatial or global scales, obtaining new theoretical understanding, and developing new results in the field of globalization will also be key to achieving breakthroughs in cryospheric research. Simulation studies based on process observation and quantitative analysis are another pathway to understanding the change mechanisms in the cryosphere, clarify interactions with other spheres, and predict the fate of the cryosphere.

(2) **Strengthening Interdisciplinary Research and Achieving New Breakthroughs in Mechanisms of Cryosphere Process**

The Qinghai-Tibetan Plateau is a multi-sphere system that includes the cryosphere, atmosphere, hydrosphere, lithosphere and biosphere. Climate warming has accelerated glacial melting and permafrost thawing, contributing to further changes in the water cycle and water resources that will eventually induce changes in ecosystems. Comprehensive simulation studies are necessary to achieve scientific breakthroughs in cryosphere science that can help researchers understand the impacts and feedback mechanisms of this complex system and climate change. Strengthening the application of atmospheric science, physics, chemistry, biology and other disciplines in cryospheric studies and interdisciplinary research, particularly taking advantage of new technologies and new methods in these disciplines, is necessary to guarantee new progress in cryospheric research. Extensive international cooperation and involvement in major international research programmes are the new normal for current international cryospheric research.

(3) **Revealing Connotation of Cryosphere Science and Cultivating New Growth Points**

Cryosphere science now emphasizes both natural science and socioeconomic one instead of exclusively the former as before. It aims to deepen our understanding of the functioning mechanisms through which the cryosphere acts on water, ecology and climate. It also strives to calibrate the service functions and calculate service values of the cryosphere. These latter foci have not yet been studied internationally and may become an important direction for cryosphere research in China. Early implementation of the cryosphere-economic/social coupling is expected to become the potential prosperous area in the near future.

11.4 Summary

The cryosphere is the surface layer of the Earth with a continuous distribution of below-freezing temperatures and represents one of the five spheres of the climate system. Because the cryosphere has a special characteristic whereby ice, water, and vapour can transform easily, it is very sensitive to climate and environmental changes and produces significant climatic, hydrologic, ecological and calamitous effects. China has the world's largest cryosphere area in the low- to mid-latitudes, and it is mainly distributed on the Qinghai-Tibetan Plateau. Internationally, ice core research in Antarctica and Greenland has led to breakthroughs in understanding the evolution of the Earth's climate system. Over the past 30 years, Chinese scientists have made remarkable achievements in cryosphere science research. Chinese scientists first proposed the concept of cryosphere science. They have developed the scientific roadmap to include the natural sciences, social economy, and sustainable development to achieve ecological civilization; completed the construction of a cryosphere database based on a large number of observations; released two Glacier Inventory Datasets of China; published permafrost maps of China; established a continuous time series of changes in glaciers and permafrost; launched major international research programs, such as the "Third Pole Environment (TPE)" program, administered by Chinese scientists; revealed feedback processes between the plateau cryosphere and the climate system; reconstructed the climate change history of the Qinghai-Tibetan Plateau; and clarified the interaction of the Indian monsoon and westerlies (Yao et al. 2012, 2013). In the field of polar research, represented by the Trans-Antarctic research activities that have accumulated data at large spatial scales, Chinese scientists discovered a two-decade oscillation in the polar vortex in the Antarctic region and a correlation between the polar atmosphere and the middle and low latitudes (Xiao et al. 2004). Future work includes simulation of the cryosphere based on observational data; strengthening understanding of the interaction processes between different spheres; producing findings with significant international influence; promoting joint research on the cryosphere and social and economic development; and determining appropriate services for sustainable development.

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12 Economic Globalization and Local Responses

Canfei He, Debin Du, Xin Tong, Fenghua Pan, Xiyan Mao, and Tianming Chen

Abstract

This chapter traces the question of globalization and reviews the efforts from geographers to understand the spatiality of economic globalization. Specific efforts have been made to review four research areas, including transnational corporations, cross-border flows, consequence of global-local interactions and local response to economic globalization. This chapter also highlights the contributions of Chinese scholars in globalization studies. As the speed-up of China's integration into the globalization process, Chinese scholars are capable of offering more insights into cross-border economic activities, regional integration and global governance. Roadmap for future research is therefore depicted to embrace this trend.

Keywords

Economic globalization • Transnational corporation • Cross-border flows • Global-local interaction • Global production network

A total of 4243 SCI/SSCI-indexed articles are analyzed in the research area of economic globalization and local responses. Articles were identified from 52 international journals from 2000 to 2014. The number of journals that have published more than 15 of the relevant articles is 52 (Appendix I). The search query is as follows: ("globalization" OR "multinational corporation" OR "transnational corporation" OR "global pipeline" OR "global finance" OR "global production network" OR "global value chain" OR "global commodity chain" OR "international spillovers" OR "global R&D" OR "multinational R&D" OR "foreign investment" OR "foreign direct investment" OR "international trade" OR "international migration" OR "multinational community" OR "transnational community" OR "global city network" OR "service globalization" OR "world city region" OR "glocalization" OR "global-local" OR "global governance" OR "world city" OR "global city" OR "global pipeline"OR "local buzz").

12.1 Overview

12.1.1 Development of Research Questions

The development of new telecommunications and transportation technologies has allowed producers located in different countries and often with different ownership structures to form cross-border production networks, resulting in the "new international division of labor" largely organized by transnational corporations. Specialized "production blocks" are coordinated through service links, which include not only activities such as transportation, insurance, telecommunications, quality control, and management specifications, but also flows of capital, labor, knowledge, intermediate inputs and finished products. The emergence of new international organizations and regimes (WTO, World Bank, IMF and International Labor Organization) that establish rules and norms for the global community also

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indicates the growing level of economic globalization (Camdessus 2001; Sassen 2007). Traditional societal, cultural, economic and political systems have been fundamentally restructured by the interactions between international institutions and footloose transnational corporations on the one hand, and nation states and localities on the other hand, leading to a reconfiguration of production networks, national development, cultural identity and knowledge creation and diffusion (Scholte 2005). This process of reconfiguration often varies across space and constantly evolves over time (MacLeod 2001; Sheppard 2002; Sassen 2013).

Despite its popularity in current academic research, globalization is still a vague concept (Robertson 1992; Brenner 1999), due not only to the complexity and comprehensiveness of the term, but also to its incessant evolution and variegated influences in political, social and cultural spheres (Brenner 1999). As globalization has constantly changed over time, our understanding of globalization has also changed, from one that conflates globalization with internationalization and generates overly descriptive work on international flows of labor, capital and products, through one that emphasizes how trade liberalization facilitates those international flows, and finally to one that pays special attention to the process of reconfiguration of social, political, economic and cultural spaces in a new wave of economic globalization (Scholte 1997).

Studies of globalization tend to be open, dynamic and poly-centric, incorporating a wide range of research questions and topics (e.g., international division of labor, international trade, transnational corporations, regional and national development, poverty and inequality), attracting scholars from different disciplines (e.g., sociology, anthropology, political science, international studies, economics and geography). Research on globalization deals with the interconnectedness between different social, political, economic, and cultural factors associated with and involved in globalization; a huge part of the debate centers around jobs, wages, and uneven regional development in different parts of the world; and there is a focus on the resistance to globalization by consumer groups, activists, and transnational social movements regarding labor issues and environmental abuses. Geographers rely on the spatial-relational perspective and network approach to examine the spatial organization of trans-border economic activities and flows of products, knowledge, etc.

12.1.2 Contributions by Scholars from Different Countries

This section analyzes the number of academic articles on globalization published in English journals and their citation scores (see Table 12.1). Statistical analysis suggests that the vast majority of papers have been published by scholars based in North American and West European institutions. Specifically, scholars in the UK and USA have published around 50 % of all academic articles in English-language journals, followed by those from Belgium, Germany, Australia and Singapore.

China has made significant progress in globalization studies according to Table 12.1. Chinese scholars published 27 journal articles in 2014 and 102 during 2010–2014, ranking third and fourth respectively. In terms of the number of citations of all papers, China ranked third in 2014 and sixth during 2010–2014. In other words, the impact of Chinese scholars' research is still smaller than that of American, British, Canadian and Dutch scholars.

Using the number of highly cited papers as an indicator of research impact, we are able to see that the gap between China and leading countries is remarkably wide. During the last 15 years, only one highly cited article was written by Chinese scholars, while 112, 104, 13 and 11 were published by British, American, Dutch and Canadian scholars. In other words, in terms of the influence of their academic research, China still lags behind those leading countries.

12.1.3 Key Research Topics

Based on the graph of Keywords Cluster during 2000–2014 (Fig. 12.1), we have identified three strands of literature on globalization: urban and regional development studies (keywords: global city, regional development, growth and economic development), cross-border flows (keywords: foreign direct investment, international trade, international migration, innovation), and political and institutional studies (keywords: politics, state, institution, governance and power). Before 2005, the term "globalization" was often used alongside other key terms like "industry", "trade", and "investment" to study economic globalization; after 2005 it was more often used together with "urban studies", "power", "governance", "neoliberalism" and "localization". This transition reflects geographers' efforts to move beyond conventional studies that focus exclusively on economic dynamics. Drawing on the above-mentioned three overlapping strands of literature, we are able to see the critical role of three interconnected actors: firms, state and locality, since cross-border economic activities organized by firms, particularly transnational corporations, are affecting localities and countries in different ways and to different extents while the latter are simultaneously responding to, embracing and/or resisting the former. The rest of this chapter will therefore focus on this interconnected conceptualization to examine the new angles, methods, perspectives and vocabularies provided by geographers in this sub-field.

Research sites in this regard include both developed and developing countries. Globalization studies in European

Table 12.1 Top 20 countries (regions) with the number and citations of SCI/SSCI-indexed articles on "Economic Globalization and Local Responses" during the period 2000–2014

	Number of articles						Cited frequency						Number of highly cited articles					
	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014
Rank	World	181	250	1,041	1,528	1,674	World	4,314	70	28,126	25,767	7,542	World	16	0	104	103	88
1	USA	56	55	322	464	401	USA	1,106	15	10,133	8,478	2,262	UK	10	0	47	36	29
2	UK	53	43	313	403	346	UK	1,910	14	9,551	8,655	1,933	USA	4	0	38	38	28
3	Canada	10	15	65	106	106	Netherlands	27	1	671	1,095	447	Netherlands	0	0	2	5	6
4	China	4	27	33	60	102	Canada	94	1	1,195	1,347	362	Belgium	0	0	2	4	3
5	Netherlands	3	8	24	48	71	Belgium	39	1	231	507	258	Italy	0	0	0	0	3
6	Germany	3	10	23	38	63	China	91	14	507	763	227	Canada	0	0	3	6	2
7	Australia	7	8	38	38	57	Australia	96	5	438	290	216	Germany	0	0	2	2	2
8	Italy	1	5	11	21	44	Norway	241	1	537	188	188	Norway	1	0	2	1	2
9	Spain	2	4	5	21	38	Italy	5	2	130	195	186	Australia	0	0	0	0	2
10	Singapore	5	4	23	24	33	Germany	24	2	1,440	684	175	Austria	0	0	0	0	2
11	Japan	1	6	13	19	30	Austria	0	2	58	68	138	Czech Republic	0	0	0	0	2
12	Belgium	1	4	7	19	29	Singapore	138	1	682	571	115	Sweden	0	0	0	3	1
13	Sweden	1	7	13	17	26	Sweden	8	0	157	347	91	Singapore	0	0	1	2	1
14	France	3	7	8	20	25	Spain	0	2	86	134	77	Denmark	0	0	2	0	1
15	Taiwan, China	1	0	3	15	23	Denmark	12	2	320	210	73	Spain	0	0	0	0	1
16	Finland	0	3	2	11	20	France	68	0	233	205	54	Malaysia	0	0	0	0	1
17	Ireland	1	4	7	14	18	Japan	24	0	263	108	46	South Africa	0	0	0	0	1
18	Denmark	1	5	11	14	16	Switzerland	142	0	194	147	43	France	0	0	1	1	0
19	Turkey	2	5	8	16	15	Finland	0	0	179	90	39	Finland	0	0	2	0	0
20	New Zealand	0	2	13	11	13	New Zealand	0	2	214	150	30	China	0	0	0	1	0

Note Countries (regions) ranked by the number of articles, cited frequency and number of highly cited articles during the period 2010–2014

countries tend to discuss the role of regionalization/regionalism, as well as flows of trade, labor and technology; those from North and South American countries seek to examine the role of policies and institutions in the process of globalization; and those in China and other developing countries pay more attention to urban and regional development and global cities. Other key topics include challenges and opportunities for developing countries in the era of globalization, and the role of large economies (e.g., the USA and China) in the global economy.

Figure 12.2 indicates that Chinese scholars often apply theoretical and analytical frameworks developed in the West to the Chinese context. Scholars from China and the rest of the world are both interested in urban studies, regional development, institutions and regulation. Topics like global networks are attracting a growing amount of attention, so are debates on flows of capital, trade, labor, knowledge and innovation. Scholars in the West have made larger contribution in studies of space, place and geographical scale and in conceptual and theoretical research, while Chinese scholars have lagged behind in this regard. Recently, with the aid of National Natural Science Foundation of China (NSFC) financial supports, Chinese scholars have made significant progress in development studies, urban studies, institutions, governance, capital flows, trade, knowledge and innovation, though their contribution in studies of labor flows and migration remains largely limited.

12.1.4 The Role of NSFC in Supporting the Research on Economic Globalization and Local Responses

The vast majority of studies of globalization by Chinese scholars were conducted after 2000. The historical development of Chinese scholars' works during the last 15 years shows a shift from an economy-centered perspective to a more diverse, multi-dimensional one that pays increasing attention to a broader range of aspects of urban and regional development, and shift from a quantitative-analysis-dominated methodology to one that incorporates both quantitative and qualitative approaches. In this process, NSFC has played a crucial role. First, the financial support provided by NSFC increased from 1780 thousand yuan during 2000–2004 to 16,090 thousand yuan during 2010–2014. Second, a wider range of research projects have received funds from NSFC. Six research institutions and nine principal investigators (PIs) have been funded during 2000–2004, while the number increased to 32 and 39 respectively during 2010–2014 (Table 12.2). In addition, before 2005 most funded projects were on transnational corporations, whereas funds were intentionally channeled towards projects on a broad range of new topics after 2005, such as global production networks, global city networks, urban and regional development, urban governance and international trade (Fig. 12.3). In other words, NSFC has been playing a steering

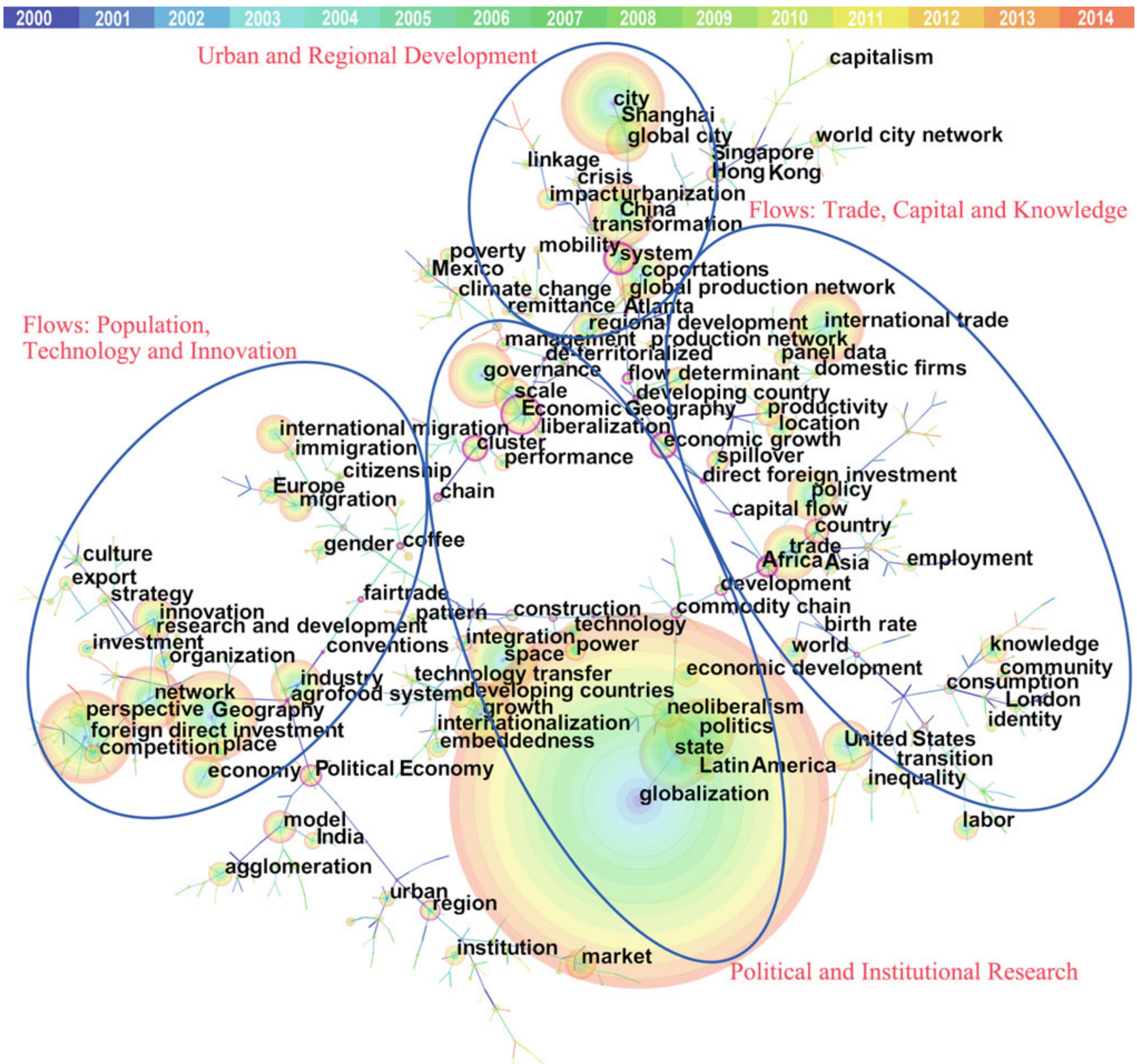

Fig. 12.1 Co-occurrence network of SCI/SSCI-indexed article keywords on "Economic Globalization and Local Responses" during the period 2000–2014

role, contributing to the diversification of globalization studies in China. NSFC also aims to generate research dealing with the political and empirical implications for national development and national development strategies, by drawing attention to topics such as the role of China in the new international division of labor, regionalization, industrial restructuring and upgrading, and global cities. It is expected that NSFC will have a larger impact in the near future, as current research funded by NSFC only accounts for 20.5 % of the total (Table 12.2).

12.2 Questions and Research Progress

12.2.1 How do TNCs Organize Cross-border, Value-adding Networks?

It was the way in which transnational corporations linked the production of goods and services in cross-border, value-adding networks that made the global economy in the last few decades qualitatively distinct from what preceded it. Transnational corporations have become the primary movers

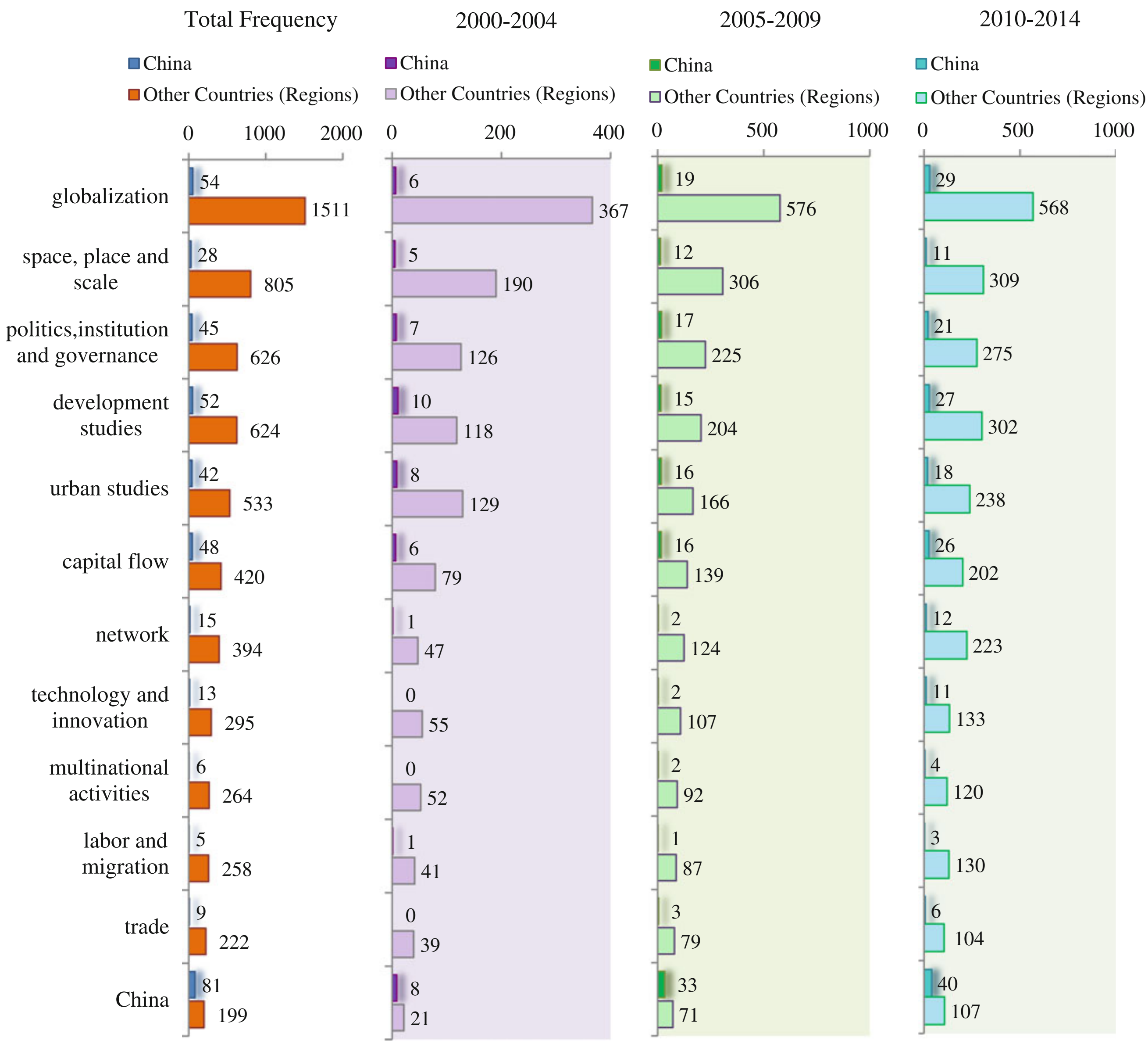

Fig. 12.2 Keyword temporal trajectory graph for SCI/SSCI-indexed articles on "Economic Globalization and Local Responses" during the period 2000–2014

and shakers of the global economy because they have the power to coordinate and control supply chain operations in more than one country even if they do not own them. Transnational corporations, their global sourcing strategies and the cross-border networks organized by them have been studied by many geographers, as all of these reveal many of the key features of contemporary globalization: it deals with international competitiveness in a way that inherently links developed and developing countries; there is a question of value creation and value capture by different actors, regions and countries in global production networks; and this further determines employment, wage levels and regional development opportunities in different localities.

Bibliometric Analysis of Contemporary Research

There are 201 papers on transnational corporations published since 2000 (excluding those published by Chinese scholars), of which 86 % are on foreign direct investment by transnational corporations (173 papers). Figure 12.1 also shows that some topics that are closely related to transnational corporations and foreign direct investment include: place, organization, geography, competition, network, location, knowledge spillover, and innovation. This also reflects the dominance of two broad issues in this sub-field: transnational corporations and firm (re)location (locational choice of transnational corporations and their local embeddedness). The number of

Table 12.2 NSFC-funded projects and SCI/SSCI-indexed articles on "Economic Globalization and Local Responses" during the period 2000–2014

SCI/SSCI-indexed articles					NSFC-funded projects			
Periods	Number of articles	% of articles by Chinese authors	% of articles with NSFC funding by Chinese authors	% of articles funded by MOST among those with NSFC funding	Number of projects	Funding (10,000 yuan)	Number of PIs	Number of institutions
2000–2004	1,041	3.2	21.2	0.0	9	178.0	9	6
2005–2009	1,528	3.9	21.7	0.0	14	335.2	13	9
2010–2014	1,674	6.1	19.6	5.0	39	1,609.0	39	32
2000–2014	4,243	4.6	20.5	2.5	62	2,122.2	58	39

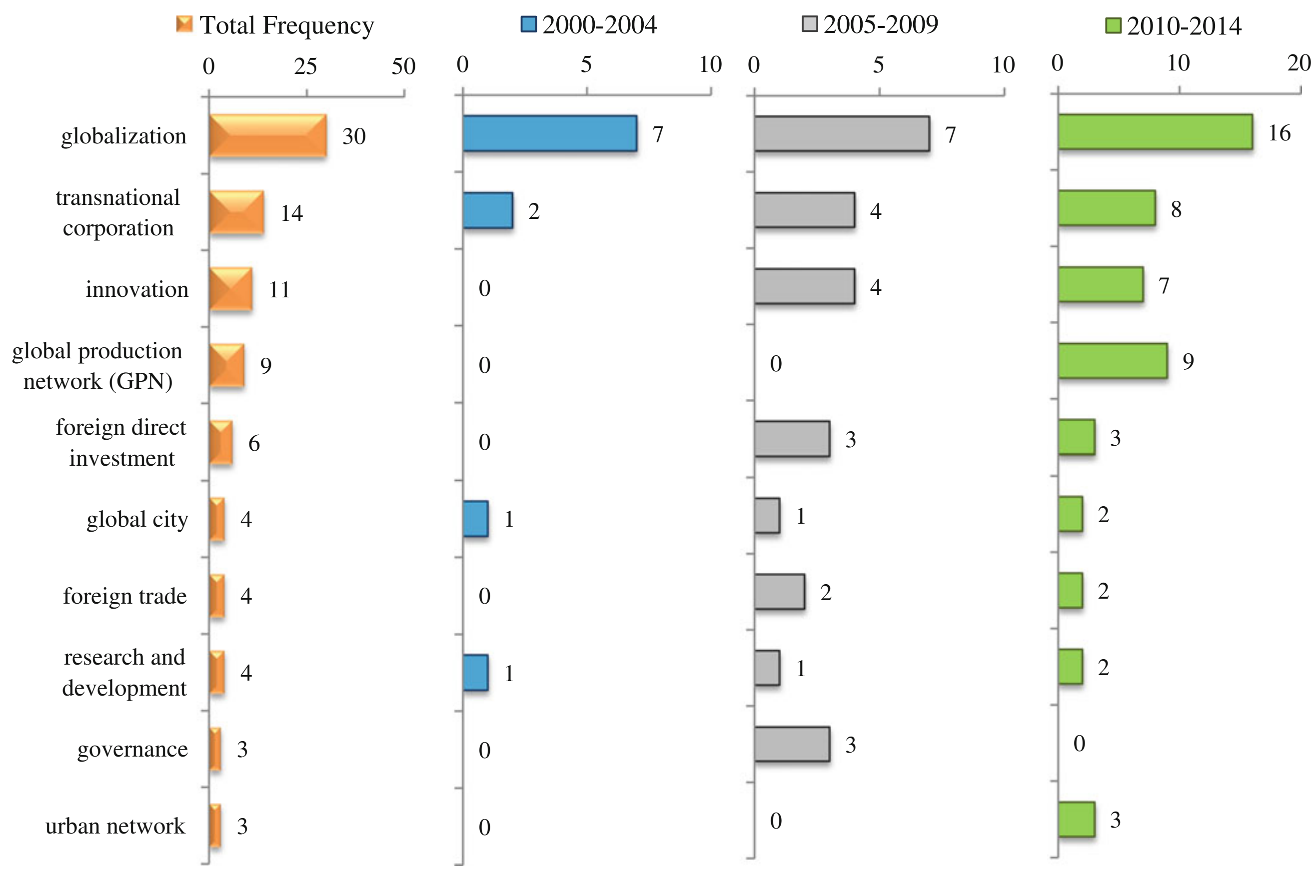

Fig. 12.3 Keyword temporal trajectory graph for NSFC-funded projects on "Economic Globalization and Local Responses" during the period 2000–2014

works in this sub-field has been increasing during 2000–2014, particularly those on organizational structure, knowledge and innovation, and production networks.

Contemporary Research

Geography matters and influences the spatial distribution of foreign investment, multinational corporations and their temporal evolution. Unlike economists who analyze transnational corporations and the inter-regional shifts in production using aggregate data and abstract modelling, geographers highlight the different ways in which and the different extents to which the process of strategic coupling between transnational corporations and local actors has unfolded in different localities (Dicken and Malmberg 2001; Morgan et al. 2001; Yeung 2002; Jones 2005). Two broad themes emerge in this regard: local embeddedness and the locational choice of transnational corporations.

Driven by the intellectual shift in the larger discipline of economic geography or even human geography, where "cultural turn", "institutional turn" and "relational turn" gradually became keywords, studies of transnational corporations start to incorporate cultural, institutional and social factors by paying special attention to the process of local embeddedness of transnational corporations into specific institutional contexts in the host countries (Yeung and Li 2000; Liu and Dicken 2006; Edgington and Hayter 2013) and how cross-border activities adapt to routines, norms, habits, conventions and social rules in different localities (Hsu and Saxenian 2000; Depner and Bathelt 2005; Faulconbridge 2008). Empirical studies of the extent to which branch facilities of transnational corporations interconnect with local economies through collaboration, knowledge spillover and technology transfer generate mixed results. Even though some case studies highlight the positive role of transnational corporations in local economic development, others based on Ireland and UK suggest that branch facilities of transnational corporations with a low level of local embeddedness have made little contribution to long-term, sustainable local economic development (Phelps et al. 2003; White 2004). Transnational corporations are always attempting to achieve a balance between being footloose and being embedded in certain localities (Phelps and Waley 2004), suggesting a need for economic geographers to rethink the concept of embeddedness in a dynamic and comprehensive way (Hess 2004; Jones 2008).

Studies of the locational choices of transnational corporations have allowed geographers to scale down from the traditional perspective focusing exclusively on dynamics at the national level towards diverse regional and local production systems, and therefore enabled geographers to examine how comparative and competitive advantages of localities (e.g., institutions, industrial base, business environment and infrastructure) affect the location of cross-border activities (Wei et al. 2008; Bel and Fageda 2008; Spies 2010) and how transnational corporations co-locate with one another rather than with domestic firms of host countries in order to circumvent the potential risks and uncertainties derived from their unfamiliarity with local institutions, culture and legal systems (He 2003; Mariotti et al. 2010).

Furthermore, studies also stress that the spatial patterns of different facilities of transnational corporations (e.g., headquarters, R&D, production and marketing facilities) vary (Yeung et al 2001; Duranton and Puga 2005). Specifically, studies of R&D facilities emphasize their role in coordinating innovation resources around the globe and forming global knowledge and innovation networks (Sun and Du 2011); those on retailing facilities argue that the ways in which transnational corporations embed into certain localities will affect how they enter the regional and local domestic market, what strategies they will choose, and their potential development trajectories (Coe 2004; Coe and Hess 2005; Tacconelli and Wrigley 2009; Lowe and Wrigley 2010); those on transnational corporations in advanced producer services tend to relate to the theory of global city networks (Grote 2008; Beaverstock et al. 2000a; Krätke and Taylor 2004).

Bibliometric Analysis of Contemporary Research in China

Since 2000, Chinese scholars have published 32 academic papers on transnational corporations, accounting for 13.73% of the total, most of which concentrate on cross-border capital flows. In China, transnational corporation study has been an important sub-field among all types of globalization study. During 2000–2014, 14 projects in this sub-field were funded by NSFC. Moreover, the number of funded projects is increasing.

Contemporary Research in China

Since the Reform and Opening-up policies, China has gradually transformed from a closed economy to a more liberalized and globalized one, and become the largest trader and one of the most important destinations for foreign direct investment. Based on empirical studies in China, particularly its coastal regions where the vast majority of foreign investments concentrate, Chinese scholars have applied theoretical frameworks developed by Western scholars to the Chinese context and pointed out that peculiar features of China's institutional, cultural and social context must be taken into account to fully understand embeddedness and the locational choice of transnational corporations in China. Efforts have been made to explore regional development and industrial upgrading through the global production network perspective (Miao 2006; Jing and Zeng 2007; Li et al 2008; Wei et al 2010a; Yang 2013; Zhu and Wang 2014), home country effects of outward foreign investments (Du 2001; Zhang and Du 2010; He and Yeung 2011; Wang et al 2011; He and Xiao 2011; He 2012), linkages between transnational corporations and other firms in their home countries (Zhou and Tong 2003; Sun and Du 2011), and the relationship between transnational corporations and domestic firms in host countries (Li 1997; Liu and Yang 2005; Liu and Dicken 2006; Liu and Yeung 2008; Ai and Miao 2011).

As China becomes both an important recipient of foreign investments and a contributor of a considerable amount of outward foreign investments, Chinese scholars have studied the "go global" strategies of Chinese firms' and the role of the central government in this process (Jiang 2006) and the spatial patterns of China's outward foreign investments (Lu 2006). Other scholars have paid attention to the underlying mechanisms of China's outward foreign investments and their impacts (Buckley et al 2007; Carmody and Owusu 2007).

Contributions by Chinese Scholars and Subsequent Problems

A comparison of Chinese and western research reveals two key features of transnational corporation studies by Chinese scholars. First, Chinese scholars tend to apply or slightly modify existing theoretical frameworks developed in the West to the particular institutional, political, cultural and social context of China. In other words, most works conducted by Chinese scholars are empirical, descriptive and heavily reliant on imported theories and methods, while little effort has been made to formulate non-Euro-centric vocabularies and perspectives. Second, transnational corporation studies by Chinese scholars are largely inward-looking, as they show more interest in China-related topics (e.g., the impact of globalization on China, China's integration into the global economy and the spatial distribution of transnational corporations in China) than in non-China-related ones, even though the latter may provide some new angles and perspectives to understand transnational corporations

Future Research

Economic geographers should aim to formulate a multi-scalar analytical framework to better understand the relationship between transnational corporations, states and regions; use the global production network approach to examine the articulation between production networks organized by transnational corporations and regional development (Coe et al. 2004); pay attention not only to transnational corporations in manufacturing sectors but also to those in service industries, and their interconnectedness with global city systems (Wrigley et al. 2005; Coe and Wrigley 2007); focus on the complicated relationships between immobile nation states and footloose transnational corporations, which shape the economic, political and institutional landscape in the world (Dicken 2003); and bring public and semi-public actors into the center of our analysis, for example, the World Bank, IMF, WTO and International Labor Organization, whose strategies and actions shape the globalization process at each point in the network.

China's outward foreign investment has expanded significantly during the past decade, suggesting that Chinese geographers will have great potential to reframe the existing Euro-centric theories and even develop new perspectives to incorporate new dynamics in the global economy as developing countries and emerging economies like China shift from being recipients of foreign investment to exporters of a considerable amount of outward foreign direct investments. Some promising topics include the spatial patterns of Chinese outward foreign investment, how Chinese transnational corporations, especially state-owned enterprises, deal with institutional, cultural and social contexts in other countries, the relationship between Chinese capital and social, political and economic actors in host countries and the impact of this relationship on Chinese capital's locational choice.

12.2.2 How do Capital, Products, Knowledge and Labor Flow across Space?

As globalization leads to an "integration of trade" and "disintegration of production", fragmented, specialized "production blocks" have been geographically located in different countries, coordinated through cross-border networks, which include not only activities such as transportation, insurance, telecommunications, quality control, and management, but also flows of capital, labor, knowledge, intermediate inputs and finished products. Studying these cross-border flows of a wide range of factors therefore allows us to better understand economic globalization.

Bibliometric Analysis of Contemporary Research

Statistical analysis of existing literature on "flow" shows that 475 academic papers (excluding those by Chinese scholars) have been published since 2000, of which papers on flows of commodities, knowledge, capital and labor account for 24 % (114 papers), 16 % (74 papers), 39 % (184 papers), and 29 % (140 papers) respectively. While attention to flows of commodities remains strong, some scholars have increasingly highlighted the importance of knowledge flows and relevant debates on technology transfer, knowledge spillover and diffusion, and innovation. Publications on capital flows concentrate on foreign investment at a global scale; the volume of work of this kind is however decreasing, indicating the rise of other types of flows as well as the necessity for scholars to take into account both capital flows and their interconnectedness with other flows (e.g., knowledge and technology). Studies of labor flows are mostly focused on transnational flows of low-skill labor.

Contemporary Research

One of the key features of economic globalization is the geographic spread of economic activities across national boundaries, linked by cross-border flows. This means cross-border flows can be a starting point for scholars to understand the complicated process of economic globalization. Unlike economists who champion the idea of "the end of geography" and analyze international flows at an aggregate level with the aid of abstract models and statistical analysis, geographers point out that geography is still of central importance but in a different form, and geographical differentiations are preconditions for globalization. To support this argument, a large number of empirical studies have been conducted, including those on cross-border flows between developed countries (North-North trade) (ÓhUallacháin and Reid 1992; Poon 1997; Pantulu and Poon 2003), between the developed and developing countries (North-South Trade) (Dunford and Perrons 1994; He 2003; Pla-Barber and Camps 2012; Bathelt and Li 2014), and more recently, among developing countries (South-South Trade) (Carmody and Owusu 2007; Brienen et al. 2010; Kedron and Bagchi-Sen 2012).

Within this strand of literature, studies of flows of labor, knowledge and technologies have gained more attention recently. First, studies of labor flows seek to understand the spatial distribution of international migrant labor, its geographical impact on host countries (Beaverstock 1991; Schiller et al. 1995; Koser and Salt 1997), the transnational migration of highly-skilled people and elites and the subsequent development of high-end producer services in different localities (Beaverstock 2002; Jones 2007), and the role of global and hub cities in the urban network (Beaverstock 1994; Findlay et al. 1996; Hannerz 1996; Beaverstock and Hall 2012). Second, as the vast majority of knowledge is un-codified and tacit, innovation and the diffusion of innovation are therefore heavily reliant on geographical proximity among firms and other actors (Florida 1995; Cooke and Morgan 1998; Lundvall and Maskell 2000; Howells 2002; Rychen and Zimmermann 2008). This explains why the spatial distribution of innovation is still uneven, in spite of the development and application of new transportation and telecommunication technologies. However, in the era of globalization, we should not overstress local factors and geographical proximity and underestimate trans-local factors that act as global pipelines for knowledge to flow across regional and national boundaries (Oinas and Malecki 2002; Coe and Bunnell 2003; Bathelt et al. 2004).

Two implications have been drawn from empirical studies: first, cross-border flows are not only organized by transnational corporations, but also shaped by institutional, cultural and political contexts in different localities (Mitchell 1997); second, the characteristics of cross-border flows vary at different geographical scales. As a result, political, cultural and social factors need to be incorporated to formulate a more dynamic, inclusive, and multi-dimensional analytical framework (Reiffenstein et al. 2002). A network perspective has also been adopted (Hughes 2000; Reiffenstein et al. 2002; Brooks 2013), to understand better the interconnected relationships and international flows that span global, national and local levels (He et al. 2008; Wei et al. 2010b).

Bibliometric Analysis of Contemporary Research in China

Since 2000, Chinese scholars have published 33 academic papers in this field, of which papers on flows of commodities, capital, and knowledge account for 12 % (4 papers), 91 % (30 papers) and 6 % (2 papers), respectively. Although the number of publications is increasing, Chinese scholars have not established strong positions in this sub-field (particularly in research on labor and knowledge flows). As China upgrades from low-end to high-end, knowledge-intensive industries and encourages firms to "Go Global", more attention should be directed towards new linkages formed between China and the global economy, in order to assess the changing role China plays in international flows of knowledge and labor.

Contemporary Research in China

China has gradually transformed itself from a closed economy to one that embraces economic globalization to some extent, and become the largest trader and one of the most important destinations for foreign investment, providing an ideal case for studies of cross-border flows. Chinese scholars have examined the spatial patterns of transnational flows in China, with respect to international trade, foreign direct investment, knowledge creation and diffusion, and innovation networks, by paying special attention to the relationship between international trade and regional development (Ge 2009; Gao et al. 2011; Ke 2015), the location of foreign direct investment and its subsequent impact on local economic growth (He and Liang 1999; He 2005; He and Zhu 2010; He and Yeung 2011; Lu 2012; Zhao et al. 2012; Huang et al. 2012), regional innovation systems and global innovation networks (Lu and Wei 2007; Sun and Du 2011), and transnational migration (Li et al. 2009; Liu and Chen 2014).

Contributions by Chinese Scholars and Subsequent Problems

There are three features of Chinese scholars' research on cross-border flows. First, it would be oversimplified to say globalization is a top-down or bottom-up process; rather it is a product of the complicated interplay between global, regional, national and local factors. However, much attention has been paid to meso- and national-level research, while little attention has been paid to dynamics at the global and local levels. Second, Chinese scholars tend to focus more on flows of capital in the form of foreign direct investment and less on flows of labor and knowledge, as well as financial globalization and the location of high-end service industries. Finally, most studies conducted by Chinese scholars tend to treat globalization as exogenous. The lack of understanding of the underlying mechanisms and the articulation between economic, institutional, social, and cultural systems indicates a need to bring back the background factors and re-place globalization per se at the center of our research. Nevertheless, Chinese scholars should take advantage of the opportunities created by China's emergence as a leading trader and its increasing integration into the global economy, and attempt to tackle the above-mentioned problems. In doing so, they will be able to offer more insightful perspectives and better interpretation with respect to debates on globalization, regional and local development, social embeddedness of transnational activities, and flows of labor and knowledge.

Future Research

Geographers insist that globalization is not smooth and homogenous, and does nor flatten geographical differences; rather it is uneven and predicated on spatial differentiations. In this sense, we should neither follow those hyper-globalists who consider globalization as a homogenizing force that has swept the planet (Ohmae 1995), nor join those skeptical internationalists who promote the idea that globalization is a state-dominated process (Rugman 2001). Globalization is not a mere extension or geographical spread of economic activates in different localities, rather it is an assemblage of economic, political, cultural, social, institutional and historical factors linked by a variety of flows (Murray 2006). Geographical studies of globalization in general and trade flows in particular therefore should move beyond describing the temporal and spatial evolution of trade flows, and seek to uncover how these shifts have altered governance structures and distribution of gains in the global economy, through a more inclusive, network perspective.

As globalization has constantly undergone alteration, a dynamic analytical framework is also necessary, to better investigate rapid industrialization in the global South, including the so-called newly industrialized economies in East and South East Asia and the emerging economies such as China, India, Russia and Brazil on the one hand, and the reverse side of de/reindustrialization in the global North on the other. This will certainly change the landscape of trade flows in terms of their direction, governance structure and complexity (Kaplinsky and Farooki 2011), suggesting a need to re-assess the role of trade flows in regional and local development and pay more attention to the dynamics of trade flows over time. Geographers in developing countries should not only examine what impacts economic globalization and cross-border trade flows have had on jobs, wages, and uneven regional development in different parts of their countries, but should also attempt to embed the process of economic globalization into specific social, institutional, and cultural contexts in order to produce more situated and embodied knowledge.

12.2.3 How is the Global Restructuring the Local?

The formation of global trade, investment, production and financial networks have been partly attributed to the increasing cross-border flows of commodities, capital, knowledge and talents coordinated by transnational corporations, further leading to a transformation of global economic geography, world urban systems and regional integration at various geographical scales. In the meantime, critics point out the dark side of economic globalization, due to the so-called governance deficit issue in global production networks and the subsequent uneven allocation of benefits around the world. As the regulation of financial capital has been largely compromised by the influence of Neoliberalism in advanced capitalist economies, the global economy is increasingly vulnerable to unexpected financial risks and uncertainties. This situation is compounded as nations are closely tied together in the process of globalization; local crisis is more likely to trigger a larger, more devastating crisis. These issues have forced recent studies to question and rethink neoliberalism and its promotion of deregulation, trade liberalization and privatization, and search for alternatives. The complicated interaction between globalization, regionalization and localization also urges us to ask questions from a different angle: how is the global restructuring the local? Is this the end of geography? Will geographical differentiation be eliminated or persist? These questions form the core of geographers' research agenda with regard to economic globalization.

Bibliometric Analysis of Contemporary Research

Economic globalization has fundamentally changed the economic landscape of the world and exerted huge impacts on urban and regional development, therefore receiving much attention from geographers. Since 2000, "globalization" has become one the most frequently used keyword in the geography literature. Interestingly, the second most used keyword is "city" and the third is "corporation". Other important key words include "network", "development", "policy", "region" and "urban". Over time, the ranking of frequently used keywords remains stable, indicating the consistency of research foci. The interactions between globalization and localization have formed the center of this sub-field. Geographers have long tradition and certain advantages in studying urban and regional development that has been largely influenced by globalization and the cross-border movements of products, capital, technology, talents, and policies.

Contemporary Research

The formation of global production networks and a new global economic landscape has profoundly restructured regional and local development, particularly through foreign direct investment, global sourcing and subcontracting organized by transnational corporations (Yeung and Coe 2015; Coe et al. 2008; Henderson et al. 2002; Hess and Yeung 2006), resulting in re/deindustrialization in the North and industrialization in the South, particularly in the emerging economies (Yeung and Liu 2008). According to the global production network approach, participation in the global economy and global production networks, particularly through a process of strategic coupling of regional assets and global production networks (Coe et al. 2004; Yeung and Coe 2015), is a necessary step for industrial upgrading and puts firms from developing countries onto dynamic learning curves (Giuliani et al. 2005; Humphrey and Schmitz 2002).

Global financial integration is a key feature of global production networks and lubricates the disintegration of production and integration of trade (van Hulten 2012), making global financial networks an important component of the global economy (Coe et al. 2014), coordinated by international financial centers (e.g., New York, London and Tokyo) (Engelen 2007; Engelen and Grote 2009) and off-shore financial centers (Buckley et al. 2015; Dörry 2015; Wójcik 2013). Cross-listing and overseas listing strategies in global financial networks have significant impacts on global production networks, as well as the regional economies in developing countries as firms from developing countries go public in foreign markets (particularly in the US) (Wójcik and Burger 2010). In addition, global venture capital is increasingly keen to benefit from the rapid economic growth in developing countries, further reinforcing the interconnectedness between global production and financial networks (Clark et al. 2002; Saxenian and Sabel 2008; Pike 2006; Zademach 2009). The global city network and the geographical dispersion and concentration of advanced producer service is also intertwined with global production networks and co-shapes the dynamics of urban and regional development (Beaverstock et al. 2000b; Derudder et al. 2003; Taylor 2001; Taylor et al. 2002).

The question is whether or not this signals the end of geography and spatial differentiation. The answer given by geographers is NO. First, at the heart of these changing geographies of production and sourcing are the twin processes of globalization and regionalization. For instance, the creation of the European Union and the North American Free Trade Agreement have led to preferential tariffs in these trade blocs, and promoted a growing consolidation of production networks within regions (Breinlich 2006; Dunford and Smith 2000; Hudson 2002; Smith 2003; Vorley 2009; Andresen 2010, Beine and Coulombe 2007; Zabin 1997). Second, even though some convergence is seen between advanced capitalist economies, complementary institutions and other forms of path dependency lead most scholars in the varieties-of-capitalism genre to argue vociferously against convergence, given their belief that unique and valued institutions will sustain national diversities despite the withering pressures of international competition in an increasingly open global economy (Clark et al. 2002; Clark and Wójcik 2003; Clark and Wójcik 2005a; Clark and Wójcik 2005b; Bathelt and Gertler 2005; Dixon 2011; Peck and Theodore 2007; Clarke 2012; McCann 2011; Peck 2011; Peck and Theodore 2012).

Finally, the 2008 global financial crisis has pushed geographers to reconsider the temporal-spatial process of economic and financial crisis and the underlying mechanisms (Pike and Pollard 2010; Pollard 2013; Engelen and Faulconbridge 2009; Lim 2012; Martin 2011; van Hulten 2012), and to question the effectiveness of current governance structure in global production networks (Lee et al. 2009; Wainwright 2012; Wainwright 2013).

Bibliometric Analysis of Contemporary Research in China

As China became one of the most important exporters and importers, recipients of inward foreign direct investment and providers of outward foreign direct investment, the ways in which China has participated in the global economy and the subsequent impact on regional and local development in China have received much attention from Chinese geographers. Since 2000, "China" has become the most frequently used keyword in this subfield. The "city" and "corporation" rank second and third, respectively. Other important keywords include globalization, foreign direct investment, region, development, investment, market, policy, urban, and growth. In addition, "China" has also been widely used in studies conducted by scholars from the rest of the world, indicating a growing, worldwide interest in China and its integration into the most recent wave of globalization.

Contemporary Research in China

Chinese scholars have contributed to this sub-field in several ways, particularly with respect to the interaction between foreign investment and local firms, local clusters' participation in the global economy, and the upgrading of economic actors, including firms, regions and nations. For instance, studies have pointed out the role of the state in facilitating knowledge spillovers and technology transfer from foreign to domestic firms through a process of "obligated embeddedness" (Liu and Dicken 2006). Others have examined the strategic coupling between regional clusters in China on the one hand and global leading firms on the other hand, as well as its meaning for developing country firms' industrial upgrading and regional economic development (Wang et al. 2005; Wang and Wang 1998).

Another topic that interests Chinese geographers is the geographically uneven impact of globalization in general and foreign investment in particular on local and regional development, which has been explored by geographers with the aid of aggregate data and disaggregated firm-level data (Li et al. 2000; He et al. 2008; He et al. 2007).

Recently, as Chinese firms seek to attract venture capital from overseas and Chinese outward investments increase dramatically, Chinese geographers have started to refine and revise existing Euro-centric theories and methods (Pan and Brooker 2014). Some comparative analyses have also been conducted to uncover the differences and similarities between Chinese cities and other cities in global city networks (Xue et al. 2010; Yang et al. 2011; Ma and Timberlake 2013).

Contributions by Chinese Scholars and Subsequent Problems

First, Chinese geographers tend to be inward-looking and are interested in China-related topics. Second, local and regional economy is often treated by Chinese scholars as a passive recipient or victim of restructuring process brought about by economic globalization, while little attention has been paid to the repercussions of the former on the process of globalization as they respond to and resist global economic forces. Third, a disproportionately large share of effort has been made to highlight research topics like development and economic growth; Chinese scholars have overlooked social, cultural and institutional issues (e.g., social and economic inequality, regional disparity, environmental pollution, poor working conditions for labor, poverty, and food security), also known as the dark side of economic globalization. Finally, Chinese geographers have not established a strong position in theoretical studies in this sub-field.

Future Research

Geographers have played a critical role in studying the global economy and the process of economic globalization, particularly through the widely used global production network approach. Recently, predicated on conceptual specification of basic building blocks in global production network theory, geographers begin to move further and aim to contribute toward the reframing of existing Global Production Network debates and the development of a more dynamic theory of global production networks that can better explain the emergence of different firm-specific activities, strategic network effects, and territorial outcomes in the global economy. This is part of a wider initiative—Global Production Network 2.0 in short—that seeks to offer novel theoretical insights into why and how the organization and coordination of global production networks varies significantly within and across different industries, sectors, and economies (Yeung and Coe 2015). Moreover, global financial network analysis has emerged in economic geography as a useful way of explaining how global financial flows influence regional development (Coe et al. 2014). Finally, the interaction between global financial networks, global production networks and global city networks is a fertile area for future research (Coe et al. 2010).

Other potential topics for future research include the effectiveness of neoliberalism and other alternatives that may compensate for the weaknesses of the dominant neoliberalist/post-Fordist system (Dixon 2011; Peck and Theodore 2007; Peck and Zhang 2013), the integration of emerging and transitional economies (e.g., China and India) into the global economy and whether or not this provides new development trajectories (Peck and Zhang 2013), and finally regional economic resilience in the face of global economic and financial crisis.

12.2.4 How is the Local Responding to the Global?

Today, we live in a world in which deep economic integration is pervasive and involves the production of goods and services in cross-border value-adding activities that redefine the kind of production processes contained within national boundaries. The key players in most international industries were large, transnational corporations, whose use and abuse of power in the global economy were chronicled by numerous authors. However, other actors are also important, including institutions like the World Bank, the International Monetary Fund, the World Trade Organization, and the International Labor Organization at the macro-level, nation state at the meso-level, and consumer groups, communities and activists at the micro-level, all contributing to the persistence of geographical differentiation. Economic geographers insist that globalization is uneven, occurring in very particular localities and strongly determined by geographical variation, differentiation and diversification. The local thus should not be considered as the passive recipient or victim of restructuring process brought up by economic globalization, but as an active constituent of the global economy, adapting and responding to economic globalization.

Bibliometric Analysis of Contemporary Research

Some 200 papers on governance, institutions, empowerment, community and policy in the process of globalization have been published since 2000 (excluding papers written by Chinese scholars). In addition, research on policy has moved beyond the role of the state and the dichotomy between state and market, by paying more attention to the development of local institutions, the empowerment of vulnerable populations and peripheral regions that receive a disproportionately small share of global wealth, and the changing governance structure and the subsequent governance deficit issues in global production networks. The number of papers on these issues has kept growing in recent years.

Contemporary Research

Two broad issues were raised by economic geographers in the study of local responses to globalization: varieties of capitalism based on an institutional perspective (Hall and Soskice 2001; Peck and Theodore 2007) and strategic coupling between the local and global or the so-called glocalization based on an organizational perspective. The emergence of globalization has weakened the sovereignty of the nation state in the traditional sense, and tipped the balance of power in favor of global factors in particular and footloose transnational corporations (Dicken 1994; Jessop 2002). As neoliberalism/post-Fordism was embraced by the advanced capitalist economies as the new doctrine since the late 1970s and early 1980s and laid the foundations of a new stage of international trade, the role of state in the global economy was to some extent compromised by the subsequent trade liberalization, deregulation, privatization and the so-called Washington Consensus (Gereffi 2014). Some believe that as economic globalization proceeds, all countries particularly those advanced capitalist economies will converge to one common pathway (Fukuyama 1992). Geographers, however, argue vociferously against convergence, given their belief that unique and valued institutions will sustain national diversities even in an increasingly open global economy (Gertler 2001), though some convergence has occurred in private firms' behavior and business practices (Wójcik 2006). Geographers have attributed this diversification to the persistence of the heterogeneity of local institutional, cultural and historical contexts on the one hand (Hofstede 1983), and to incessant capital accumulation and uneven (re)production of space it generates on the other hand (Massey et al. 2003; Harvey 1999). These debates can be seen in several related approaches that deal with the governance of modern capitalist economies, including regulation theory, national systems of innovation, social systems of production, and varieties of capitalism (Hall and Soskice 2001; Peck and Theodore 2007).

Globalization has placed the state in a problematic position. It is called upon to regulate the activities of capital in the national interest at the same time as it is forced to create a good business climate, to shift from managerialism to entrepreneurialism (Mair 1993), to act as an inducement to transnational corporations and foreign direct investment (Markusen 1996), to upgrade by actively participating in the global economy (Humphrey and Schmitz 2002; Smith et al. 2002; Coe et al. 2004; Yeung 2009; Nadvi and Wältring 2004; Cox 1995), and to deter capital flight to greener and more profitable pastures. In this scenario, the power of state has to be curbed. However, the outbreak of the 2008 financial crisis urges scholars, policy-makers and analysts to reconsider the dark side of economic globalization and about the possibility of disconnecting local communities from the turbulent global economy in some cases (Horner 2014). This reconsideration further brings the limits of capital back to the center of our research, calling for more attention to be directed towards the resistance to economic globalization by consumer groups, activists, NGOs, civil societies and transnational social movements (Yeung and Coe 2015), and to corporate social responsibility and ethical trade strategies that are designed to reshape the governance structure in the global economy (Barnett et al. 2011; Hughes et al. 2008).

Bibliometric Analysis of Contemporary Research in China

As with their counterparts in the West, Chinese scholars emphasized the importance of policy, and the role of state and Chinese economic reform, used as keywords by no less than 60 papers. This indicates that government-led trade liberalization, globalization and marketization has been an emerging topic in China's globalization studies. Moreover started to pay attention to the impact of varieties of governance on globalization and trade liberalization.

Contemporary Research in China

There are three key research areas where Chinese scholars have made significant contribution. First, industrial cluster studies have investigated the various ways in which local production systems in developing countries were upgraded by participating in global production networks (Zhou 2005; Wang et al. 2005; Wang and Wang 1998), and their responses to the 2008 global financial crisis (Zhou et al. 2011). Second, empirical studies have examined the reform of state-owned enterprises and the impact on regional and local development, as well as the formation of joint ventures between state-owned enterprises and foreign firms through a process of "obligated embeddedness" (Liu and Dicken 2006). Finally, recent studies have discussed the importance of sustainable development, environmental management and equality issues in China's integration into the global economy, in response to the emergence of a new understanding of globalization in the West in terms of its social and environmental impact (Tong et al. 2012; Tong and Yan 2013).

Contributions by Chinese Scholars and Subsequent Problems

Geographers base their global-local studies on the persistence of geographical differentiation and the heterogeneity of local institutional, cultural and historical contexts. Chinese scholars contribute to the glocalization debate by adopting theoretical and analytical frameworks developed by Western scholars and situating them in the Chinese context. In addition, China's economic reform and China's role in the global economy as the second largest economy and one of the most important emerging economies means that Chinese scholars have the potential to offer more insightful ideas to existing debates and breathe new air into current globalization studies. Specifically, China's state-led globalization, trade liberalization and marketization are a particularly interesting topic in terms of local responses to economic globalization. Chinese scholars have pointed out the complicated interaction between domestic firms, foreign firms, migrant labor, central and regional governments, and industry associations as well as the ways in which organizational and geographical strategies (such as factory consolidation, upgrading, delocalization/relocation, and outsourcing) have been implemented to deal with new challenges and opportunities posed by globalization, the 2008 financial crisis, new dynamics on labor market and rising labor cost, and changing governance structure.

Future Research

Economic geographers should move beyond existing Euro-centric analytical frameworks, methodologies, perspectives and vocabularies (Yeung and Lin 2003), particularly as developing countries and emerging economies start to play an increasingly important role in the global economy (Kaplinsky and Farooki 2011). When the global South is participating in the international market not only as a supplier and export platform for labor-intensive, low-end, low-tech and low-value-added production, but also as a buyer and end market for consumer goods and producer services, it is necessary to rethink the traditional methods that tend to freeze complex and diversified circuits of economic activity into fixed geographical frame works where consumption is presumed to be largely located in the North and production has been increasingly out-sourced to cheap labor markets in the South. This is also calling for attention to the diverse ways in which developing countries are able to participate in the global economy, in addition to providing export processing zones and cheap labor to entice transnational corporations and foreign direct investment (Yang 2013).

12.3 Roadmap for Further Research

As economic globalization is sweeping the planet, we should not overlook other dynamics that co-exist with globalization and are equally important—localization, regionalization and nationalization, as well as the complicated ways in which a variety of factors articulate with one another at the local, regional and national levels. In addition, economic globalization incorporates not only firms in developing and developed countries but also labor, social groups and local communities, resulting in a complex, multi-dimensional process that spans different political, social, historical, institutional, and cultural contexts. The integration of the so called peripheral countries in Asia, particularly China and India, Africa and Latin America into the world economy adds further complexity to the process of globalization. China as the second largest economy and one of the most important emerging economies offers an ideal case for Chinese geographers as well as other human geographers to study globalization in a multi-scalar, multi-dimensional way. There are three fertile areas for future research:

(1) Building a Multi-scalar Analytical Framework for Economic Globalization

The rise of globalization does not mean "the end of geography" or give rise to a "flat" world where all places are converging towards one common pathway, since the process of globalization is not seamless, eliminating all geographical differences. The spatial distribution of economic activities has been affected not only by the process of globalization, but also by other dynamics—localization, regionalization and nationalization. Economic geographers therefore should seek to form a multi-scalar analytical framework to study economic globalization.

First, at the local level, the geographical characteristics of places determine the spatial patterns of foreign direct investment, multinational corporations and their temporal evolution, the ways in which firms are managed and the spatial organizations they forge, inter-regional shift in production, how global commodity chains connect distant places to one another, and industrialization and de/reindustrialization around the globe. The process of localization and the subsequent geographical differentiations are thus preconditions for globalization.

Second, even though some argue that the traditional power of the nation state in regulating, containing, and coordinating productions and transactions have been weakened in the era of globalization, the state still matters fundamentally as a container with diverse cultural and institutional contexts, a regulator that creates different regulatory regimes, and a competitor/collaborator that interact with one another in a variety of ways. Such a national differentiation must have substantial impact on the geographical spread of economic activities, leading to a process of nationalization alongside globalization.

Finally, the emergence of new considerations in global sourcing, such as the importance of short-cycle replenishment, lean retailing, or just-in-time production, has added further stickiness to the flow of global financial capital and investment, reinforcing the importance of spatial proximity and the process of regionalization. This has been further enhanced by the rise of regionalism predicated on the establishment of regional integration schemes, such as the European Union, North America Free Trade Agreement, and ASEAN (Association of Southeast Asian Nations) Plus Three.

(2) **Formulating a Multi-dimensional Theoretical Framework**

Production networks can be regarded as vertically organized structures configured across increasingly extensive geographical scales. Cutting across these vertical structures are the territorially defined political, cultural, institutional, historical, social and economic systems which, again, are manifested at different geographical scales. It is at the points of intersection of these dimensions in "real" geographical spaces where specific outcomes occur, where the problems existing within a globalizing economy—whether as a business firm, a government, a local community or an individual—have to be resolved. Human geography therefore should establish a multi-dimensional, multi-disciplinary theoretical framework that pays attention not only to global production networks that are connecting economic activities in developing and developed countries, but also to the equally important political, societal, historical and cultural processes that are co-shaping the global economy. In other words, such a framework should acknowledge the importance of the fact that any economic activity is embedded in, and facilitated, regulated and enabled by its peculiar social, political, historical and cultural context. Finally, the integration of the so called global peripheral countries in Asia, Africa and Latin America with variegated social, political, historical and cultural contexts into the world economy adds further complexity to the process of globalization, calling for a more inclusive, open, diversified and dynamic understanding that allows us to move beyond the conventional, Euro-centric framework.

(3) **Situating Globalization in the Chinese Context**

China, as the second largest economy and one of the most important emerging economies in the 21st century, provides an ideal case for economic geography to study political and economic restructuring, cultural conflict and integration between the local and global, and new international division of labor. It is acknowledged that China will play an increasingly crucial role in shaping the international market, establishing new trade and regulatory regimes, and shouldering more responsibilities with regard to economic as well as political, cultural and social issues, particularly after China announced its ambitious "the Belt and Road Initiative". To better understand China's integration into the process of globalization, we need to focus on:

- Analyzing the various ways in which China has integrated into the global economy, and the consequent impact over China's own political, economic and social systems;
- Understanding China's changing role in the process of globalization and regionalization and how global city networks, production networks, financial networks and knowledge networks have been affected by China's integration into the global economy;
- Studying the spatial and organizational dynamics of not only firms but also labor and other input factors, in order to reveal what opportunities and challenges have been presented by the new wave of globalization to Chinese enterprises;
- Using a network perspective which emphasizes the interconnectedness between social, economic, political and cultural systems at the local, national, regional and global level to investigate how local and national development becomes a product of a dynamic process where actors in regions coordinate, mediate, and arbitrate strategic interests between local actors and their counterparts in the global economy.

12.4 Summary

On the one hand, in response to the rise of globalization, new conceptual vocabularies and theoretical frameworks have been forged, as well as new methods, such as global networks, global commodity chain analysis, and the analytics of transnational corporations. All have contributed to studies of the changing spatial patterns of foreign direct investment and multinational corporations, inter-regional shifts in production, and the subsequent rise and fall of industrial regions around the world. On the other hand, human geographers criticize statements about "the end of geography" and argue that globalization is not smooth and homogenous, and does not erase geographical distinctions; rather it is uneven, occurring in very particular places and strongly determined by spatial variation, differentiation and diversification. In doing so, human geographers embrace the idea of scaling up from the local and regional scale to the broader scale of global city networks, production networks, commodity networks, financial networks, and innovation/knowledge networks, and scaling down the global perspective on local and national development, by paying special attention to the ways in which specific localities and nations have been incessantly shaped by the articulation of global and local factors. Chinese scholars have made significant progress in empirical studies of urban development, innovation, localization of production, and the role of the institutional and regulatory context, but failed to establish strong positions in developing theoretical and conceptual frameworks that will lead to novel angles, perspectives, vocabularies and methodologies. Consequently, it is essential for Chinese geographers to adopt the above-mentioned multi-scalar, multi-dimensional analytical framework, to better understand the complicated process of globalization as well as its interaction with the institutional, political, cultural, social and economic systems in China.

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Regional Sustainable Development 13

Weidong Liu, Hui Liu, Li Ma, Tao Pan, Zhigao Liu, Mingxing Chen, and Qing Tang

Abstract

This chapter first reviews major trends and popular research topics in the field of regional sustainable development, and then summarizes major progress in the study area in China by focusing on five sub-topics, that is, how to understand the coupling relationships between human and nature, how to delineate the carrying capacity of natural resources and the environment, how to evaluate the status of sustainable development of a region, how to utilize natural resources in a sustainable way, and how to achieve regional sustainable development with better governance. Lastly the section calls for multi-disciplinary studies for guiding practice of regional sustainable development and for more attention to the role of regional governance.

Keywords

Human-land system • Carrying capacity • Regional governance • Natural resources utilization • Evaluation

A total of 4178 SCI/SSCI-indexed articles were collected from 94 international journals from 2000 to 2014 in the research area of regional sustainable development. Of these journals 54 published no fewer than 15 articles each on this topic (see Appendix J). The articles were selected by searching for the keywords "sustainable development*", "natural resources*", "carrying capacity*", "sustainable development assessment*", "man-land system*", "man-land relationship*", "ecological economy*", "ecological security*". However, the articles published with the words "global" and "community" and "social" in titles, abstracts, and author keywords were excluded.

13.1 Overview

13.1.1 Contributions by Scholars from Different Countries

The 4178 research articles on regional sustainability are unevenly distributed geographically. More specifically, they are concentrated in several leading countries, including the United States (the USA), China, the United Kingdom (the UK), Australia, Canada, Netherlands, Germany, Turkey, Spain and India. The USA, China and the UK accounted for 15.8, 11.9 and 11.5 %, respectively, of the total articles. Since 2010, the number of articles published by Chinese scholars each year has exceeded that of the USA, and China has ranked the first in the list of countries. In 2010–2014, 340 articles were contributed by China, 35 % more than that by the USA. In 2014 alone Chinese scholars published 84 articles, 50 % more than their counterparts in the USA.

According to Table 13.1, the top 10 countries in terms of the number of articles published are on the whole the most cited. In terms of the total number of citations, the USA, UK and China are the top 3, accounting for 19.4, 16 and 7.7 %, respectively, of the global total. Although China's total number of citations in 2000–2010 was lower than those of UK and the USA, the figure rose to 1706 in 2010–2014, making China the first in the citation list, higher than the USA and UK.

In terms of the number of the most highly cited articles, China ranked the third in 2000–2014, accounting for 10.8 % of the world total, lower than that of the USA (16.9 %) and UK (15.7 %). In the most recent four years (2010–2014),

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Springer Geography, DOI 10.1007/978-981-10-1884-8_13

Table 13.1 Top 20 countries (regions) with the number and citations of SCI/SSCI-indexed articles on "Regional Sustainable Development" during the period 2000–2014

	Number of articles						Cited frequency						Number of highly cited articles					
	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014
Rank	World	116	428	709	1,434	2,035	World	2,968	255	15,831	23,483	10,891	World	12	0	52	92	105
1	China	2	84	33	125	340	China	32	42	502	1,651	1,706	China	0	0	2	6	19
2	USA	34	55	168	241	252	USA	768	25	4,678	3,912	1,154	UK	5	0	11	19	12
3	UK	25	32	138	195	149	UK	935	51	3,301	3,711	1,038	USA	4	0	16	14	9
4	Australia	9	20	35	76	99	India	22	1	410	286	617	Malaysia	0	0	0	3	9
5	Canada	5	12	34	65	79	Malaysia	0	26	0	331	589	Turkey	0	0	6	8	7
6	Netherlands	3	11	24	40	69	Turkey	2	0	721	1,195	491	India	0	0	1	2	7
7	Germany	6	15	17	30	69	Australia	179	10	579	1,670	463	Germany	1	0	3	2	4
8	Spain	0	12	3	36	62	Germany	200	5	439	468	459	Canada	0	0	0	4	4
9	Malaysia	0	13	0	7	59	Spain	0	2	63	514	453	Spain	0	0	0	1	4
10	Turkey	1	5	16	37	57	Canada	74	4	455	1,096	411	Netherlands	0	0	1	5	3
11	Brazil	1	12	6	25	57	Netherlands	107	7	730	899	397	Sweden	0	0	1	2	3
12	India	2	7	19	24	53	Brazil	14	6	173	244	242	Australia	0	0	1	10	2
13	Italy	2	17	10	17	48	Sweden	57	4	520	753	236	Brazil	0	0	1	0	2
14	Sweden	1	7	18	43	42	Italy	18	10	561	259	198	Taiwan, China	0	0	1	0	2
15	Japan	2	7	9	18	34	Taiwan, China	0	0	177	250	122	Italy	0	0	3	1	1
16	Finland	0	6	14	27	31	Finland	0	1	211	407	116	Switzerland	0	0	0	3	1
17	France	1	5	5	19	31	Austria	0	1	264	354	110	Austria	0	0	2	1	1
18	Greece	2	3	9	27	28	Switzerland	29	1	98	599	78	Slovenia	0	0	0	2	1
19	Austria	0	3	11	19	21	Denmark	50	0	184	576	53	France	0	0	0	1	1
20	Switzerland	1	3	8	31	18	Norway	0	3	91	434	27	Norway	0	0	0	3	0

Note Countries (Regions) ranked by the number of articles, cited frequency and number of highly cited articles during the period 2010–2014

however, China ranked the first in terms of the most highly cited articles with 19 articles in total.

13.1.2 Key Research Topics

The highly cited articles are from journals in such research fields as energy, environmental management, production, development, global environmental change, and planning (see Table 13.2). Major topics addressed by these articles include energy, land, forests, carbon (climate change), and water.

According to the keywords co-occurrence network analysis for regional sustainable development research (Fig. 13.1), the high frequency keywords appeared since 2000 can be divided into five research clusters. Sustainable, development, energy and renewable energy form the first cluster. Among them, energy and renewable energy have become high frequency keywords since 2008. The second cluster includes environmental, governance, community, political and strategy, and the third includes sustainability, system, and urban. The frequency of sustainability and system has steadily increased since 2005. The keywords in the fourth cluster are management, climate change and agriculture, and model. Among them, management has been one of the highest frequency keywords since 2000, and the frequency of climate change has risen rapidly since 2008. The fifth research cluster consists of such keywords as natural resources, policy, conservation and environment, among which policy, however, has been a high-frequency keyword since 2000, increasing in frequency year by year. The frequencies of natural resources and resource policy have declined since 2008.

In addition, model, impact and index (indicator) are also high-frequency keywords. Apart from energy, elements like land, water, and forests are also high frequency keywords. Among these elements, the keywords which are highly associated with global climate change, such as energy, forests, and land, have risen in frequency in recent years, while the frequency of water has declined. Among all the keywords, governance, system, energy, assessment, climate change, ecology, and research methods have high frequencies, which still keep rising; economic and environmental are high-frequency keywords, but their frequencies remain relatively stable. This reflects the fact that more attention has been paid to governance issues related to climate change in the international academic community.

13.1.3 The Role of NSFC in Supporting the Research on Regional Sustainable Development

Regional sustainable development has been an important area of study supported by NSFC since its foundation. Sub-research fields include human-land relationships, resource utilization and carrying capacity, and the regional sustainable development situation. In 2000–2014, the total number of various research projects funded by NSFC on

Table 13.2 The journals with highly cited SCI/SSCI-indexed papers on "Regional Sustainable Development" during the period 2000–2014

Field	Main journals	Number of highly cited articles	Proportion (%)
Energy	Renewable and Sustainable Energy Reviews	39	22.5
	Renewable Energy		
	Energy		
Environmental management	Journal of Environmental Management	32	18.5
	Environmental Management		
Production	Journal of Cleaner Production	15	8.7
Development	World Development	14	8.1
Global environmental changes	Global Environmental Changes: Human and Policy Dimensions	10	5.8
Planning	Landscape and Urban Planning	10	5.8
Geography	Political Geography	19	11.0
	Progress in Human Geography		
	Antipode		
	Annals of the Association of American Geographers		
	Economic Geography		
Sum		139	80.3
Total		173	100.0

regional sustainable development was 197, among which about 60 % were funded after 2010. These projects have contributed a lot to the academic advance of regional sustainable development research in China, enabling China to occupy an increasingly important position in the field in the international academic community. However, due to the location-specific features of regional sustainable development research and language issues (i.e., English proficiency), early NSFC-funded research projects yielded few English articles.

Since 2003, with the rapid increase in the number of scholars with a good command of English and the institutionalization of publishing SCI/SSCI-indexed articles, the number of articles published in 99 major SCI/SSCI-indexed journals by Chinese scholars on regional sustainable development has grown rapidly. In 2000, only 2 papers were published, but the figure rose to 7 in 2003, and further to 20 in 2007. In 2010, the figure reached 66, and climbed to 84 in 2014. In 2010–2014, the number of articles published by Chinese scholars in this research field accounted for one sixth of the world total (Table 13.1). In the meantime, the number of articles funded by NSFC increased rapidly. In 2000–2004, NSFC-funded articles accounted for 15.2 % of the total number of papers published by Chinese authors while the figure rose to 30.4 % in 2005–2009, and to 41.5 % in 2010–2014 (Table 13.3).

Due to differences in development stages, governance structures and natural conditions, different countries and

Table 13.3 NSFC-funded projects and SCI/SSCI-indexed articles on "Regional Sustainable Development" during the period 2000–2014

SCI/SSCI-indexed articles					NSFC-funded projects			
Periods	Number of articles	% of articles by Chinese authors	% of articles with NSFC funding by Chinese authors	% of articles funded by MOST among those with NSFC funding	Number of projects	Funding (10,000 yuan)	Number of PIs	Number of institutions
2000–2004	709	4.7	15.2	0.0	39	1,459.0	39	26
2005–2009	1,434	8.7	30.4	34.2	48	2,301.0	46	31
2010–2014	2,035	16.7	41.5	32.6	110	6,982.5	108	73
2000–2014	4,178	11.9	36.9	32.1	197	10,742.5	179	93

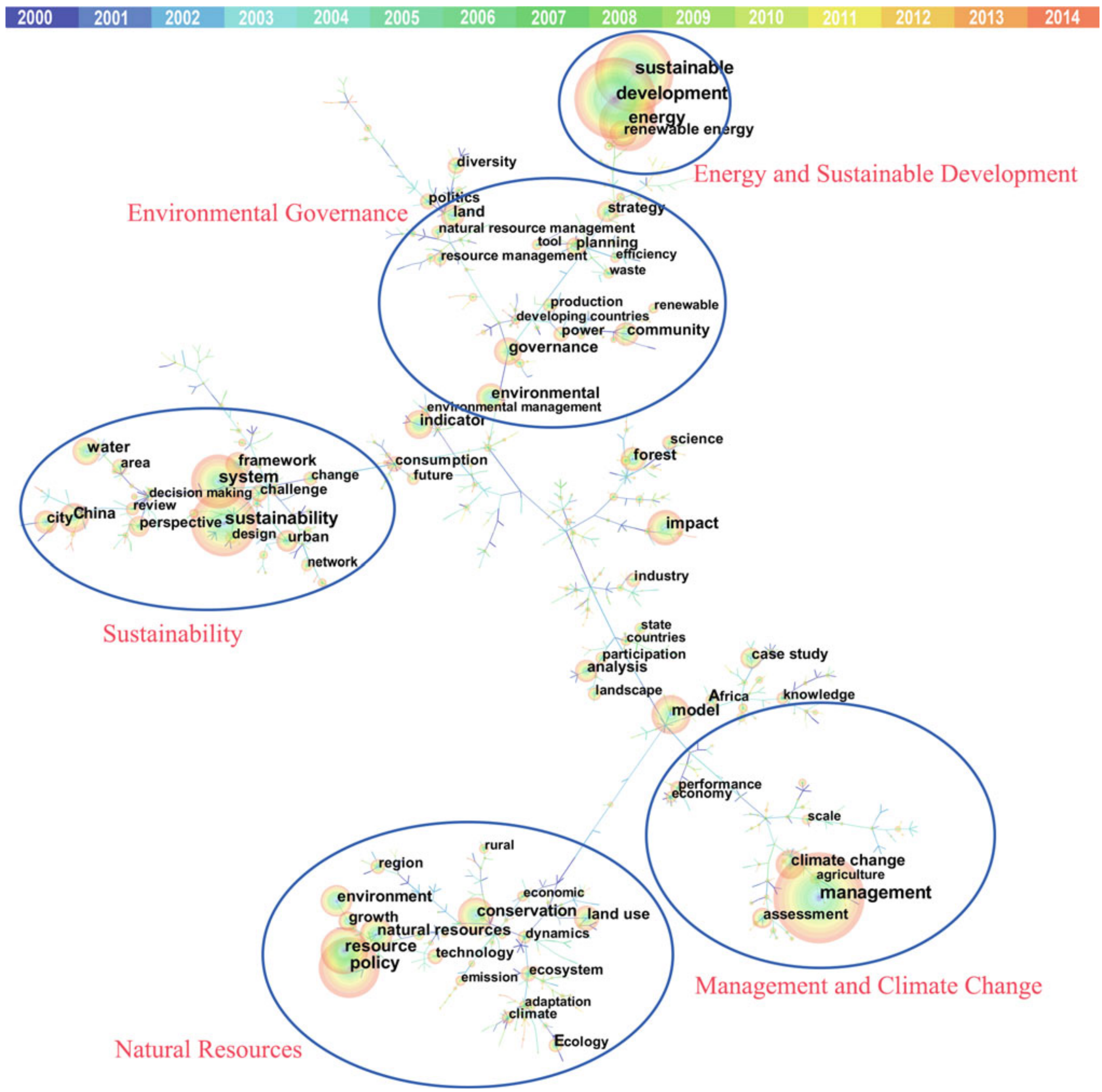

Fig. 13.1 Co-occurrence network of SCI/SSCI-indexed article keywords on "Regional Sustainable Development" during the period 2000–2014

regions face different sustainable development problems. This leads to differences in frequent keywords used by scholars from different countries (Figs. 13.2 and 13.3). Management, energy, natural resources, policies, systems, land, water, sustainability, and impact are the commonly used high-frequency keywords by both Chinese and foreign scholars. Foreign scholars pay more attention to protection, governance, forest, community, strategy and assessment, while Chinese scholars study more about urban, regional, urban, growth, and ecological system. These differences reflect to a certain extent the development stage of China. In addition, there is a strong correlation between the high-frequency keywords used in articles published and the keywords used in the application documents for NSFC projects. The difference is that NSFC-funded projects put more emphasis on ecological carrying capacity, the human-land relationship and decision support systems. In addition, changes in the high-frequency keywords in applications for NSFC projects (Fig. 13.3) show that a concern with human-land relationships, decision support systems, and dynamic mechanism declined, while model, simulation, land, ecological carrying capacity, urbanization,

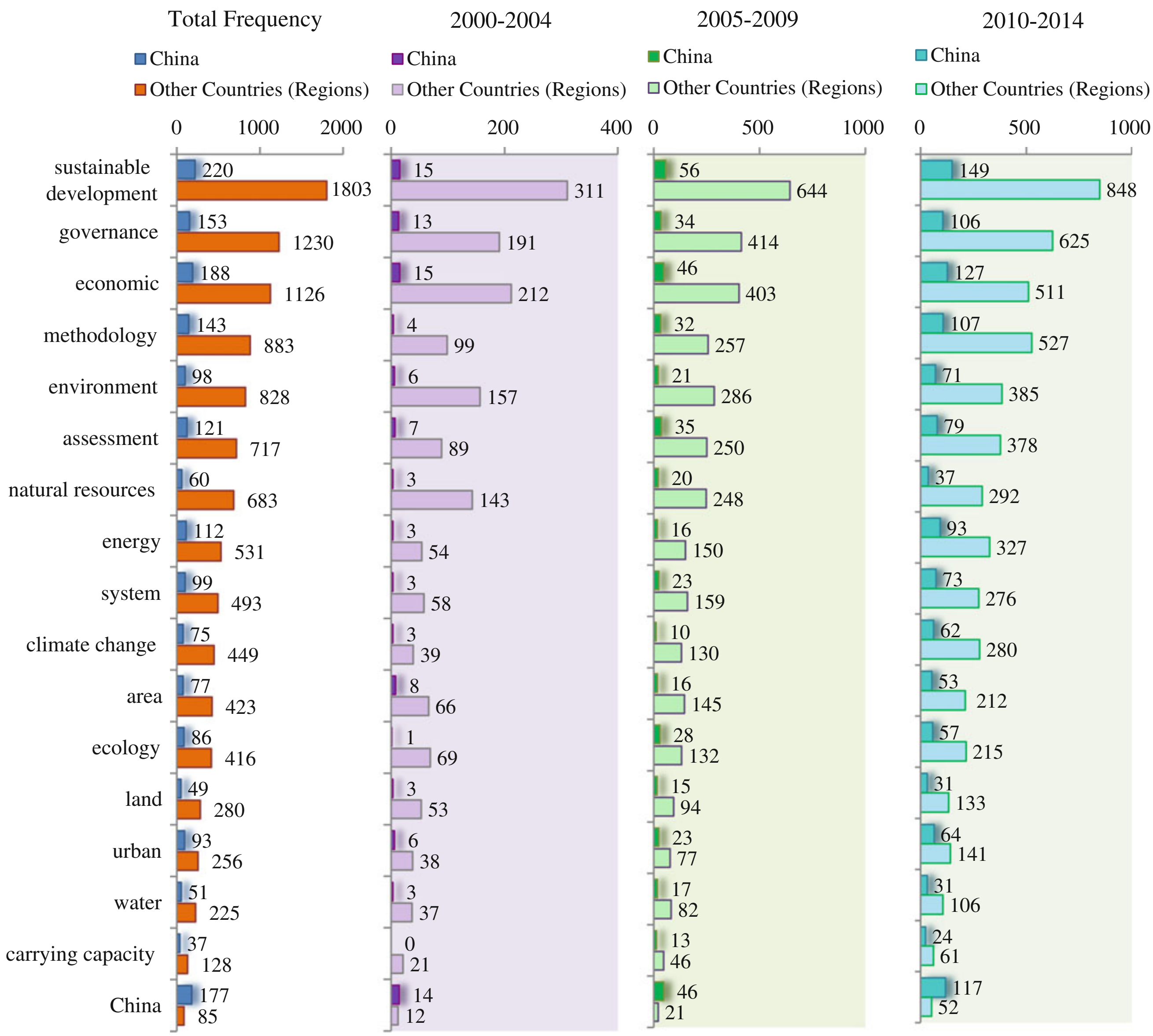

Fig. 13.2 Keyword temporal trajectory graph for SCI/SSCI-indexed articles on "Regional Sustainable Development" during the period 2000–2014

environmental effects, and resource utilization received increasing attention.

13.1.4 The Role of the Geographical Sciences in Regional Sustainable Development

The geographical sciences emphasize integration and regional differences, are relatively strong in syntheses and spatial visualization of knowledge, and play a leading role in regional sustainable development theory and practice (NRC 2010). Of the top 10 articles on regional sustainable development, five articles have a first author majored in human geography (Ph.D.), and other two articles have a first author majored in geography-related disciplines. This indicates that geographers can be leaders in the field of sustainable development research.

The sustainable development of a region is related not only to its ecological environment and natural resources, but also to its economic conditions like industrial structure and technology as well as its social, cultural and political conditions. Therefore, scientists from both the natural and social sciences have been widely engaged in this field of research. Natural scientists study the natural laws of sustainable development while economists and social scientists examine relevant economic and social rules. As a result of increasing subdividing of modern sciences, it is difficult from the perspective of a single discipline to reveal comprehensively and

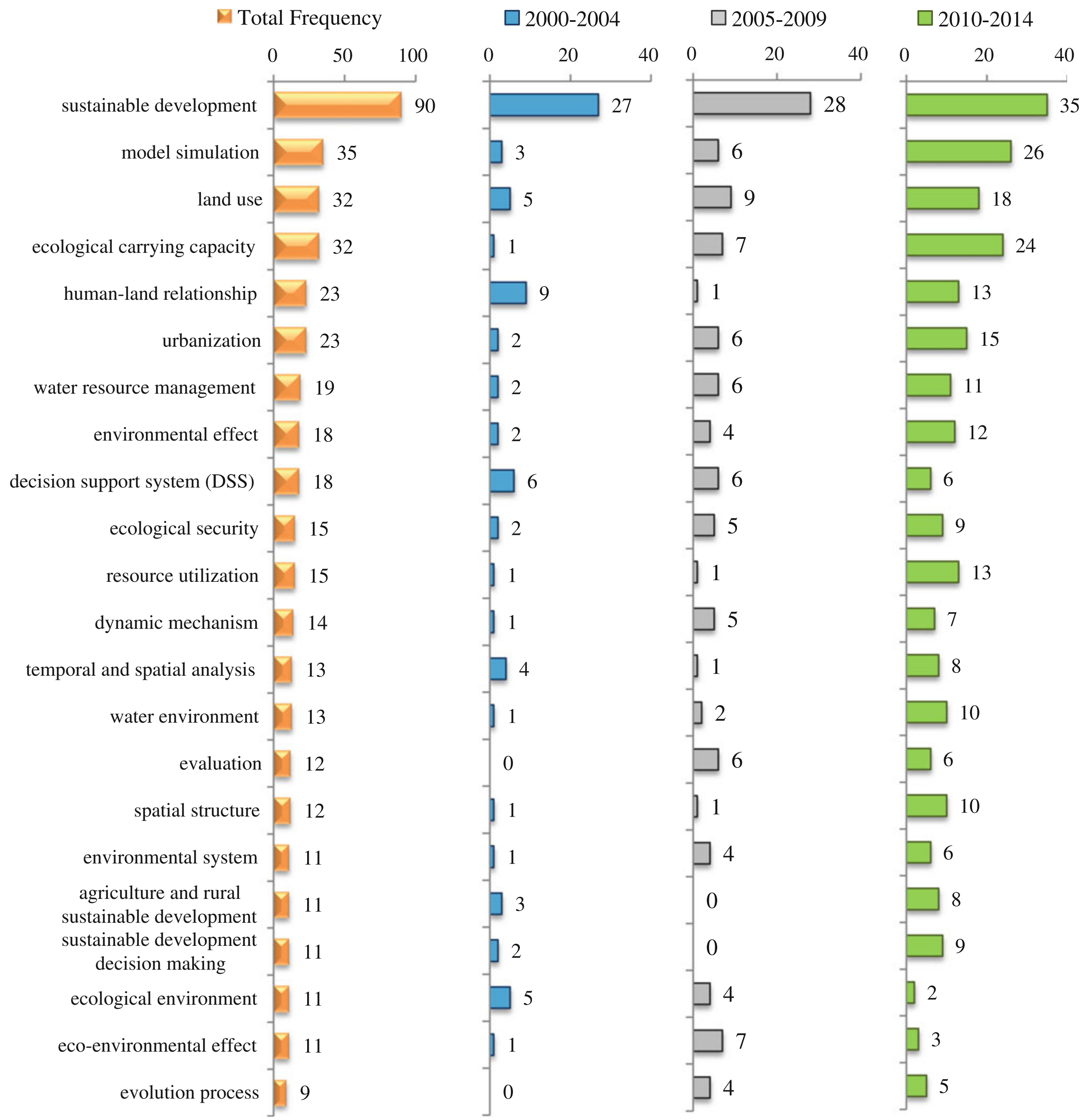

Fig. 13.3 Keyword temporal trajectory graph for NSFC-funded projects on "Regional Sustainable Development" during the period 2000–2014

profoundly the complexity of sustainable development. Therefore, integration thinking is needed when studying regional sustainable development. The geographical sciences, including physical geography and human geography, adhere to the principle that "the whole is greater than the sum of the parts" and emphasize "considering and solving problems from the whole" (Cai et al. 2012).

Geographers borrow concepts from biology such as resilience and adaption to construct a framework to understand the adaptation of territorial systems in increasingly complex environments (Adger 2000). In addition, geographers began a dialogue with economists and political scientists, and employ the concepts of spatial agglomeration (Rosenthal and Strange 2001) and social capital (Pretty and Ward 2001) to deepen understanding of the efficient utilization of natural resources and the operating rules of economic activities. The geographical sciences do not simply apply concepts from other disciplines, but transform them creatively and endow them with spatial connotations. At the same time, they put more emphasis on the interactive relations and temporal and spatial variations in the outcomes of natural laws, economic laws and government actions and conventions (Bulkeley 2005).

In recent years, geographers have paid more attention to the application of new technologies and new methods, especially spatial analysis and visualization techniques (Verburg et al. 2002), input-output models (Liu et al. 2012) and modeling (Yu and Lu 2003). At the same time, regional development databases have been constructed for natural-human coupling process research (Tang et al. 2010). The employment of these techniques has improved the quality of research into sustainable development on the one hand, and has increased the competitiveness of geographical scholars in supporting national strategic decision-making on the other hand.

Many geographical scholars have been actively involved in national and local consultancy with regard to sustainable development and played an important role. Professor Adger Neil, one of the world's top 10 most highly cited authors, is a contributor to the third and fourth IPCC scientific assessments. Professor Bulkeley Harriet has offered advice on the sustainable development of agriculture and the rational use of water resources in the UK. Professor Pretty Jules is an important member of the UK government environment and resources advisory board.

Since the 1990s, geographers in China have tried to continuously develop scientific understanding of national and regional sustainable development (Lu 2003; Fan 2011; Liu et al. 2006), and have provided important technical supports for major national spatial planning projects, e.g., major function-oriented zoning, national territorial planning, Northeast Region revitalization planning, Western Region development, planning for the rise of Central China, planning for resource-exhausted cities, eco-region development planning, and the planning for key regions including the Yangtze River Delta region, Beijing-Tianjin-Hebei, Chengdu-Chongqing region, Tianshan Economic Belt, post-earthquake reconstruction planning, and planning for the Silk Road Economic Belt and the 21st Century Maritime Silk Road.

13.2 Questions and Research Progress

13.2.1 How to Understand the Coupling Relationship Between Man and Nature?

With the rapid development of industrialization, urbanization and globalization, the pressure and impact that human activity exerts on the geographical environment has increased. More and more research focused on the relationship between regional human activity and the geographical environment, especially on the resource and environmental change caused by land use and land cover change, the relationship between population and economic growth and resource and environment, and the human-environment relationship in typical regions.

International Research Progress

Land use/land cover change is one of the important contents of regional environmental change and sustainable development researches, whose main aim is to model and monitor human-land system. In the report "The Emergence of land use change sciences for global environmental change and sustainability", Turner et al. (2007) point out that the dynamics of land use and land cover should be understood as a coupled human–environment system to address theory, concepts, models, and applications relevant to environmental and societal problems. In the past two decades, research progress in land use change has been mainly made in the observation, monitoring, and understanding of the coupled system—causes, impacts, and consequences, modeling, and synthesis issues.

As the major reflection of human-land system, the relationship between population and economic growth and resource environment is studied by numerous scholars. In 1972, Club of Rome studied the stress situation of water and land resource, corn production and mineral resource caused by rapid development of population and industrialization, and put forward the pessimistic conclusion of zero growth. Moreover, some economists probed into the conditions and process of the coordinated development of economy and environment and the interrelationship among factors based on economic growth theory. For example, Solow (1974) and Stiglitz (1974) analyzed the optimized situation and path of resource exploitation. Leontief (1970) applied the input-output model to the correlative research of economic behavior and environment. In 1990s, Grossman and Krueger (1991), Shafik and Bandyopadhyay (1992), and Selden and Song (1994) put forward the "Inverted U Type" curve of economic development and environmental quality, i.e., *Environmental Kuznets Curve* (EKC). Although subsequent researchers have carried out a number of empirical researches to verify the existence of EKC in different conditions with different environmental pollution indices and samples at different temporal scales and drawn different conclusions, the EKC has been a good reference to the harmony between the human-land system. As for the analysis of specific factors, relative researches are focused on the effect of economic growth on energy consumption, and the relationship between economic growth and environmental pollution.

The studies of human-land system in typical regions are mainly concentrated on coastal areas, resource based cities, rural-urban fringe areas, islands and communities, and are mostly concerned about the impact of global climate change on sustainable development in coastal areas and the countermeasures (Prandle 1991; Juhasz 1991), transformation of resource-based cities (Lockie et al. 2009), and rural-urban fringe areas.

In sum, foreign research on human-land relationship was initiated earlier, starting from basic theoretical research to empirical research with the progress of technology and methods, and finally formed several research fields around human-land relationships. A great part of the research was concentrated on regional, systematic and integrative research, the main research topic of which is the impact mechanism of human activity on natural environment. At the same time, more attention has been paid to observational data accumulation in typical regions over long periods of time, analysis of social and economic statistics, and integrative research of multi-factors in order to better reveal the mechanism and process, pattern and regulation of the effect of human activities on the natural environment.

Research Progress in China and Representative Achievements

Geographical and environmental factors and human-land relationship are the major research fields of geography and geographers in China. Huang (1999) pointed out that the relationship between the two major categories (groups) —"human" and "land", is the most important relationship in the terrestrial system. Wu (1991) introduced the system theory into geography, and put forward that the human-land relationship refers to the interaction and feedback effect between human and nature on the earth's surface. The two elements of "human" and "land" are intertwined in a certain way and form an intricate, complicate and opening system with a certain structure and function in a certain territorial area. Therefore, it can be called a "Human-land Territorial System", abbreviated as "human-land system". This system consists of human beings' dependence on nature and the active role of human beings. It is an open, contingent and unstable system (Lu 2002).

The central objectives of human-land system research are to explore the spatial and temporal patterns of the interaction between human activities and the natural resources and environment factors, to analyze and model the differential effect and strength of different factors, to reveal the dominant factors and their relationships with regional development, to find the basic characteristics of the human-land system in different types of regions, and to evaluate and forecast the evolution of the system. The ultimate goal of human-land territorial system research is to achieve regional sustainable development (Zheng and Cheng 2001).

The study of "human-land system" in China was firstly seen at the end of 1980s. It mainly focused on the concept and contents of human-land system, the relationship between system optimization and regional sustainable development, and the dynamics of the system. The research outputs were about 10 papers per year. By 2000, the research outputs of "human-land system" had seen explosive growth. Afterwards, the number of published articles in this topic has gone back to a steady growth while the research field has been diversified. Especially with the integration of natural science and social science, the research on human-land system has been expanded with focuses on sustainable development theory, vulnerability evaluation, coupling mechanism, structure and regulation, and typical regions studies (Fig. 13.4).

The sustainable development of human-land system is mainly discussed through theoretical and typical regional studies (Pan 2000; Fang 2002). The compatible coexistence of human-land system is the theoretical basis for regional sustainable development. Only in a specific human-land system can regional sustainable development be realized. Action and reactions are initiated by human activity and realized by conjugate evolution, and the ultimate result is dynamic balance between the two subsystems (Zhang and Zheng 2000).

Human-land system is a complex system composed of social, economic, resources and environmental factors. The study on the coupling mechanism of human-land system is a study of the interaction of different factors in the system, and the factors affecting this interaction process, which mainly include human needs (Yang 2002), science and technology (Cai 1995), and globalization and urbanization (Luo and Chen 2003), property system (Luo 2007b). In addition, the assessment and evaluation on the coupling state and degree of human-land system are the main contents, which can be done using gray correlation analysis method or the entropy weight gray correlation method, etc. As for the system structure, it is mainly analyzed from the spatial (Fan 2014a), systematic (Li 2008), classification and flowing (Ren and Ren 2006) perspectives.

The study on the vulnerability of human-land system was initially analyzed from the qualitative perspective. It is pointed out that the cause of human-land system vulnerability lied in the initial turbulence as a result of the interaction between natural and social systems, and was enlarged by positive feedback and deviated from the equilibrium state eventually (Cai et al. 2002). The main analysis objects are mainly concentrated in the areas of desertification, mining cities, oil cities and so on. Afterwards, the research method has gradually been quantitative, and the researches have

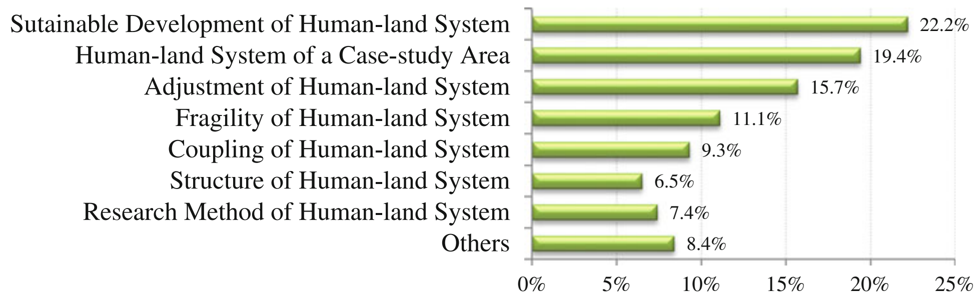

Fig. 13.4 Distribution of the keywords on "Human-land Coupling System Research" in CNKI journals during the period 2000–2014 (*Data source* Based on the result of grouping of "Chinese Keywords" in China Knowledge Resource Integrated Database (CNKI))

mainly been focused on analyzing the main factors leading to fragility of human-land system with the establishing of vulnerability assessment index system.

The typical areas for Chinese human-land system research are mainly concentrated in two types of regions: one is areas with rapid social and economic development and significant effects on the natural environment, such as coastal areas; the other is in areas with fragile natural environments easily influenced by human activities, such as Wei River Basin, Guanzhong Plain, Minqin Basin, mining city, farmland-pastoral ecotones, etc.

An important output of Chinese human-land system research is to provide advisory services to the government. Thus, the optimization control of the human-land system has become the focus of regional sustainable development. The analytical research on the focuses of regulating and controlling mainly concerns response and interaction mechanism (Zhao 2000), fairness (Wang 2010), coordinated development (Yang 2002) and system optimization (Fang 2003) and so on. The objects to be optimized involve population, resources, environment, development and related systems, which mainly focuses on the input and output relationship between the human society subsystem and the natural material subsystem (Cheng 2006).

China's representative achievements in recent years are as follows:

First, exploration on the factors and coupling mechanism of human-land system in the view of impact of industrialization, urbanization and globalization on local land, water and ecological environment (Liu and Jin 2006; Zhang et al. 2004; Luo 2007a). For example, NSFC Key Programme (KP) "The Urbanization Process and Its Ecological Impact of North-West Arid Area Under the Water Resource Restriction", which probes into the mechanism and main driving factors of the coupling process between water resource change and urbanization process (Fang and Yang 2006; Qiao and Fang 2005).

Second, analysis of the process and factors of human-land relationship evolution in a temporal view. For example, land use and land cover change is one of the main topics, which probed into the droving action and mechanism of human economic exploitation and urbanization activity on the scale and structure of land use based on long term data (Li et al. 2006; Yang 2004). Another topic is the study on the relationship between human settlement relocation with natural environmental change, such as Huang's research (2001) on the relationship between the resources degradation of man-natural relation in Weihe River Basin 3100 years before, which found that the climate drought trend and water-soil degradation had facilitated the replacement of the agricultural culture to nomadic culture and led to the great changes in land use patterns.

Third, the quantitative measurement of the coupling relationship between human and nature mainly uses the concept of "vulnerability", "coupling" and others. Many Chinese scholars carried on the coupling degree research between industrialization, urbanization and environmental pollution, such as the Key Programme (KP) of NSFC "Vulnerability and Sustainability of Human-land System of the Mining Cities in Northeast China", which made a quantitative evaluation of the economic development vulnerability of mining cities (Li and Zhang 2008).

Future Research

Compared with foreign studies, domestic research focuses more on the mechanism, process and spatial patterns of human-land system, and is concerned with the difference in different spatial scales and the dynamic optimization model of typical regions. As for research methods, it has made quantitative assessment on the coupling degree of human and nature system, resource and environment carrying capacity and ecological footprint based on social and economic data, combined with the observation data at a long period of time and sequence data of large spatial scale. Therefore, in China, human-land system theory has been widely applied to the cognition and resolution of sustainable development problem in national and regional scale. As for research methods, much emphasis has been placed on data analysis and simulation while little has been placed on theoretical development. In the future, it should strengthen the theory research on the mechanism, process and pattern of human-land system regulation. For research methods, it should pay more attention to the study of integrated technical support system, combination of qualitative and quantitative, scientific and technological methods and the "3S" technology.

13.2.2 How to Delineate the Carrying Capacity of the Resource-Environment System for Human Activities?

International Research Progress

The concept of resource-environment carrying capacity derives from the thought of carrying capacity in early ecology. Recently, it has evolved into a comprehensive concept focusing on the reasonable exploitation of resources, the sound cycles of ecological environment, and the carrying capacity of resource-environment conditions for population size and economy scale. As a scientific concept for reflecting the relationship between resource-environment background and social-economic activities, resource-environment carrying capacity is one of the important scientific themes in current regional sustainable development research. It is significant for regions to cope with changes in resources and environment and achieve sustainable development.

International research on resource-environment carrying capacity originated from the book entitled "Road to Survival" by American scholar Vogt in 1949. He firstly named the over-exploitation of natural resources and environment by human beings as "ecological unbalance", and defined the concept of regional carrying capacity to reflect the population and economic development capacity of regional resources and environment (Vogt 1949). Afterwards, system dynamics models were used for the research on resource-environment carrying capacity. By analyzing the interrelations among the multiple factors in the system, identifying system structure and the correlations among factors, and considering the relationship between population, resources, environment, and development, relationship changes under different development strategies could be simulated, and optimized scheme of regional development under long-term goal could be determined (Sleeser 1990). The article of theoretical discussion by Arrow (1995) in Science aroused tremendous attention to related issues of resource-environment carrying capacity. Since 2000, the international research focusing on resource-environment carrying capacity has rarely appeared. On the one hand, the research on resource-environment carrying capacity is affected and restricted by multiple factors, which cause uncertainty. On the other hand, research focus has started to shift onto environment and energy fields due to the relatively abundant resource reserve in developed countries.

In recent years, there has been little research taking resource-environment carrying capacity as a direct subject in the highly cited articles in the field of sustainable development. Most of them address environment, energy, ecology, or sustainable development issues. From the perspective of hot keywords, carrying capacity has not appeared, while resources, natural resources, environment, land use, energy, sustainability, sustainable development, and related words could be found.

Research Progress in China and Representative Achievements

China's research on resource-environment carrying capacity first originated from land carrying capacity based on the relationship between land, food, and population. The quantitative research could date to the study of productive potential of grain crops in China in 1964 (Zhu 1964). With the introduction of carrying capacity in the 1980s, a large amount of research on land carrying capacity based on food security appeared. In regard to water carrying capacity, the water resources research team of Xinjiang autonomous region of Chinese Academy of Sciences led by academician Yafeng Shi firstly developed the concept of water carrying capacity in 1989 (Shi and Qu 1992). Afterwards, a lot of research on water carrying capacity emerged in China, especially those focusing on the arid areas in northern China. In the late 20th century, the environmental issues attracted more concerns as regional environmental problems arose in China. Since then, China's scholars have started to carry out intensive research on environment carrying capacity, mainly focusing on atmosphere environment, water environment, and soil environment. Besides, ecological capacity has been gradually developed based on the concept of carrying capacity and the understanding of the population-resource-environment-society-economy system (Gao 2001). As a usual descriptive concept of restrictive extent of regional development, the carrying capacity evaluation has been extended to various fields of population, resources, environment, society, and economy. Ocean carrying capacity, lake carrying capacity, tourism resource carrying capacity, and mineral resource carrying capacity have also been studied.

With continuous development of research on resource-environment carrying capacity, more and more scholars have realized the limit and partiality of single factor carrying capacity research in resource or environment fields. It is an important trend to discuss theories and methodology of the integrated research on resource-environment carrying capacity. Since 2000, taking the coordinated development of "nature-economy-society" combined system as the goal, the integrated research on resource-environment carrying capacity has prevailed, of which the research on resource-environment integrated carrying capacity has become a hot topic (Fan 2009, 2010, 2014b).

China's representative achievements in recent years are as follows:

First, the status space method of regional carrying capacity. By summarizing the international and China's research methods of regional carrying capacity, Mao and Yu (2001) and Yu and Mao (2003) put forward the idea that the status space method could be used for measuring regional carrying capacity. The deviation value between real carrying status and theoretical capacity could be used as basis for quantitative measurement of regional carrying capacity. By establishing an evaluation indicator system which included the pressure-bearing, pressure, and interregional exchange categories, the regional carrying capacity in Bohai-Rim area was quantitatively evaluated. With the help of system dynamics models, the changing trends of regional carrying capacity and carrying status were also simulated and predicted. The empirical studies prove that the status space method is an effective method of measuring regional carrying capacity or resource-environment carrying capacity.

Second, evaluation of resource-environment carrying capacity for post-disaster reconstruction planning. Based on China's five emergency disaster relief programs including those for Wenchuan, Yushu, Zhouqu, Lushan, and Ludian, taking geological disasters as major factors, water and land resource conditions, ecological environment, engineering and hydrological geology as important factors, industrial economy, urban development, infrastructure as auxiliary factors, Fan (2009, 2010, 2014b) established an indicator system of basic evaluation, carried out single factor and integrated evaluation, revealed spatial differences of resource-environment carrying capacity for post-disaster reconstruction, and identified the boundary and scope of areas with different carrying capacity from 3 aspects including geological conditions and hazard risks, physical geographic conditions, and population and economic base. Besides, by analyzing the influence mechanism of water and land resources conditions, regional economic development level, and urbanization level on carrying population, the simulation method of measuring population capacity was established, and the reasonable population size in the earthquake stricken area was calculated. The research on resource-environment carrying capacity effectively guided the reconstruction work after disasters, proving that it has significant practical value.

Third, research on ecological footprint and ecological capacity. The methodology of ecological footprint was introduced into China in the early 21st century based on which some empirical research were conducted. For instance, taking Gansu province and 12 provincial administrative regions in western China as case study areas, Xu et al. (2000) and Zhang et al. (2001) conducted an empirical research on the calculation of ecological footprint. Using high-resolution remote sensing data of land-use and land-cover change, Yue et al. (2009, 2011) calculated the ecological footprint and ecological capacity in the five provinces in northwestern China. In addition to the three common indicators including ecological footprint per capita, biological capacity per capita, and ecological surplus/deficit per capita, three new indicators e.g., biological capacity per unit area, ecological footprint per unit GDP, and biological capacity pressure index were also adopted.

Fourth, research on land carrying capacity. It is a typical way of geographic research to clarify the spatial differences of capacity in different regions from the perspective of land resources and provide suggestions accordingly. Using Agro-Ecological Zone (AEZ) model and Geographic Information System (GIS) technology, Feng et al. (2007, 2008) calculated grain productive potential at a 1 km × 1 km grid and county levels in China. By classifying the resource endowment of grain productivity, the resources potential of grain yield in China's different regions was revealed. Based on the man-grain relationship, the model of land resources carrying index was established, and the spatial-temporal dynamic patterns of land carrying capacity from 1949 to 2005 in China were quantitatively evaluated at country, province, and county levels. Also, the land carrying capacity of pasturing areas, urban areas, and poverty-stricken counties were discussed.

Future Research

With the gradual extension of its content, the concept of carrying capacity has naturally extended from ecology to other disciplines. The decisive variables of carrying capacity include not only natural resources and environment basis, but also social-economic factors, such as social-economic development level, social consumption mode, technology development status, social institution arrangement, and social value system. The carrying objects include not only the quantity of population or the economic volume, but also the content of economic activities. Therefore, completing and developing the concept and content of resource-environment carrying capacity has become urgent work to do. At present, China's research on resource-environment carrying capacity is mainly based on single factors and static and closed systems, and the standards and criteria of evaluation methods are still to be established. In the future, the quantitative research on resource-environment carrying capacity which integrates multiple factors should be determined as development direction, and a scientific and reasonable evaluation indicator system is to be explored. We need to conduct indicator evaluation on subsystems including economic system, ecological-environmental system, resources system, sustainable development system, and analyze the interactive relationship among the factors of resource-environment carrying capacity. In this way, a set of operable and consistent evaluation methods and models of resource-environment carrying capacity will be formed.

13.2.3 How to Evaluate the Status of Regional Sustainable Development

International Research Progress

Sustainable development strategy is a common objective for the development of human beings, and the assessment of the state and capability of regional sustainable development is the means to make such target explicit. In other words, once an index system and research methods are established, we can identify whether the development of a region is sustainable or not, what the degree of sustainable development is, and how to strengthen the capacity of sustainable development. And a judgment on whether the development mode of the region has facilitated its realization of sustainable development strategy can be made. In brief, such assessment is the essential tool and the significant premise for the implementation, evaluation and establishment of a sustainable development strategy. Thus, selecting reasonable index system is of great significance for the understanding of the sustainability of human-land relationships (Mccool and Stankey 2004). Decision makers can make such judgments as which behaviors are beneficial for building a sustainable society from both global and local, natural and social, short-term and long-term perspectives (Ness et al. 2007). In this way, sustainable development is no longer a concept (Robinson 2004).

First, research on the evaluation index system of sustainable development is deepening. The assessment should contain multi-dimensional objectives. It not only refers to the sustainability of the environment, biodiversity, protection of natural resources, and pollution etc. but also includes economic and social aspects, such as economic efficiency, social fairness, rural-urban integration, and regional equalization (CSD 2006; Moldan et al. 2012). According to different emphases, the index system can be mainly divided into three types: the first one is environment-oriented, like environmental pressure index (European Commission and Eurostat 1999), environmental performance index (World Economic Forum 2002), the environmental-friendly index (Statistics Finland 2003), and ecological index (Pré Consultants 2001); the second one is economy-oriented, like sustainable economic welfare index (Daly and Cobb 1989); the third one is society-oriented, which mainly includes human development index (UNDP 1990), happiness index system (Prescott-Allen 2001), and so on. Based on a comprehensive research, UNCSD put forward the index of sustainable development, which included foundational well-being and economic well-being, identifying its present situation and change (Stock and Flow). Specifically, life expectancy, education level, clean water, residence and 28 other indicators are covered (UNCSD 2008).

Second, new approaches to evaluate sustainable development are emerging. Wackernagel et al. (2002) published a paper on PNAS about evaluating the capability of sustainable development based on ecological footprint, which tried to measure the ability for humans to meet their demands, like food. The results showed that the demands had exceeded the regeneration ability of the earth itself. To be more specific, the human ecological footprint of the total global biosphere ecological bearing capacity increased from 70 % in 1961 to 120 % in 1999. In addition, there are many newly-emerging methods, like energy analysis, lifecycle assessment, energy analysis, DPSIR analysis framework, and energy analysis and so on.

Third, the capacity of dynamic monitoring of sustainable development status has been enhanced. Since the 1980s, with the development of 3S techniques, i.e. remote sensing, geographical information systems, and global position system, the dynamic monitoring platform has been established gradually in the world. Researches on "digital earth" and "digital city" are also in full swing in many countries and regions of the world.

Topics of international research on the evaluation of regional sustainable development include sustainable development, sustainability, assessment methodology, evaluation model, the human development index, sustainable economic welfare index, green net GNP, performance of sustainability, ecological sustainability index, ecological footprint, energy analysis, energy sustainability, comprehensive index of sustainable development, sustainable asset management, sustainable development enterprises, product lifecycle, urban sustainability, environmental quality, environmental sustainability and vulnerability, cleaner production technologies, happiness index, the performance of national health system, sustainable society and sustainable communities, and so on.

Research Progress in China and Representative Achievements

In recent decades, research on the state and capability of regional sustainable development in China has made great progress, one of which is fundamental research on the formation process, structure and theories of the human-land territorial system, new factors and patterns of regional sustainable development, the concept and mode of circular economy, and the coordinated development among population, resources, environment and economy. Moreover, current researches focus on the construction of the evaluation index systems of the sustainable development capability. They can be divided into the sustainable development index systems of states, provinces, regions, cities and certain themes according to their research scales and objects. The third progress is in the model and methods for evaluation of the capability of sustainable development. Quantification is the major method of evaluation research. Commonly used methods are: Entropy Method, Delphi Method, Data Envelope Method, Analytic Hierarchy Process, Fuzzy Mathematics and Neural Network Method, etc. In recent years, ecological footprint, energy analysis, system dynamics, and recycling economy have become new approaches of evaluation research. The representative achievements are as follows:

First, evaluation of regional sustainable development state. Researches in this sub-field started relatively early and have yielded fruitful achievements. Mao (1996) applied multi-index comprehensive analysis method, and established an index system concerning four aspects, i.e. economic growth, social progress, resources and environment support, and the sustainable ability, to evaluate the sustainable development state of Shandong Province. The weights of these indicators, a total of ninety, were determined by analytic hierarchy process. The Research Group on Sustainable Development of the Chinese Academy of Sciences (1999) also put forward a set of comprehensive evaluation index systems of sustainable development. The systems were divided into five grades with 45 indexes and 208 specific indicators. Later on, according to the requirements of ecological civilization, the index systems were revised. Moreover, comprehensive evaluation of sustainable development in regions has been carried out in China (Sustainable Development Strategy Research Group 2014).

Second, evaluation on regional sustainable development capacity. Quantitative evaluation is conducted on regional sustainable development capacity based on multidisciplinary analyses, like ecological footprint, energy synthesis, and scenario prediction based on system dynamics model. Based on the method of ecological footprint, Qin and Xu (1998) analyzed the spatial structure and dynamic changes of Henan input-output potential. Geng et al. (2013) published an article in *Science*, presenting a new method to discuss the feasibility of evaluating the performance of China's circular economy based on the method of energy analysis. As for the method of system dynamics model, taken Huangling County, Shaanxi Province as an example, Cheng et al. (2004) established three economic growth scenarios, i.e. natural growth, high-speed growth and moderate-speed growth. Predictions of the growth state of indicators like economy, population, water consumption and three wastes emission in 2050 were made under different scenarios, which have provided decision-making support for the selection of regional sustainable development modes.

Future Research

Taking regions as research objects, the evaluation of the capability and state of regional sustainable development involves natural elements like water and soil, and human elements like population, economy, and their interaction and relationship, showing that geography is a comprehensive discipline. Another trend is the combination of natural science and social science which embodies the interdisciplinary characteristics of geography. Researches on the evaluation of the capability and state of regional sustainable development in China have three characteristics: First of all, it has strong practicality. In order to meet the real needs for the sustainable development, geography is of great significance and value; secondly, the priority is given to innovation. Main methods of evaluation are derived from foreign theories, and researches fully oriented to China's own conditions still lack originality and innovativeness; thirdly, it is highly connected with natural science. Due to the research funding system in China, the role of human factors in sustainable development has still not received sufficient attention. An emphasis on human factors is a feature of international research.

13.2.4 How to Utilize Natural Resources in a Sustainable Way?

International Research Progress

Natural resources are not only the material basis for maintaining human existence, activities and development, but also the support conditions for balanced operation of regional spatial structures. The sustainable exploitation and utilization of natural resources are crucial components of sustainable development strategies. To fully, reasonably, economically and efficiently utilize the existing resources and in the meantime develop new substitute resources constantly is a new value for human beings to exploit and utilize resources, which can ensure the consistent and sustainable utilization of natural resources for human beings, and meet the needs of the development of both contemporary and future generations.

Scholars from different countries have been paying high attention to researches on sustainable use of natural resources, including rational exploitation, conservation and management of conventional resources, such as water, land, organism and energy, as well as the exploitation and use of clean resources (Hepbasli 2008). The scope of researches involves several topics, e.g., approaches of sustainable use of different natural resources, assessment of resource use efficiency etc. Due to the growing shortage of global water resources, multi-objective optimization research on multiple-use of water resources is increasingly valued. Safavi et al. (2010) developed principles and methodology of multi-objective and multi-stage optimal management on multiple uses of surface water and groundwater. A trained artificial neural network model was developed as a simulator of surface water and groundwater interaction while a genetic algorithm was developed as the optimization model. In recent years, against the background of global change, numerous researches about the impacts of global climate change on sustainable use of resources have been conducted, including how climate change affects water and biotic resources, how to address climate change by reducing greenhouse gases emission with reasonable energy production and use (Bilgen et al. 2008) and how land use and land cover changes feed back to climate system. Meanwhile, international academic community highly emphasizes the importance of social study and management on sustainable natural resources use, and considers that sustainable management should be transformed into sustainable governance (Plummer and Fitzgibbon 2004).

Research Progress in China and Representative Achievements

In recent years, research progresses in the sustainable use of resources in China include management of sustainable water resources use and construction of water-saving society, intensive and efficient use together with optimal allocation of land resources, approaches and efficiency assessments for sustainable use of energy, global environment changes and sustainable use of resources, etc. For instance, the dualistic natural-social water cycle theory (Wang et al. 2007, 2013) dialectically identified the relationship between development of human socioeconomic system and sustainable development of the ecological environmental system, which could provide a scientific basis for coordinating human society water use and ecological water use as well as a theoretical basis for rational exploitation and use of water resources. Process model of intensive agricultural land use based on material flow analysis (MFA), and sustainable land use patterns with input reduction and low environmental risk are able to provide scientific basis for improving environmental quality of high-intensive farming areas and sustainable development of agriculture and rural areas (Yin et al. 2015). China's representative achievements in recent years are as follows:

First, sustainable water resources use and management and water-saving society. In recent years, Chinese scholars have made significant progress in several aspects including theories of dualistic water cycle system, high efficiency water use, water resources management, etc. (1) The theoretical framework of compound water cycle system with nature-artificial dualistic driving force and structure was proposed. It holds that watershed water cycle has nature-social dualistic evolution effect under the influences of human activities, which presents an explicit "nature-social" dualistic feature (Wang et al. 2007, 2013; Qin et al. 2014). (2) Based on integrated research of watershed ecology, hydrology, and economy, agricultural water-saving technologies were developed and integrated. And integrated management schemes to improve benefits of basin water under the changing environment were proposed, including hydrology-ecology basic researches, engineering and biological water-saving technologies, and development of watershed integrated management (Cheng et al. 2008). (3) Virtual water strategy was redefined by employing extended analytical framework. The core of virtual water strategy is to select an approach route to develop the secondary and tertiary industries that leads water resources flow to industry and service sectors by dint of positive feedback ring (Xu et al. 2013). (4) According to the features of watershed in arid region, a quantification framework for the sustainable management of water resources was proposed. This framework highlights quantitative criteria, index systems, fundamental models and quantitative methods (Zuo et al. 2006).

Second, intensive and efficient use and optimal allocation of land resources. The major contributions include efficiency assessments of land use in Chinese cities, process simulations of intensive land use in rural areas and optimal allocation of land resources. For instance, based on data envelope analysis of the input-output and scalable efficiency of land use in 655 cities across China, Wu et al. (2011) reported that the input-output efficiency of urban land use in China is low by and large and ascends by the level of city scales, high in Eastern China and low in Central and Western China. In addition, Song and Liu (2010) used the theories and technology of ecological construction and urban-rural areas integration to analyze coupling mechanism of suburban areas from multiple dimensions. Moreover, they took Beijing as an example to find out the main contents and methods of modern suburban agricultural program on environmental construction.

Third, is energy sustainable utilization mode and efficiency assessment. (1) According to the theory and method of life cycle assessment, a model of cleaner production was built for enterprises to achieve sustainable development. From the aspects of scoping definition, inventory analysis, data processing, program determining and program implementation, the model was used for determining the objects of developing cleaner production audit in enterprises, analyzing material and energy losses of the audit object, discussing the causes of pollutants generation and discharge, thus the foundation was built for seeking opportunities to develop cleaner production and implement programs (Cao and Jin 2010). (2) According to the basic demand of economic and social development, as well as the core conception of energy sustainable development, an evaluation index system of China's energy sustainable development was designed. Based on this index system, the 2000–2010 sustainable development level of energy in China, and the energy scenarios in 2020 were quantitatively evaluated (Miao et al. 2012). (3) Research on spatial patterns and heterogeneous characters of sustainable energy development constructed a framework of sustainable energy development zoning of China, especially at the national and regional scales (Shen and Liu 2011). (4) Researches on how to cope with the impacts of global climate changes on energy have been conducted. Wang et al. (2014) reported that new factors including distribution and competition of international carbon emission, competition of low carbon technology and new energy technology, low carbon finance and carbon market system, and carbon tariff and low carbon trade barrier are significantly affecting current patterns of geopolitics.

Future Research

Compared with international researches on sustainable energy use, researches made by Chinese scholars are mainly focused on formations, variations and spatial patterns of energy, and impacts of human activities on natural resources, such as water cycle in natural-social system, changes and drivers of land resources, etc. Considerable researches on approaches, patterns and management of sustainable use of resources have been conducted, but current researches still focus on qualitative analysis while little attention has been given to quantitative researches, especially to researches on integrated analytical models, resulting in a huge gap between international leading researches and Chinese researches. Moreover, there is a shortage of researches on fundamental theory and technical methods. It is beneficial for Chinese scholars to use international researches which investigate sustainable energy use from the viewpoint of sociology, management science and economics for reference. Furthermore, how to guide policy makers to effectively strengthen the sustainable exploitation and use of resources through scientific research is still an urgent issue which needs to be solved by Chinese scholars at present.

13.2.5 How to Achieve Sustainable Development Through Regional Governance?

International Research Progress

Regional governance is the important foundation of achieving sustainable development. There have been a lot of studies on regional sustainable development since 1987 when the concept of sustainable development was put forward. However, regional governance was not a popular concept in regional sustainable development research until the last decade. From 2000 to 2013, the frequency of the word "policy" in literature increased from 56 to 188 ranking second among all of the hot words in sustainable development research domain. The frequency of the word "planning" in literature increased from 42 in the year of 2000 to 134 in 2014 and ranked 11th in terms of total frequency. After 2005, the frequency of "governance" in literature has been increasing very quickly. In 2005, the word only appeared 4 times, whereas in 2013, the frequency of it increased to 36 times and ranked 38th.

Regional governance research in the world can be consolidated into two core meanings: one is theoretical/analytical and the other more empirical. At present, the vast majority of contributions are empirical ('governance as an empirical phenomenon') studies. Few attempts have been made to produce a dedicated theory of sustainable development governance (Jordan 2008), and the integrated theoretical system has yet to be established. In European countries, regional governance in practice has a relatively long history. The most representative works are the spatial planning of Germany, the spatial planning of Dutch, and the regional planning of French. In recent years, the European Union has carried out a large number of practices on cross-region environmental management and constructed a series of new concepts on regional governance. At the same time, the focuses of regional governance have been shifted. On the one hand, environmental governance has become a more and more important content of spatial planning (Bulkeley 2005; Opdam et al. 2006; Adger et al. 2003); on the other hand, urban region or network society has turned into an important object or unit in regional planning and regional governance studies (Deas and Ward 2000). Along with the rapid development of computer technology, GIS has been utilized more and more broadly in spatial planning, especially in simulation of urban space evolution (McCall 2003; Barredo et al. 2003).

Jordan (2008) conducted an in-depth analysis of the meanings of sustainable development and governance. He argues that sustainable development is a political concept to replace governance, and the UN's Agenda 21 is a flexible international law to carry out sustainable development by means of governance. He thinks that governance includes not only governmental system but also non-governmental institution. Governance cannot be restricted in a specific period of time or a specific geographic area. It should be applied to totally different geographic scales, such as global system, state, and region, etc. or cross different spatial scales and generate a hierarchical governance.

Bulkeley (2005) configured a new spatial grammar of environmental governance, i.e. to construct a geographic space of "scale" and "networks", to coordinate relationship between vertical connection in scales and horizontal relation in networks, and to shape a new geographic space for environmental governance. This new geographic space has transcended the ranking of traditional space governance. The "scale" and "network" of space are not opposite to each other, but become a part of each other. This kind of space classification can not only re-build the administration area of a country by networks but also generate a new network space, which is a new space organization form for environmental governance.

Research Progress in China and Representative Achievements

The early regional planning in China emphasized particularly on industry, town distribution, and economic benefit. After the reform and opening up, great importance has been attached to natural resources and ecological benefit in national territory planning and town system planning (Hu 2006). In recent years, the territory space planning, major function-oriented zoning, and urban agglomeration planning have become the hot issues in regional governance (or regional planning) in China.

Compared with international study focus, the total frequency of "policy" ranked 6th in all Chinese literature on sustainable development, and its annual frequency increased from 4 times in 2000 to 34 times in 2014, which is close to the international hot word rank. Although the frequency of the word "planning" ranks relatively low (27th) compared with its international rank, it has grown very quickly and its annual frequency increased from once in 2000 to 19 times in 2014. However, the literature on "governance" is very limited. The total frequency of the word ranked 227th in all Chinese literatures of sustainable development, and its annual frequency is only about two and even zero in some years.

At present, there exist some differences between the projects supported by NSFC and international hot issues. In published papers supported by NSFC, the total frequency of the hot word "policy" ranked 15th, while "planning" ranked 53rd increasing from once in 2008 to 9 times in 2014. The total frequency of "governance" was only two and ranked 210th. However, among the highly cited articles on regional governance (regional planning), almost half of them are funded by NSFC.

China's representative achievements in recent years are as follows:

First, the methodology of territory space planning. Territory space planning is a comprehensive and strategic planning at national or local level, which includes regional planning, space planning, and territory planning etc. (Lu et al. 2011). Although physical geographic background controls the macro frame of territory development, economic globalization is one of the important factors in shaping China's regional development pattern (Lu et al. 2011). Therefore, strengthening regional competitiveness by constructing "urban regions" should be the focus of space planning in many regions (Liu and Lu 2005). Besides, the distribution and the urban and rural population by region and their spatial-temporal changing trends must be considered in territory space planning due to the rapid progress of urbanization (Lu et al. 2011). Determining development axes, gateway cities, and regional space areas are the major steps of regional space planning, in which analysis of inter-city space relations and mathematic modeling analysis are the key methods for defining urban space (Liu and Lu 2005).

Second, methodology on major function-oriented zoning. Major function-oriented zoning is the guideline for optimizing the spatial pattern of regional development in China (Fan 2007: 339–350). To clearly define the basic category of territorial function and put forward the goal orientation of each major function zone are essential conditions for identifying territory function and expressing it scientifically. At present, the index system for major function-oriented zoning at national level and provincial level is composed of regional resources and environmental carrying capacity, current development intensity and future development potential. The dominant factor evaluation and comprehensive index evaluation methods are used for zoning. The space overlay analysis and clustering analysis by GIS are also used in zoning based on the classifications of ecological restriction and regional social economic development potential (Zhu et al. 2007). Fan (2007) holds that the difficulty of comprehensive geographic research still lies in the integrated methodology of major function-oriented zoning. The major function oriented zone cannot satisfy the basic requirement of rational spatial organization structure. The reason is that although it is the key presentation method for "area" geographical entities, it lacks presentation of the "line" set such as axis and corridor. Therefore, major function-oriented zoning cannot solve all problems of rational organization of spatial structure, and cannot substitute for spatial planning at the same level.

Third, eco-city construction. The metropolitan area, which consists of central city and periphery towns in terms of its spatial area and impact area, becomes a new spatial unit for contemporary urban development (Cui 2001). Eco-city is a social-economic-natural harmonization development system according with the ecological principle (Wu et al. 2005). It is one of the main countermeasures to climate change. The eco-city theory is one of the important bases for urban planning. Actually, the main objective of eco-city construction is to achieve sustainable development. Therefore, the index system for evaluating the effect of eco-city development can be included in a sustainable development index system. The index system of eco-city consists of social, economic and natural subsystems, and the assessment of eco-city's integrated development ability is based on the status, dynamics, and strength of these three subsystems(Wu et al. 2005). Apart from the integrated weighting method, the entire-array-polygon method is also used for systematic and scientific multi-objective evaluation for eco-cities.

Future Research

The cross-administration regions (urban agglomerations, metropolis, and great regions) based on "hierarchy" and "network" will become the main spatial units for regional governance. Although major function-oriented zoning has been widely used by China's national government, the theory and methods need further study. Eco-city, being a new urban development mode, will be an important measure for regional governance in the future. New regional governance mode must be employed; the relationship between sustainable development and regional governance needs to be studied, and the consequence of the intervention of "governance" on regional sustainable development must be discussed. Although some practices on regional governance have been carried out in China, e.g., territory planning, major function-oriented zoning, urban agglomeration planning, etc., compared with foreign academia, there still remains a large gap in the construction of new governance ideas and theoretical system, especially in the research on relationship between regional governance and regional sustainable development.

13.3 Roadmap for Further Research

Regional sustainable development is not an area of enquiry that has a clear boundary and fixed objects of analysis, but an area that focuses on specific problems encountered by societies as they develop. Since sustainable development involves various factors, the study of regional sustainable development is an almost all-embracing topic. Its mission is not only to reveal scientific rules of the interactions between human being and nature, but also to promote actions and the practice of sustainable development. At present, the truth is that the outputs of many studies remain silent on library shelves and cannot be turned into policies and actions. As such, the Future Earth program jointly proposed by the International Council for Science and International Social Science Council calls for multi-disciplinary studies to support decision-making relating to environmental management of our earth. In addition to a more dynamic cognition of man-land relationships and developing theories, methods and technologies to achieve such cognition, this area of study needs to make further progress in the following three aspects to enhance its role as a field of science and as a contributor to society.

(1) Undertaking Multi-disciplinary Integrated Research Towards Guiding Sustainable Development Practice

Geography has a long history of advocacy of comprehensive research, but this type of research has figured less and less prominently in the last few decades as a result of the continuous sub-division of the disciplines and self-consciousness of scholars as belonging to different disciplines. Only if research is organized to address specific problems, and managed not to follow closely existing research traditions in which different disciplines have particular strengths, can the study of regional sustainable development provide useful knowledge for social practice. Such problems can be common problems faced by many regions like climate change, but can also be local problems like economic recession or local pollution.

(2) Understanding the Critical Role of Governance Structure in Regional Sustainable Development

Scholars have indicated that sustainable development is an area that raises many governance issues. Governance structures decide how resources are allocated in a country or region, and hence play a major role in solving sustainable development problems. After the 2008 global financial crisis, neoliberal governance has been widely queried. How to make the market, the state and society play appropriate roles in governance for sustainable development is not only affected by prevalent theories and ideology, but also based on historical, cultural and natural conditions. Therefore, comparative national and regional research on governance structures is a critical topic in the field of regional sustainable development research.

(3) **Enhancing Recognition of Interactions Among Different Scales**

Most sustainable development problems involve issues that arise at different spatial scales, from the global to the national, the regional and the local. Sustainable development at a regional level is affected by global environmental and economic change, such as global warming and world-wide economic crisis. It is also affected by local resources, and by environmental, social and economic problems like pollution and poverty, which are in part related to development stages. Thus, regions need to strive for local sustainable development and must at the same time assume responsibilities for global sustainable development. No regional "fix" is possible without a deep understanding of the interactions among different things happening at different geographical scales.

13.4 Summary

Sustainable development embraces a wide range of research themes, and involves many disciplines in both the natural and social sciences. In this area, geographers have particular skills in research at regional and local levels and have made important contributions to studies at these spatial scales, although they are also involved in studies of global environmental change. This review reveals that scholars in western countries are particularly concerned with the dynamic drivers of regional sustainable development, and in particular with governance mechanisms. As for the objects of research, in the early days, western scholars undertook a lot of research dealing with natural resources and their management, especially resource conservation and bio-diversity. More recently, they have focused more on global issues, perhaps because western countries had started to resolve some local environmental problems soon after the notion of sustainable development was coined. Besides, many western scholars have asked whether neoliberal reform or environmental policy was the most important driver of policy outcomes. As well as the global level western scholars also pay attention to the local level in part due to changes in governance which have seen responsibilities (but not necessarily resources) moved downwards releasing central government from responsibility for handling some intractable issues. On the contrary, Chinese scholars tend to examine the meaning of sustainable development and to study practical issues that are closely related to policy making. They also focus studies at national and regional levels since the goverments at these two levels play a more important role in governance related to sustainable development. Chinese scholars should undertake more studies of theories and dynamics of regional sustainable development while maintain their advantages in serving the demands of the state. In addition, they need to pay more attention to the role of social, cultural and economic factors, and to undertake more integrated studies.

In general, the study of regional sustainable development in China has made a great progress in the last three decades. Since 2010, China has ranked first in the world in terms of both the number of articles published in SCI/SSCI indexed journals and the number of citations, while a gap exists in the number of top 50 most highly cited articles at present. This situation indicates that, in the field of regional sustainable development, China is still far from being a leading country. To further increase the degree of international influence of Chinese research in this study area, NSFC should give more support to integrated studies that address major regional sustainable development problems while maintaining the strengths of sponsoring free-application projects. In addition, NSFC should encourage collaboration with top research universities and top scholars in the world.

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Remote Sensing Modelling and Parameter Inversion

14

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Abstract

This chapter analyses the development of remote sensing modelling and inversion during the last 15 years, and evaluated the international impact of China based on the literatures. Then role of geography science in improving remote sensing modeling and inversion is introduced. The development of modeling and inversion of key parameters in land carbon cycle, hydrologic cycle, and energy balance as well as the contribution from Chinese scientists is elaborated in detail. Finally, the future trend of Chinese remote sensing modeling and inversion is discussed.

Keywords

Remote sensing modelling • Inversion • Validation • Data assimilation • Earth surface parameters

A total of 2705 SCI/SSCI-indexed articles are analyzed in the research area of remote sensing modelling and parameter inversion. Articles are identified from 18 international journals from 2000 to 2014. The number of journals that have published more than 15 of the relevant articles is 13 (Appendix K). The search query is as follows: ("albedo" OR "leaf area index" OR "gross primary productivity" OR "land surface temperature" OR "soil moisture" OR "thawing soil" OR "evapotranspiration") AND ("model" OR "retrieval" OR "calibration" OR "validation").

14.1 Overview

14.1.1 Development of Research Questions

The development of remote sensing technology depends on application requirements and progress with satellite technology. Due to environment problems and climate changes, people are paying more attention to the water resources, land use and biodiversity of the earth surface system. This requires observation data connected with the energy balance, water cycle and carbon cycle in global and continental scales, thus posing a challenge to remote sensing science, especially remote sensing modelling and parameter inversion.

In 1991, the National Aeronautics and Space Administration (NASA) of the USA launched the Earth Observing System (EOS) to conduct comprehensive scientific investigations to the land, ocean, atmosphere and their correlations. Before the launch of these satellites, research on the remote sensing of different parameters related to land, ocean and atmosphere had been carried out. The launch of satellites such as Terra, Aqua and Aura has greatly improved the observational capability of the Earth-atmosphere system, indicating that remote sensing has entered a new phase. Moreover, NASA's free opening of its retrieved parameter products has greatly promoted the applications of earth remote sensing in geographical science.

In response to the urgent demand for observing the earth system, as proposed by the World Summit on Sustainable Development held in Johannesburg, South Africa in 2002, the major developed countries and developing countries established a comprehensive, coordinated and sustainable Global Earth Observation System of Systems (GEOSS). Through quantitative observation of the Earth, it promotes scientific research for better understanding of the complex processes of the earth surface system.

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14.1.2 Contributions by Scholars from Different Countries

This section analyzes the number of academic articles on remote sensing modelling and parameter inversion, published in English journals during 2000–2014, and their citations (see Table 14.1).

Statistical analysis suggests that the vast majority of articles have been published by scholars from the USA, China and Western Europe. Specifically, China has made significant progress in three aspects of remote sensing research (Table 14.1) with 107 articles published. In terms of the number of citations of all articles, China ranked second during the period 2010–2014. However, if use the number of highly cited papers as an indicator of research impact, the gap between China and the leading countries was wide during the periods 2000–2004 and 2005–2009, and the gap was smaller during the period 2010–2014, when China ranked second in the world with 8 highly cited articles. China's contribution in this field has shown a step-by-step increase over the past 15 years. The increase of its international academic impact lags behind the growth of the number of articles published.

14.1.3 Key Research Topics

According to the Keywords Cluster graph (Fig. 14.1), there are five strands of literature in remote sensing modelling and parameter inversion during the period 2000–2014: (1) parameter modelling of ecological and energy balance (keywords: leaf area index model, satellite, AVHRR); (2) land surface temperature/emissivity and reflectivity retrieval (keywords: land surface temperature, emissivity, vegetation index, spectral reflectance); (3) soil moisture and land surface evapotranspiration estimation (keywords: soil moisture, surface roughness, and synthetic aperture radar); (4) vegetation scattering and microwave detection of roughness (keywords: radiometer, scattering, backscatter, forest index); and (5) data assimilation (keywords: data assimilation, microwave radiometry, water content). This analysis indicates that the "retrieval", "assimilation" and "modelling" of data, such as "vegetation index", "land surface temperature", "evapotranspiration", "soil moisture", using measurements from "satellite" and "lidar/radar" are the key terms on "remote sensing modelling and parameter inversion" during the past 15 years. Before 2006, the terms "albedo", "emissivity" and

Table 14.1 Top 20 countries (regions) with the number and citations of SCI/SSCI-indexed articles on "Remote Sensing Modelling and Parameter Inversion" during the period 2000–2014

	Number of articles						Cited frequency						Number of highly cited articles					
	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014
Rank	World	67	344	502	801	1,402	World	3,020	182	25,354	22,529	8,431	World	10	0	82	67	72
1	USA	30	70	202	254	323	USA	1,671	54	13,638	8,993	2,676	USA	5	0	48	31	26
2	China	0	107	12	70	314	China	0	45	141	1,297	1,245	China	0	0	0	3	8
3	Spain	2	20	18	50	87	Spain	55	9	793	1,101	646	Italy	0	0	1	0	8
4	Canada	4	11	36	51	72	France	587	10	2,835	2,201	525	Spain	0	0	4	2	7
5	France	11	15	66	72	68	Italy	47	5	788	889	513	France	3	0	8	6	6
6	Italy	2	14	22	41	67	Canada	228	5	2,125	1,383	438	Netherlands	0	0	0	6	5
7	Germany	0	9	8	34	60	UK	189	0	952	514	356	UK	0	0	3	1	5
8	UK	11	11	35	20	46	Germany	0	5	546	914	323	Portugal	0	0	0	0	2
9	Australia	0	16	12	18	44	Netherlands	0	8	200	1,306	319	Canada	1	0	6	4	1
10	Netherlands	0	6	12	36	42	Australia	0	9	460	695	184	Australia	0	0	1	2	1
11	South Korea	0	8	2	4	25	Finland	0	0	170	402	140	Switzerland	0	0	0	2	1
12	India	2	7	8	25	25	Japan	0	3	414	348	110	Japan	0	0	1	0	1
13	Japan	0	4	13	18	24	Austria	63	3	63	198	103	Finland	0	0	0	0	1
14	Finland	0	4	6	18	22	Portugal	0	0	56	98	103	Denmark	0	0	4	2	0
15	Austria	1	5	1	6	19	Denmark	0	0	951	237	77	Germany	0	0	2	3	0
16	Belgium	1	4	2	13	18	Switzerland	0	4	105	439	67	Belgium	0	0	0	3	0
17	Brazil	0	1	1	5	14	Belgium	44	1	59	473	64	South Korea	0	0	1	0	0
18	Switzerland	0	6	6	14	13	South Korea	0	6	163	17	63	Austria	0	0	0	1	0
19	Denmark	0	2	10	4	9	India	14	0	74	214	55	Russia	0	0	1	0	0
20	Portugal	0	1	2	4	9	Israel	17	1	280	116	1	Mexico	0	0	0	1	0

Note Countries (Regions) ranked by the number of articles, cited frequency and number of highly cited articles during the period 2010–2014

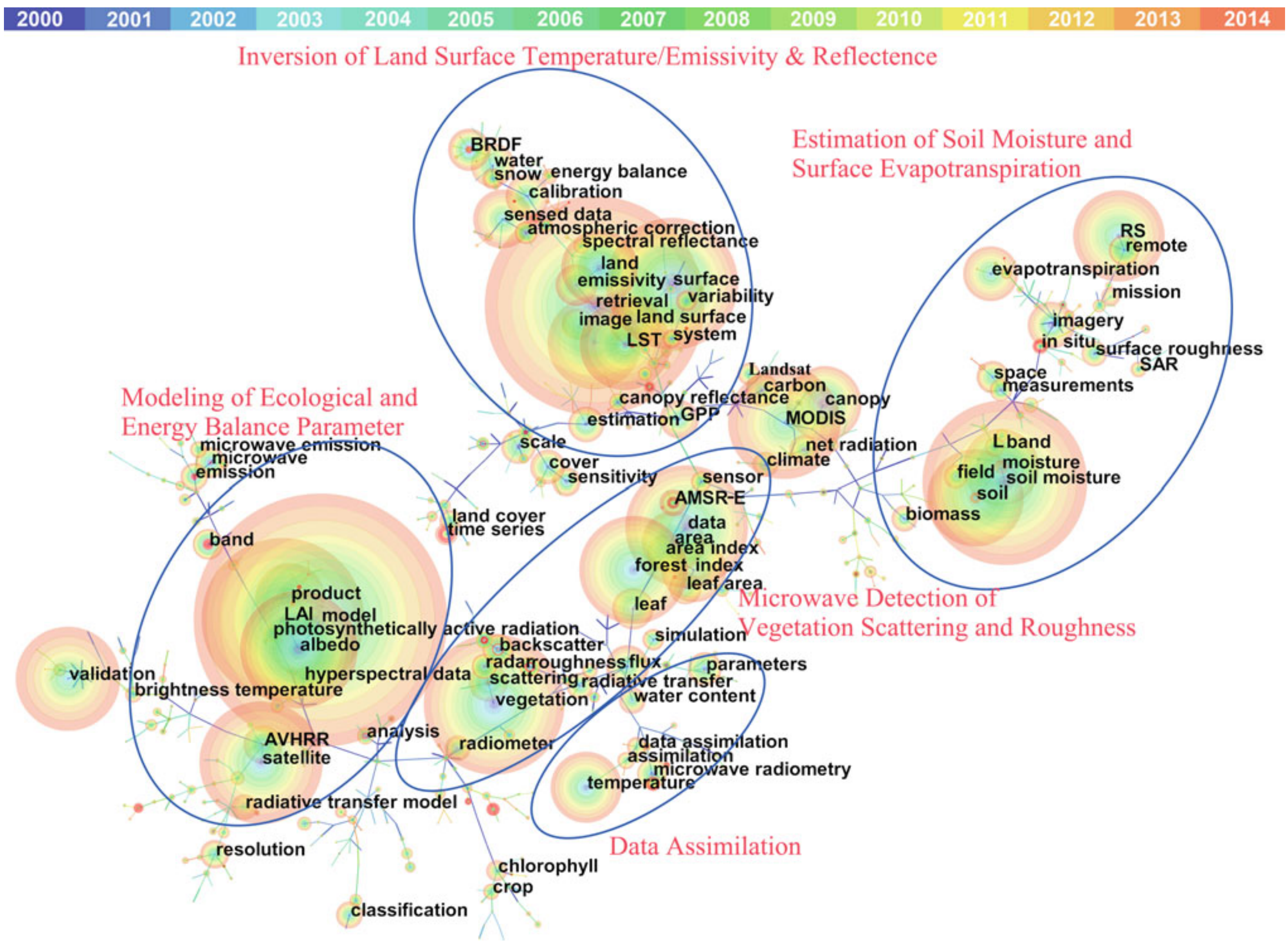

Fig. 14.1 Co-occurrence network of SCI/SSCI-indexed article keywords on "Remote Sensing Modelling and Parameter Inversion" during the period 2000–2014

"forest index" appeared frequently, while the terms used more often after 2006 are "biomass" and "evapotranspiration". The transition reflects that the scholars extend the basic remote sensing parameters to the studies of more complex processes connected with energy flux and climate problems.

Based on the abovementioned popular terms, we can draw a conclusion that, to benefit the research of the earth surface system, further improvements are needed in LAI and PAR modelling, the retrieval of LST, land surface emissivity and bidirectional reflectance, the estimation of soil moisture, evapotranspiration and vegetation scattering based on the remote sensing data. However, the key word "data assimilation" appears at a much lower frequency and at a smaller scale, showing that the assimilation of satellite data is still in the early stage of development.

Based on the frequency of keywords usage during the period 2000–2014 (Fig. 14.2), it is found that worldwide scholars have been paying close attention to the "modelling" and "retrieval" in remote sensing, and the "validation" of these models, and retrieval is drawing increasing attention. In remote sensing research, the most often used keywords are "bidirectional reflectance/albedo", "LAI", "soil moisture", and "surface temperature", etc. Specifically, BRDF/albedo drew the most attention during the period 2000–2004, then such attention gradually transferred to the study of "LAI" and "soil moisture" during the period 2010–2014.

The search results from Chinese scholars were no more than 10 in 2000–2004, indicating that there was a huge gap between the contributions from Chinese and international scholars. Fortunately, the search results from Chinese scholars have been greatly improved during the periods 2005–2009 and 2010–2014, and Chinese scholars have contributed one-third of the search results with "model", "retrieval" and "validation". Notably, the word frequency of "surface temperature" of Chinese scholars (123) has contributed half of the total word frequency (235).

The remote sensing technology includes "optical remote sensing", "microwave", and "active microwave". The "optical remote sensing" plays a dominant role and it is the technique

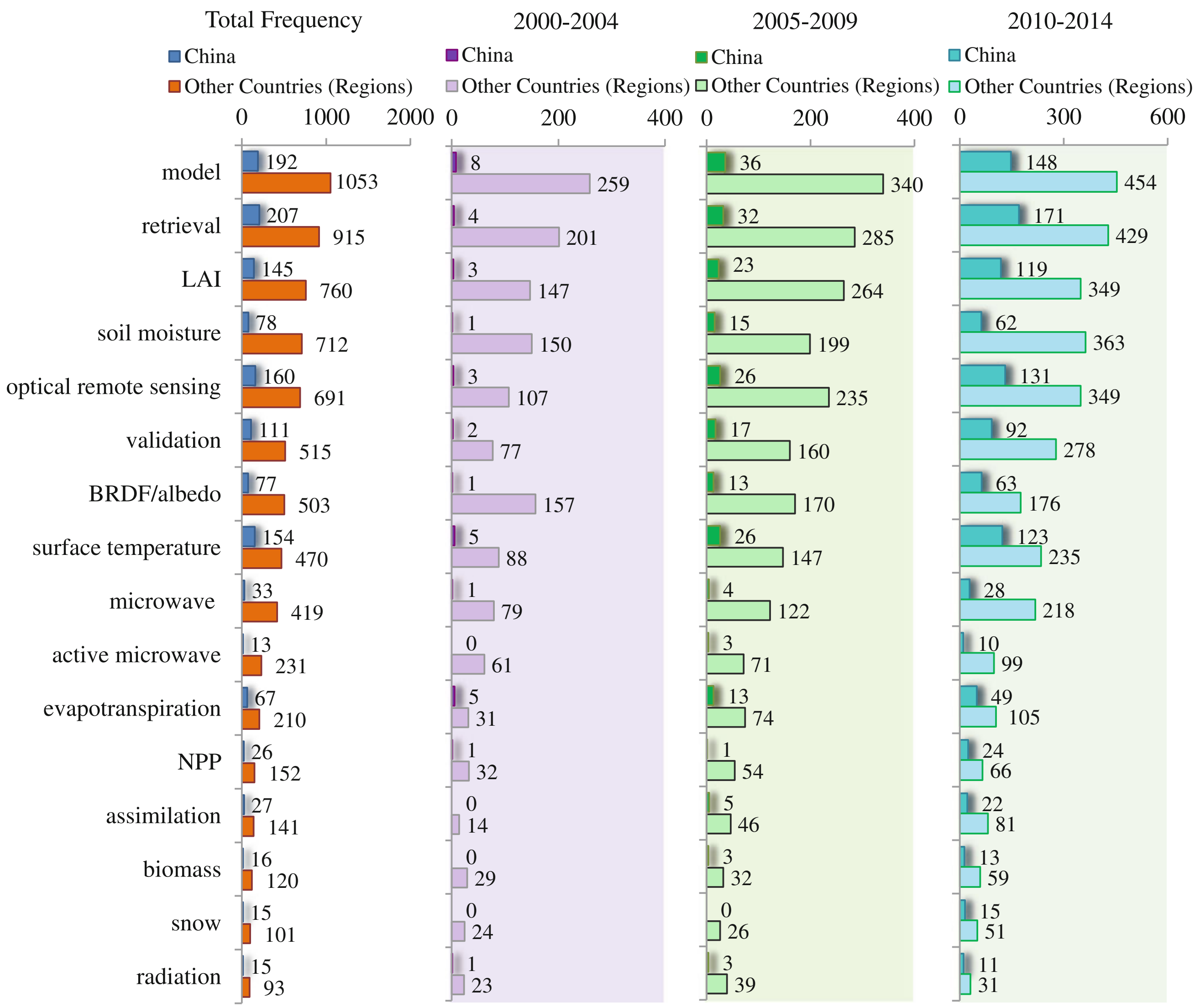

Fig. 14.2 Keyword temporal trajectory graph for SCI/SSCI-indexed articles on "Remote Sensing Modelling and Parameter Inversion" during the period 2000–2014

mostly adopted by Chinese scholars. Overall, the keywords frequency of NSFC-funded projects for Chinese scholars has a similar distribution with that of SCI/SSCI articles published by other countries (regions). In view of time scale, the keywords' distribution in NSFC-funded project is late by one stage, but have grown rapidly in the past five years.

14.1.4 The Role of NSFC in Supporting the Research on Remote Sensing Modelling and Parameter Inversion

According to the keywords sequential variation of NSFC-funded projects (Fig. 14.3) on "Remote Sensing Modelling and Parameter Inversion", we can identify three stages: the keywords in this field is no more than 5 in 2000–2004, and gradually increased to about one third of the total funded projects, and further increased to a percentage of more than 50 % of the total funded projects in 2010–2014.

The keywords in NSFC projects on "Remote Sensing Modelling and Parameter Inversion" are directly related to the development of remote sensing technology. Other terms like "multi-spectrum" and "thermal infrared" are the focus in 2000–2004, while in 2005–2009, the dominant keywords are "structural parameter of vegetation", "land surface temperature", and "evapotranspiration", later in 2010–2014, the keywords like "microwave remote sensing" attracted much attention. The variation of keywords indicates that more sub-fields in remote sensing are developed with the funding of NSFC. The keyword variations of NSFC-funded projects show a similar trend to that of the SCI/SSCI articles.

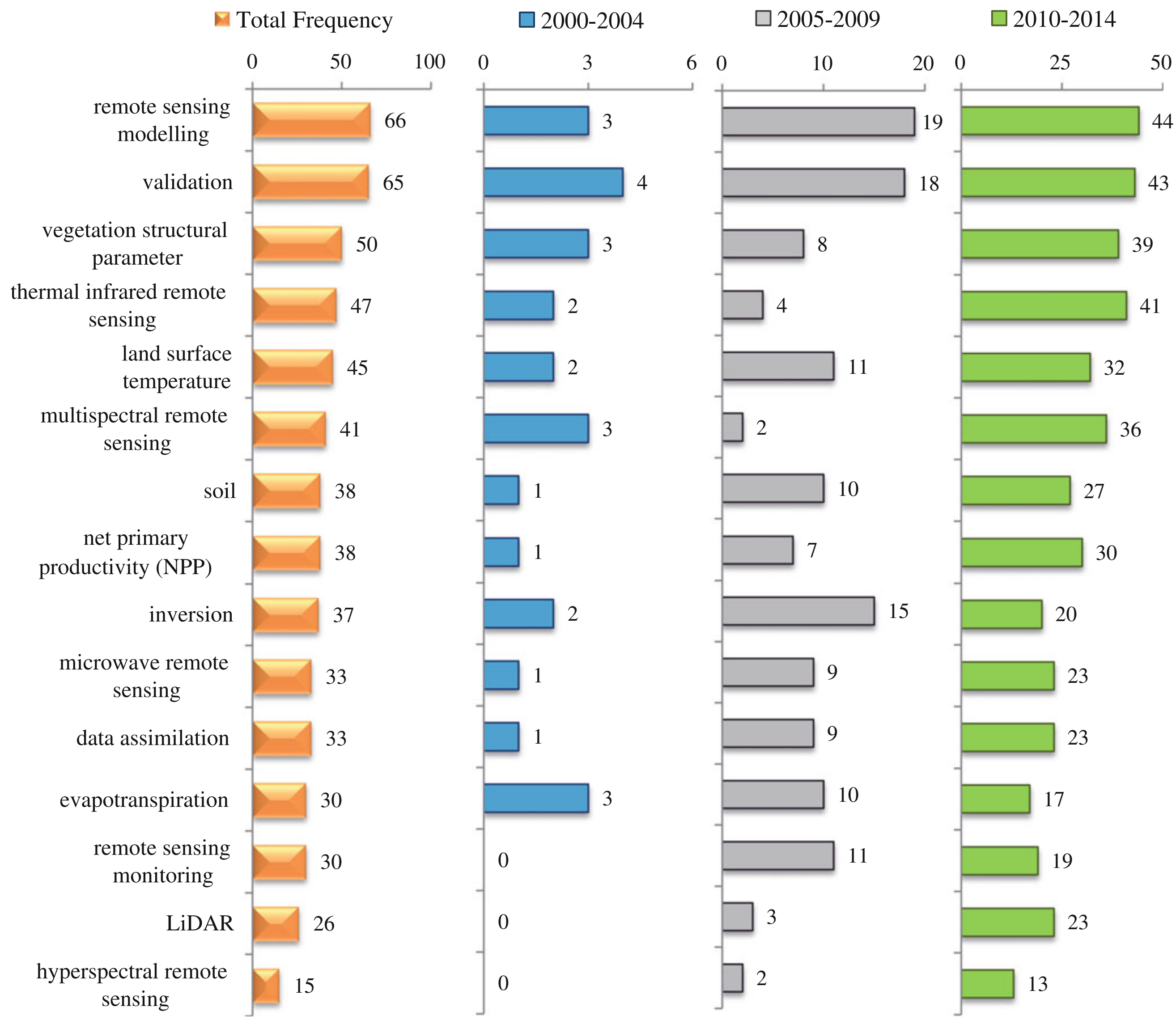

Fig. 14.3 Keyword temporal trajectory graph for NSFC-funded projects on "Remote Sensing Modelling and Parameter Inversion" during the period 2000–2014

NSFC has played a steering role in improving the research on "Remote Sensing Modelling and Parameter Inversion" (Table 14.2). NSFC has funded a total of 244 projects from 2000 to 2014, with a total funding of more than 125,433 thousand yuan, which supported more than 200 scholars from 74 units nationwide. In view of specific stages, the level of financial support provided by NSFC increased from 4050 thousand yuan during the period 2000–2004 to 100,853 thousand yuan during the period 2010–2014. Six units and 11 PIs were funded in 2000–2004, while these numbers increased to 69 and 170, respectively in 2010–2014. The total funding in the past 5 years reached 100,000 thousand yuan, which is 4.1 times the total amount in the previous 10 years. The funding of NSFC directly contributes to the diversification of the remote sensing research.

The statistics in Table 14.2 show that the portion of SCI/SSCI articles published by Chinese scholars accounted for 14.6 % during the period 2000–2014. Specifically, the academic papers funded by NSFC accounted for 69.7, and 58.3 % of the total articles were jointly funded by the Ministry of Science and Technology (MOST). The percentage of papers funded jointly by NSFC and MOST increased from 0 % in 2000–2004 to 61.9 % in 2010–2014, indicating that most scholars in the area of "Remote Sensing Modelling and Parameter Inversion" in China have received funding support from MOST.

Table 14.2 NSFC-funded projects and SCI/SSCI-indexed articles on "Remote Sensing Modelling and Parameter Inversion" during the period 2000–2014

SCI/SSCI-indexed articles					NSFC-funded projects			
Periods	Number of articles	% of articles by Chinese authors	% of articles with NSFC funding by Chinese authors	% of articles funded by MOST among those with NSFC funding	Number of projects	Funding (10,000 yuan)	Number of PIs	Number of institutions
2000–2004	502	2.4	25.0	0.0	11	405.0	11	6
2005–2009	801	8.7	48.6	38.2	56	2,053.0	52	23
2010–2014	1,402	22.4	76.1	61.9	177	10,085.3	170	69
2000–2014	2,705	14.6	69.7	58.3	244	12,543.3	203	74

14.2 Questions and Research Progress

14.2.1 How Can the Remote Sensing Model Describe the Surface Parameters More Accurately

The remote sensing model is based on the interaction between the electromagnetic wave and the ground target and the description of the relationship between the electromagnetic wave signal and the target parameters. The optical remote sensing models can be used to retrieve the parameters of vegetation structure, vegetation productivity, effective radiation, albedo and land surface temperature (Xiao et al. 2004). The microwave remote sensing model has advantages in the estimation of soil moisture, soil roughness, snow equivalence, forest biomass and other related parameters (Davidson et al. 2000; Wigneron et al. 2001, 2007).

Bibliometric Analysis of Contemporary Research

A total of 1053 articles on remote sensing modelling have been published since 2000 (excluding those published by Chinese scholars). Figure 14.2 shows that only 259 articles focused on modelling during the period 2000–2004, while the number increased to 454 during the period 2010–2014. Figure 14.1 shows some topics that are closely related to the increase of articles on remote sensing modelling including: LAI, albedo, radiative transfer model and vegetation backscattering model.

Contemporary Research

Plant canopy models are the fundamental basis for inversion in remote sensing, including radiative transfer models, geometrical optic models and other simulation models from computational views (e.g., Ray-tracing). Several radiative transfer models have been proposed over the last 40 years, such as the SUIT model (Suits 1971), SAIL (Scattering by Arbitrarily Inclined Leaves) model (Verhoef 1984), PROSPECT (Jacquemoud and Baret 1990), LIBERTY (Leaf Incorporating Biochemistry Exhibiting Reflectance and Transmittance Yields), MCRM (Markov Chain Canopy Reflectance Model) (Kuusk 1995), geometrical optic (Li and Strahler 1985), and the 4-Scale (Chen and Leblanc 1997) models. Computer simulation models mainly consist of BRDF reconstruction of vegetation canopy using Monte Carlo theory (Ross and Marshak 1988; Antyufeev and Marshak 1990) and the RGM model (Goel et al. 1991; Qin and Gerstl 2000) based on real vegetation structures. This approach has a bright future with the development of computer technology. The gross primary productivity (GPP) models based on light use efficiency theory include the CASA/GPP model (Carnegie Ames Atandor Approach, CASA) (Potter et al. 1993) and the Glo-PEN model driven by AVHRR observations (Prince and Goward 1995).

Remote sensing of land surface energy balance is based on the modelling of land surface albedo, LST/emissivity, and land surface heat fluxes. AMBRALS (Algorithm for Modelling Bidirectional Reflectance Anisotropies of the Land Surface) is a kernel-driven BRDF model derived from geometric-optics model (Strahler and Muller 1999). Models of LST/emissivity firstly try to define "average true temperature" and "equivalent emissivity" in non-isothermal mixed pixel (Becker and Li 1995), and then simulate thermal radiation transfer in vegetation canopy using models such as CUPID (Norman 1979).

Many models have been developed and applied successfully in remote sensing of land surface evapotranspiration (heat and vapor fluxes) in the last decade, such as land surface energy balance models, Penman-Monteith type models, land surface temperature-vegetation index relationship models, Priestley-Taylor type models, and statistical models (Timmermans et al. 2007; Wang et al. 2006; Carlson 2007; Mu et al. 2007; Bateni and Liang 2012). Study of spatial scale in remote sensing of land surface evapotranspiration over heterogeneous surfaces (mixed pixels) has grown in importance lately (McCabe and Wood 2006; Gebremichael et al. 2010; Chen et al. 2007).

The microwave remote sensing modelling of land water cycle parameters mainly includes remote sensing modelling of soil moisture, the freeze/thaw cycle, snow cover and snow water equivalent, etc. Much progress has been made in the remote sensing modelling of soil moisture in terms of soil dielectric constant models and random rough surface scattering theory and vegetation scattering models. The recent development in models used to calculate the soil dielectric constant includes the generalized refractive mixing dielectric model (Mironov et al. 2004), in which the refractive index of soil was expressed as the volume-weighted average of refractive indexes of various soil components. Progress in random rough surface scattering models mainly includes the Integral Equation Model (IEM) and its parameterization (Shi et al. 2005), and the numerical model based on the three-dimensional Maxwell equations. The IEM has been improved continuously with the IEM2 M (Integral Equation Model for the Second-order Multiple Scattering), AIEM (Advanced Integral Equation Model) models (Chen et al. 2003) and EAIEM (Extended Advanced Integral Equation Model), etc. In order to adapt to various surface conditions, a variety of models with different application scope were integrated, such as the L-MEB model developed for the SMOS (Soil Moisture and Ocean Salinity) mission (Wigneron et al. 2007).

Microwave scattering effects of the snow layer should be considered in snow modelling. A representative model is the dense media radiative transfer theory model (Tsang et al. 2000), which considers the snow layer as a random medium by treating snow particles as spherical particles using a quasi-crystalline approximation. The model of Bi-continuous medium (Ding et al. 2010) further implemented snow microstructure simulation by considering the cross-polarization signal produced by the irregular structure. In addition, the simplified snow radiation models were further developed, including the multi-layer version of the HUT (Helsinki University of Technology) (Lemmetyinen et al. 2010) and MEMLS models (Microwave Emission Model of Layered Snowpack) (Wiesmann and Mätzler 1999). The latest study adapted the backscattering calculation to the current collaborative observations of active and passive microwave remote sensing.

Bibliometric Analysis of Contemporary Research in China

During the period 2000–2014, 192 academic articles on remote sensing modelling were published by Chinese scholars, accounting for 15.42 % of the total as shown in Fig. 14.2. Chinese scholars paid more attention to the sub-fields of remote sensing modelling, where the keyword “remote sensing modelling” has become the most frequent in the keywords sequential variation graph.

Contemporary Research in China

Remote sensing physical models can be classified into two categories: The radiative transfer models and the geometrical optics (GO) models. The former category are represented by European and American scientists, and the latter category is mainly studied by Chinese scientists. Li and Strahler (1985) developed a GO model to explain the BRDF phenomenon in forest regions. Jingming Chen continued this path of thought, and developed the four-scale model, which improved the calculation accuracy of forest radiative transfer, and achieved great success in the study of the global carbon cycle using remote sensing data. At the beginning of this century, Chinese scientists focused on introducing the geometric optics model to the thermal infrared domain. They proposed the concept of non-isothermal mixed pixel emissivity (Li and Wang 1999) and built the non-isothermal mixed pixel component effective emissivity concept model (Chen et al. 2000, 2004). They also proposed the use of the matrix expression formula of the directional thermal radiation within the non-isothermal open system (Xu et al. 2002), and developed the directional thermal radiation model over row structure canopy (Chen et al. 2002; Yan et al. 2003, Du et al. 2007). Liu et al. extended the computer model RGM to the thermal infrared domain to form the TRGM model (Liu et al. 2007). Based on the TRGM and 3D Cupid models, Huang et al. (2010) simulated the “hot spot” effect of the thermal radiation over the crop canopy. Those works have laid a theoretical foundation for the studies of large-scale energy balance and the water cycle using remote sensing data. In recent years, Chinese scholars began to apply the idea of geometric optics models to large-scale rugged terrain (Wen et al. 2009, 2014), to improve the accuracy of the albedo model in mountainous area of China.

Among the variables for carbon cycle research, the leaf area index (LAI) and gross primary productivity (GPP) are the main focus of scientists in China. For example, using hyperspectral and multi-angle data, Fan et al. (2010) developed an algorithm for LAI modelling. Yuan et al. (2014) found that the original set of input parameters in the LUE-based (light use efficiency) GPP model may not be necessary across plant functional types. Furthermore, scientists in China developed new GPP models that separate contributions of sunlit and shaded leaves within the vegetation canopy (Chen et al. 2012; He et al. 2012). For net primary productivity (NPP) modelling, the NPP-age relationship was introduced to provide benchmark simulations in the reconstruction of historical NPP variations (Wang et al. 2011). The modelling of vertical distribution of LAI within the canopy is a new opportunity for LAI inversion modelling. The biochemical constrains on GPP from leaf chlorophyll contents need better characterization (Gitelson

2013). The incorporation of physical variables in the LUE models may be a promising way to improve the universality of these models among plant functional types as well as the theoretical explanations under extreme climates (e.g., drought) (Wu et al. 2012; Wagle et al. 2014).

Turning next to the terrestrial water cycle, Chinese scholars took the influence of ice component in frozen soil into account and then expanded the former Dobson model (Zhang et al. 2010), by using the law that unfrozen water content in frozen soil varies exponentially with temperature. Du et al. (2007) proposed the extended advanced integral equation model EAIEM. Chinese scholars are committed to the development of high precision parameterized models based on theoretical ones. The Qp parameterized model was developed according to the AMSR-E characteristics of large incidence angle (Shi et al. 2005). This model eliminates the roughness influences in the retrieval of soil moisture (Shi, et al. 2006). A snow parameterized model was developed based on the theory of dense media radiative theory and the advanced integral equation model (Jiang et al. 2007).

Contributions by Chinese Scholars and Subsequent Problems

In terms of remote sensing modelling, Chinese scholars made significant contributions in developing and improving the geometric optical models. Numerous detailed works promoted the development of remote sensing modelling and retrieval of the carbon and hydrological cycles. In the future, more efforts are needed to support application of remote sensing modelling in complex terrain and work with more advanced sensors.

Future Research

In the modelling of complex surfaces, the complex spatial heterogeneity and the three dimensional fluctuation characteristics of the terrain, as well as the influence of human activities are the main challenges in the modelling of the surface parameters. In the future, attention should be paid to the complex surface modelling, the inversion of surface parameters and its validation.

Taking advantage of visible, thermal infrared and microwave remote sensing techniques, and performing the full-spectrum, active-and-passive-combined measurements in modelling, will become new directions for the accurate study of surface parameters in remote sensing modelling.

14.2.2 How to Improve the Retrieval Accuracy of Surface Parameters?

The inversion is to infer the properties or specific parameters of the target based on the electromagnetic signal of the satellite. The parameters that recently have been noticed and can be directly inferred include leaf area index, surface albedo, surface temperature, soil moisture and so on. These parameters are related to the carbon cycle, energy balance and water cycle of the Earth's surface. The remote sensing models should be built as accurately as possible. However, how can we improve the inversion accuracy of surface parameters in remote sensing?

Bibliometric Analysis of Contemporary Research

A total of 915 articles on remote sensing inversion have been published since 2000 (excluding those published by Chinese scholars). Figure 14.2 also shows that among all the published articles only 201 focused on retrieval during the period 2000–2004. This number increased to 429 during the period 2010–2014. Considering there are 515 articles during the last 5 years, the modelling in remote sensing is playing a more and more important role in this field, as confirmed by the keywords analysis in Fig. 14.1.

Contemporary Research

Remote sensing of parameters related to carbon cycling includes LAI, LUE and plant primary (both gross and net) productivity. The NASA MODIS team proposed the operational LAI estimation approach based on three dimensional radiative transfer perspectives, but empirical methods are also used due to unstable performance of the above models (Myneni et al. 2002). The accuracy of GPP modelling depends on the accuracy of input parameters in LUE (Zhao et al. 2010). For example, better representation of water and temperature stress can be achieved from Eddy covariance measurements (Xiao et al. 2004; Yuan et al. 2007). A single vegetation index (Hall et al. 2008; Hilker et al. 2010) and integrated form with temperature (Wu et al. 2012a, b) can also improve LUE modelling.

The inversion algorithm of the land surface albedo is based on the kernel-driven BRDF model and multi-angular dataset. For example, the MODIS albedo product is derived from hemispheric integration of BRDF collected in 16 days (Strahler and Muller 1999). In order to mitigate uncertainties of retrieving, pre-knowledge of land surface BRDF (BRDF shape prototype, BRDF database) was used (Strugnell and Lucht 2001; Bacour and Bréon 2005), such as in the MERIS albedo product (Li et al. 2006). Other research adopted different strategies, i.e., to establish relationship between TOA (top of atmosphere) reflectance and the shortwave albedo of the land surface (Liang et al. 1999; Liang 2003).

Due to the unknown emissivity of each channel and the atmospheric effects, the inversion of LST is ill-posed (Li et al. 2013a, b). The split-window (SW) algorithm

(Becker and Li 1990a, b) has become the primary LST inversion method (Li et al. 2013, Jiang and Li 2008; Hulley et al. 2011), which is adopted by the operational procedure of MSG SEVIRI (METEOSAT Second Generation-1/ Spinning Enhanced Visible and Infrared Imager) (Sun and Pinker 2003), AVHRR (Kerr et al. 1992:) and MODIS (Wan and Dozier 1996). Data measured from two channels of the Thermal Infrared Sensor (TIRS) are used to improve the retrieval accuracy of LST based on the SW algorithm. TES (Temperature and Emissivity Separation) method was designed for ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) (Gillespie et al. 1998). The Iterative Spectrally Smooth Temperature/Emissivity separation (ISSTES) algorithm is used to synchronously retrieve surface temperature and emissivity (Ingram and Muse 2001), and the day/night LST algorithm (Wan and Li 1997) and two-step algorithm (Ma et al. 2000) are also two important methods to estimate LST.

Soil moisture retrieval mainly includes passive microwave remote sensing using radiometers, active microwave remote sensing by radar/scatterometer, as well as the joint active and passive microwave retrieval method. Passive retrieval algorithms could be distinguished from the method dealing with vegetation effects, which include the optical normalized difference vegetation index (Jackson et al. 2002), microwave vegetation indices (Shi et al. 2008) and the microwave polarization difference index (Owe et al. 2001), etc. The iterative retrieval algorithm based on physical models can obtain a variety of parameters simultaneously such as the SMOS algorithm. The SMAP (Soil Moisture Active Passive) satellite mission proposed a brightness temperature downscaling algorithm based on the synergy between active and passive observations (Das et al. 2011), and aimed to develop soil moisture products with higher spatial resolution of 9 km.

Snow parameter (snow water equivalent/depth) retrieval algorithms include the linear brightness temperature gradient algorithm (Chang et al. 1987; Markus et al. 2006), the algorithm based on physical models, and the iterative and assimilation algorithms (Pulliainen 2006; Che et al. 2014). Due to the strong space heterogeneity of snow parameters, the key issue of the current studies is to develop high-resolution active detection techniques with radar/ scatterometer (Shi and Dozier 2000). Passive microwave remote sensing of surface freeze/thaw status includes the single/dual thresholds algorithm (Kim et al. 2011), the decision tree algorithm (Jin et al. 2009) and the discriminant function algorithm (Zhao et al. 2011). SMAP is designed to acquire freeze/thaw status products with a resolution of 3 km for improving the accuracy limited by coarse spatial resolution.

Bibliometric Analysis of Contemporary Research in China

Since 2000, Chinese scholars have published 207 articles on remote sensing parameter retrieval, accounting for 18.45 % of the total. A total of 171 articles were published during the period 2010–2014, accounting for 82.61 % of all the articles. Since 2000, NSFC has funded 244 projects in remote sensing modelling and inversion, among which 177 projects were funded during the period 2010–2014.

Contemporary Research in China

Chinese scholars have contributed to the retrieval of surface parameters. Zhaoliang Li proposed the LST SW algorithm (1990a, b) and temperature independent spectral index (TISI) method. Zhengming Wan designed the GSW algorithm (Wan and Dozier 1996) and day/night LST algorithm (Wan and Li 1997). This early research promoted the LST inversion, though these works were mainly achieved abroad. Domestic researchers focused on the improvement and application of the SW algorithm, and the SW algorithm is modified to adapt to the characteristics of China's regions (Mao et al. 2005; Sun and Pinker 2003; Tang et al. 2008; Jiang and Li 2008). The uncertainties induced by atmospheric radiation and other sources were further reduced (Ren et al. 2011, 2014). In addition, the data were expanded from thermal infrared measurements to microwave measurements (Mao et al. 2007). Chinese scholars conducted a pioneering attempt to estimate the component temperatures of mixed pixels based on the directional thermal radiation characteristics (Jia et al. 2003; Song and Zhao 2007).

Contributions by Chinese Scholars and Subsequent Problems

The Chinese scholars have done many works in retrieval of surface parameters. One of the most prominent is the retrieval of land surface temperature and emissivity, which the Chinese scientists developed several famous retrieval models. Other parameters such as LAI and albedo, and especially land surface evapotranspiration were also paid much attention to. The problems, such as the use of priori knowledge, the ill-posed problems, the lack of constraint conditions, as well as combination of multi-satellite observations are also big challenge for the parameters inversion.

Future Research

The following techniques need to be strengthened in the future research: A priori knowledge can be used to increase the number of equations so as to achieve the balance between the number of variables and equations. In the inversion of remote sensing, it is required to increase the constraint condition of the parameters, and improve efficiency of optimizing the parameters, so as to make the inversion results closer to the true values. The characteristics of the temporal and spatial complementarity of multi-source data should be used to improve the retrieval accuracy and temporal resolution. With the rapid increase in the number of satellites in orbit, the remote sensing inversion strategy by assimilation of multi-source data has gradually become a new direction.

14.2.3 What Is the Role of the Remote Sensing Inversion Parameters in Geoscience Research?

Since 2000, more and more remote sensing products have been used in the evaluation of the Earth's surface changes at global and regional scales. Over the past 20 years, land surface process models have been developed for simulating continuous changes of the energy and water processes of the "soil-vegetation-atmosphere" (Dickinson et al. 1986; Sellers et al. 1996; Dai et al. 2003). None of these models can simulate the whole land-atmospheric exchange process well (Henderson-Sellers, et al. 1995). The reason is that it is very difficult to determine the land surface condition in a particular region, because the observed data from ground stations are not representative when they are extended to the regional scale. Thus, the use of satellite data in the parameterization of land surface process will be a growing trend in the future.

Bibliometric Analysis of Contemporary Research

Statistical analysis of existing literature on data assimilation shows that only 141 academic papers (excluding those by Chinese scholars) were published since 2000. There were 14, 46 and 81 papers, respectively published in the three 5-year stages during the period of 2000 to 2014. Figure 14.1 also shows that some topics that are closely related to data assimilation including: temperature, microwave radiometry and water content. This reflects the dominance of two issues in this sub-field: LST and soil moisture assimilation. Compared with the published papers on remote sensing modelling and parameter inversion, Fig. 14.2 shows that a big gap exists in the applications of retrieved parameters in the field of earth system science. Therefore, the studies on remote sensing parameter assimilation are insufficient.

Contemporary Research

The land data assimilation (LDA) based on the satellite-retrieved parameters data is a popular topic in land-surface and hydrological process research (Moradkhani et al. 2005). There are two ways of assimilating remote sensed data into land surface process models (LSPMs): one is that the land parameters and energy flux estimated from satellites are directly used or assimilated into the LSPMs; the other is that the microwave data are directly assimilated into the LSPMs to achieve the optimal estimation of the state variables which are coordinated within the models.

In soil moisture estimation, the assimilation of the on-site soil moisture observation data and low-frequency microwave brightness temperature data can improve the distribution and estimation accuracy of soil moisture (Walker and Houser 2001; De Lannoy et al. 2007; Entekhabi et al. 1994; Houser et al. 1998; Galantowicz et al. 1999; Crosson et al. 2002). The soil temperature profile (Huang et al. 2008), land surface water and heat flux can be obtained by assimilating the LST data derived from satellites (GOES, MODIS, AVHRR, and SSM/I), which are used to accurately estimate the energy and momentum fluxes between the land surface and the atmospheric boundary layer (Kumar and Kaleita 2003; Caparrini et al. 2004). However, the satellite-retrieved land surface parameters, such as snow cover, have large uncertainty in the course of assimilation (Wegmuller and Matzler 1999; Njoku and Chan 2006).

The applications of LDA in snow parameter estimation include the assimilation by integrating satellite-retrieved snow products and models to improve the estimation accuracy of the snow cover area, snow depth, snow water equivalence, runoff and so on. Rodell and Houser (2004) directly assimilated the MODIS snow cover products into the Global Land Data Assimilation System (GLDAS); Andreadis and Lettenmaier (2006) and Durand and Margulis (2006) carried out the assimilation of satellite snow cover products and snow water equivalence based on the ensemble Kalman filter (EnKF) algorithm, the Variable Infiltratiion Capacity (VIC) model and the Simple Biosphere Model version 3 (SiB3), respectively.

Hazarika et al. (2005) and Demarty et al. (2007) applied the LDA to estimate the carbon flux, carbon storage and vegetation productivity, and used this model to assimilate the LAI parameter for estimating the net primary productivity (NPP) in the Carbon Cycle Data Assimilation System (CCDAS) based on satellite and other data.

In recent years, the land data assimilation system (LDAS) has been developed rapidly. Currently, the major LDASs include the Global and North America Land Data Assimilation System (GLDAS, NLDAS) developed by NASA and the European Land Data Assimilation System (ELDAS).

Bibliometric Analysis of Contemporary Research in China

A total of 27 articles on data assimilation have been published by Chinese scholars since 2000. Figure 14.2 shows that most of these papers were published in the last 5 years, accounting for 81.48 % of the total in this sub-field, and that Chinese scholars published only 5 papers during the period 2005–2009. This reflects that data assimilation is a new sub-field, but developing rapidly in China.

Contemporary Research in China

LDA research based on remote sensing products by Chinese scholars has a late start. However, in recent years, there has been considerable progress, especially in soil moisture and soil temperature, surface energy flux, parameters and state variables at the same time, the assimilation method, and the construction of LDAS.

In soil moisture assimilation, the EnKF or extended Kalman filter (EKF) algorithm was used to study related problems of soil moisture assimilation (Zhang et al. 2006; Tian and Xie 2008; Huang et al. 2008; Jin et al. 2009). Li et al. (2004) combined the SiB2 model and the land microwave radiative transfer model to improve the accuracy of soil moisture simulation; Li et al. (2010) incorporated the ensemble square root filter (EnSRF) algorithm and four-dimensional variational assimilation scheme to retrieve the soil moisture profile; Based on the Monte Carlo method and the proper orthogonal decomposition (POD) technique, Tian et al. (2011) developed an ensemble four-dimensional variational assimilation method (PODEn4DVar), which incorporated advantages of both ensemble and variational methods and was applied to soil moisture data assimilation (Tian et al. 2008, 2009, 2010a, 2011). Zhang et al. (2012) developed a wetland surface microwave emissivity inversion method and a soil moisture assimilation scheme, which considered wetland sub-grid surface characteristics and solved the soil moisture assimilation problem for a model grid with a wetland sub-grid.

The MODIS LST data were assimilated to retrieve the soil temperature profile and surface water heat flux (Huang et al. 2008; Xu et al. 2011, 2014). The dual-pass data assimilation systems of microwave satellite data were developed to optimize soil moisture, which optimized model parameters and state variables simultaneously (Yang et al. 2007; Qin et al. 2009; Tian and Xie 2009; Tian et al. 2010b; Xie and Zhang 2010).

Chinese scholars have made great progress in the development of LDAS, which have realized the coupling of land surface process model, land microwave radiative transfer models and assimilation algorithms, and have established the China Land Data Assimilation System (CLDAS), China Land Soil Moisture Data Assimilation System (CLSMDAS), and the global Land Data Assimilation System (IAP-LDAS). Most of these systems can correct the model parameters and optimize the land state variables, and provide a dataset with spatiotemporal and physical consistency for studying the water cycle at both large and basin scales.

Contributions by Chinese Scholars and Subsequent Problems

Notwithstanding the late start in land data assimilation, Chinese scholars have conducted research on soil moisture and soil temperature, surface energy flux, complex surface parameters and state variables, as well as the development of data assimilation methods and the construction of land data assimilation systems. By now, applications of the traditional land surface process models at point scales still need to be fixed for satellite pixel scales as well as the radiative transfer model.

Future Research

Owing to the difference from satellite observations, traditional point scale land surface process models that used to be a predictor in the assimilation, must now be fixed for the grid-scale of satellite data. Moreover, the sub-grid-scale heterogeneity of the complex underlying surface should be carefully considered in the positive radiative transfer process that is part of remote sensing modelling. Therefore, the assimilation of remote sensing data and radiative transfer models is a hot topic and an important part in the assimilation of land surface data. The assimilation of land surface data offers a potential way to improve the accuracy of the earth surface system modelling. This work is just starting in China, and is expected to become the new avenue for scientific research about the Earth.

14.3 Roadmap for Further Research

Remote sensing modelling and parameter inversion provide a cost-effective and efficient way to obtain the quantitative spatial distribution data required by the research of global changes and earth system science. China has made great progress in the research of remote sensing modelling and parameter inversion, and in some aspects it leads the world with the support of NSFC during the past 15 years. According to the development of remote sensing modelling and parameter inversion, research topics that require special attention and improvements include the following:

(1) **Strengthen Application-Driven and Quality-Controlled Basic Theory Research in Remote Sensing**

China has published a large number of SCI/SSCI articles on remote sensing modelling and parameter inversion in the past 30 years, but their scientific citations are still much less than those of some other leading countries. The Chinese scholars should strengthen the accuracy of remote sensing modelling and parameter inversion, and pay more attention to the validation and quality control of the products. In addition, more attention should be paid to applications research, especially in solving important resource and environmental problems.

(2) **Strengthen Innovative Research of Integrated Remote Sensing System**

China lacks the original theory and sensor technologies in the development of the integrated remote sensing system. Most of the Chinese scholars' research of remote sensing modelling and parameter inversion just follows the track of international satellite projects in the past 15 years. Chinese scholars need to strengthen the comprehensive demonstration and design of new satellite sensors, including the radiative transfer modelling and simulations in the early stage of design, and post-launch calibration and validation, develop the inversion algorithms for parametric synthesis, and achieve integrated retrieval of relevant parameters, to push forward scientific research in water and energy cycles, land surface and ecological processes, as well as atmospheric-ocean exchange. Chinese scholars have proposed the Water Cycle Observation Mission (WCOM) program, which aims to achieve multi-approach comprehensive observation and high-precision retrieval of the key elements. More programs like WCOM are needed in China to achieve original innovation in remote sensing.

(3) **Apply Satellite Data for Earth System Science**

The international research on land surface data assimilation has made headway in many aspects, such as soil moisture, the energy flux of land surface, carbon cycle and crop growth in recent years. Chinese scholars have achieved the coupling of the land-surface process model, land-surface microwave radiation transmission model and assimilation algorithm in the study of the land-surface data assimilation system, which directly assimilated the satellite remote sensing observation data, and initially built Chinese land-surface data assimilation systems. However, efforts are still needed to strengthen the research on the uncertainty and stability of the asynchronous results at different temporal and spatial scales and multi-satellite observations, to improve the parameterization scheme for the analogy model, to innovate the assimilation methods for remote sensing parameters, and to increase the simulation accuracy of the global change trends.

14.4 Summary

"Remote sensing modelling and parameter inversion" provides an important way to obtain earth surface parameters. China has made significant progress in this field during the past 15 years, as evidenced by the rapid growth in the number of SCI/SSCI articles and citations, which is close to the leading counties. The research of Chinese scholars leads the global scientific community on some topics. However, the studies of Chinese scholars still lack innovative theories and methods, as well as academic influence in this field. In future studies of remote sensing modelling and parameter inversion, efforts should be made to meet the demands of earth science and regional applications, by (1) strengthening the comprehensive modelling and coordinated retrieval of parameters at global and regional scales; (2) strengthening the assimilation method and assimilation system; and (3) better meeting the needs of scientific forecasting of climate changes and thereby pushing the research of remote sensing modelling and parameter inversion to an advanced level.

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15 Spatial Analysis and Simulation

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Abstract

The chapter provides a historical perspective on recent methodological developments and theoretical insights in the theme of spatial analysis and simulation. The research questions and how they developed are first described. Contributions of different countries to this theme are then assessed in light of bibliometric results, followed by the analysis on the role of NSFC in supporting the research. Five key topics are refined based on the bibliometric result of keywords and reviewed systematically: the geo-ontology, spatial relationship analysis, the spatial estimation, the spatial simulation and the geovisualization. The future direction and dissimilarities between domestic research and overseas are also summarized in the end.

Keywords

Geo-ontology • Spatial relationship • Spatio-temporal analysis • Spatial estimation • Spatial simulation • Geovisualization • Virtual geographic environment

A total of 4920 SCI/SSCI-indexed articles are analyzed in the research area of spatial analysis and simulation. The articles, published from 2000 to 2014, were selected from 21 international journals. The number of journals that have published more than 15 of the relevant articles is 21 (Appendix L). The search query is as follows: ("spatial information" OR "spatial data" OR "spatio*" OR "lattice*" OR "DEM" OR "digital elevation*" OR "terrain" OR "grid*" OR "trajector*" OR "point*" OR "line*" OR "polygon*" OR "network*" OR "spatial*pattern" OR "spatial*process" OR "propert*" OR "vector") NOT ("radar" OR "LiDAR" OR "remotely sens*" OR "remote sens*" OR "landsat" OR "image*" OR "ASTER" OR "quick bird" OR "ikonos" OR "world view" OR "geoeye" OR "*infrared*" OR "MODIS" OR "ETM*" OR "spot*" OR "TM image*" OR "rock*" OR "satellite data" OR "radiation").

15.1 Overview

15.1.1 Development of Research Questions

As research progresses, it has become a challenge for traditional geographic analysis methods to precisely describe and analyze complex geographic phenomena. Owing to the development of Earth observation technology, the acquisition of spatial information has changed substantially in terms of cost, type and coverage. Spatial analysis and simulation methods combine geographical sciences with quantitative models. Modern geographical research depends more on analysis of measured data than ever before. Establishing how to quantify geo-objects and geographical phenomena, discover geographical patterns and reveal the nature of geographical problems has become the driving force behind the development of spatial analysis and simulation.

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Spatial information differs from ordinary information in two ways. On the one hand, spatial information includes not only general attributes but also locational information, which generates complex spatial relationships. On the other hand, the spatial information may be in different formats because of its many sources. The representation of geographical objects, the analysis of spatial relationships and the simulation of geographical systems have forced the separation of spatial analysis and simulation methods from traditional analysis methods, and thereby spatial analysis and simulation has become an independent research area. The development of spatial analysis and simulation methods are the result of the growth of geographical science which has provided the theoretical foundation and scientific base for spatial analysis and simulation.

The history of spatial analysis and simulation can be traced back to the "quantitative revolution" of geography in the 1930s. Although the quantitative revolution led to the birth of "quantitative geography" and the development of many statistical methods to solve geographical problems, quantitative geography is essentially rooted in these statistical techniques and cannot address the description of geographical patterns and evolving processes. This task was undertaken by another revolution, marked by the emergence of GIS in the 1960s in Canada. In 1982, Esri released its core product, ArcInfo, initiating the commercial application of GIS. The advent of GIS provided a platform for the development of spatial analysis and simulation research.

Until the 1990s, the progress of Earth observation technology resulted in a variety of sources and types of spatial information, which generated many spatial data structures for representing spatial relationships. In 1992, Michael Goodchild proposed the term "geographic information science" in the *International Journal of Geographic Information System* and clarified its unique mode of development (Goodchild 1992). In this period, spatial analysis began to develop its theoretical framework based in tandem with GIS technology. The driving force for the development of spatial analysis and simulation, therefore, came from both geographical science and GIS technology, and the theory mixes geographical science, information science and computational technologies.

In the 21st century, data acquisition technologies have diversified. Spatial information can be seen as "big data". The study of spatial analysis and simulation has merged with numerous fields, including machine learning, evolutionary methods, and complex networks. In addition, more technologies have been combined with spatial analysis and simulation, including parallel, grid and cloud computing. Current research displays three characteristics: (1) more micro- and macro-scale research; (2) dynamic research focused on processes; and (3) comprehensive studies based on the analysis of mechanisms. The growth of the big data era makes the relationship between geographic information science and high-performance computation closer, and facilitates research emphasizing process simulation and information services.

15.1.2 Contributions by Scholars from Different Countries

Table 15.1 shows the top 20 countries/regions by the number of articles on the study of spatial analysis and simulation published in SCI/SSCI-indexed journals. Over the last 15 years, research in this area has developed so fast that the number of articles has increased six-fold from 2000 to 2014. The share of articles for the top 20 countries/regions is more than 88 % of the total. The statistics show that the number of articles published by scholars in the USA is far greater than other countries. Further, eight out of the top ten countries are European or North American. The other two are China and Australia.

Compared with other counties, China has experienced a rapid growth in the study of spatial analysis and simulation in the last 15 years. Specifically, the total number of SCI/SSCI-indexed articles from China has increased from 10th to 2nd place while the citations increased from 5th place in 2000–2004 to 2nd place in 2010–2014, as did the number of highly cited articles. However, using average citations per article in 2014 (i.e., the citations in 2014 divided by the number of articles published in the same year), we find that China falls out of the top ten countries, which indicates a gap in the level or impact of research between China and Western countries.

15.1.3 Key Research Topics

We used a keyword co-occurrence graph to identify the research topics in the study of spatial analysis and simulation. The idea is that if several keywords co-occur in many articles, then they are clustered in the graph, which may then indicate a topic. As a result, a topic can be identified by finding the clustered high-frequency keywords in the co-occurrence graph. We found five significant clusters (Fig. 15.1). The first is located in the mid-left of the graph, and includes the keywords "object", "scenario", "time", "space time", "semantic", "fragmentation", "geospatial", "context", "ontology", and "generalization". Keywords mentioned above indicate the topic of "semantic relationships between geographic objects". The second is located in the mid-right of the graph, which covers many keywords, including "GIS", "spatial information", "representation", "classification", "scale", "DEM", "spatial association", "cluster", "decision making", "spatial analysis", "space", and "uncertainty". These keywords represent the topic of "spatial representation

Table 15.1 Top 20 countries (regions) with the number and citations of SCI/SSCI-indexed articles on "Spatial Analysis and Simulation" during the period 2000–2014

	Number of articles						Cited frequency						Number of highly cited articles					
	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014
Rank	World	109	642	656	1,417	2,847	World	2,393	352	14,124	18,688	10,956	World	7	0	45	78	145
1	USA	32	149	170	398	724	USA	690	109	3,684	6,009	3,145	USA	3	0	14	26	43
2	China	2	89	63	146	393	China	44	29	738	1,252	1,191	China	0	0	2	6	17
3	UK	23	36	81	107	221	UK	374	22	1,894	1,269	1,008	Germany	0	0	3	2	12
4	Spain	3	36	15	47	144	Germany	94	21	758	547	647	Italy	0	0	2	5	8
5	Australia	3	37	28	69	128	Spain	121	14	319	655	544	UK	0	0	7	3	7
6	Germany	5	29	19	43	122	Netherlands	45	14	1,134	1,167	477	Belgium	0	0	2	4	7
7	Netherlands	4	28	24	75	115	Italy	41	9	394	858	455	Spain	1	0	2	2	6
8	Italy	2	20	15	54	111	Australia	56	44	527	768	415	Australia	0	0	0	2	6
9	Canada	5	22	32	83	108	Canada	101	7	472	1,384	376	Iran	0	0	0	0	5
10	France	3	17	20	31	71	Belgium	41	5	582	612	342	Netherlands	0	0	5	5	4
11	Belgium	1	17	11	31	60	France	81	9	454	356	304	Canada	0	0	0	8	4
12	Iran	0	6	1	5	45	Sweden	67	5	334	275	161	France	1	0	2	1	4
13	Brazil	1	12	4	19	41	Switzerland	0	6	259	514	137	Norway	0	0	0	0	4
14	Japan	4	6	25	39	38	Japan	25	2	214	434	112	Ireland	0	0	0	0	3
15	Switzerland	0	9	13	30	38	Turkey	0	1	42	226	89	Switzerland	0	0	1	3	2
16	Sweden	2	12	9	13	36	Brazil	39	1	79	163	85	Japan	0	0	0	1	2
17	Turkey	0	9	8	9	36	Taiwan, China	0	0	78	186	74	Taiwan, China	0	0	0	1	2
18	Austria	0	13	3	14	29	Finland	0	0	274	135	63	Sweden	0	0	1	2	1
19	South Korea	1	11	7	12	27	Greece	0	8	157	210	43	Finland	0	0	1	1	1
20	Greece	0	6	7	16	22	Israel	142	1	236	113	27	Greece	0	0	0	2	1

Note Countries (Regions) ranked by the number of articles, cited frequency and number of highly cited articles during the period 2010–2014

and analysis". The third is located to the left of the second, and includes the keywords "interpolation", "autocorrelation", "spatiotemporal", "distance", "regression", "geographically weighted regression", "statistics", "modeling", "grid", and "mapping". These keywords imply the topic of "spatial estimation". The fourth is located at the left of the graph, and includes the keywords "dynamics", "cellular automata", "evolution", "genetic algorithm", "time geography", and "movement". These keywords symbolize the topic of "geographic simulation". The fifth is located at the bottom of the graph, and is composed of keywords such as "visualization", "interactive", "mobile", and "reconstruction". These keywords indicate the topic of "geovisualization". From these five clusters, we were able to identify the main topics in spatial analysis and simulation research and the specific meaning of each topic.To analyze the temporal change of the five topics from 2000 to 2014, we divided each topic into one or more subtopics, each of which was the combination of several keywords. Ten subtopics were generated as follows: "ontology", "interpolation", "spatial analysis", "trajectory", "DEM", "point pattern", "vector analysis", "network analysis", "simulation" and "visualization". The number of published papers on each subtopic can be obtained by summing the frequencies of keywords in each subtopic. The frequencies for each subtopic were then summed for every five-year period. Figure 15.2 shows the statistics for these three periods. Four plots are included in the figure. From left to right there are, the statistics for 2000–2014, 2000–2004, 2005–2009 and 2010–2014 as a whole. The two bars for each subtopic in Fig. 15.2 indicate the total number of papers published by international scholars (excluding Chinese scholars) and those by Chinese scholars on this subtopic. The summed frequencies of keywords for international scholars in each subtopic showed a linear increase over the three periods. The frequencies of keywords in the majority of subtopics for the third period increased by 4–6 times compared with the first period while for Chinese scholars the frequencies increased by 6–13 times. Among all subtopics, those related to spatial data analysis occupied the largest proportion, including "spatial analysis", "trajectory" and "DEM" while for the remainder of the subtopics, the frequencies from high to low were "visualization", "simulation", "interpolation" and "ontology".

15.1.4 The Role of NSFC in Supporting the Research on Spatial Analysis and Simulation

To analyze the role of NSFC in supporting spatial analysis and simulation research, we divided the five abovementioned topics into fifteen subtopics: "data representation model",

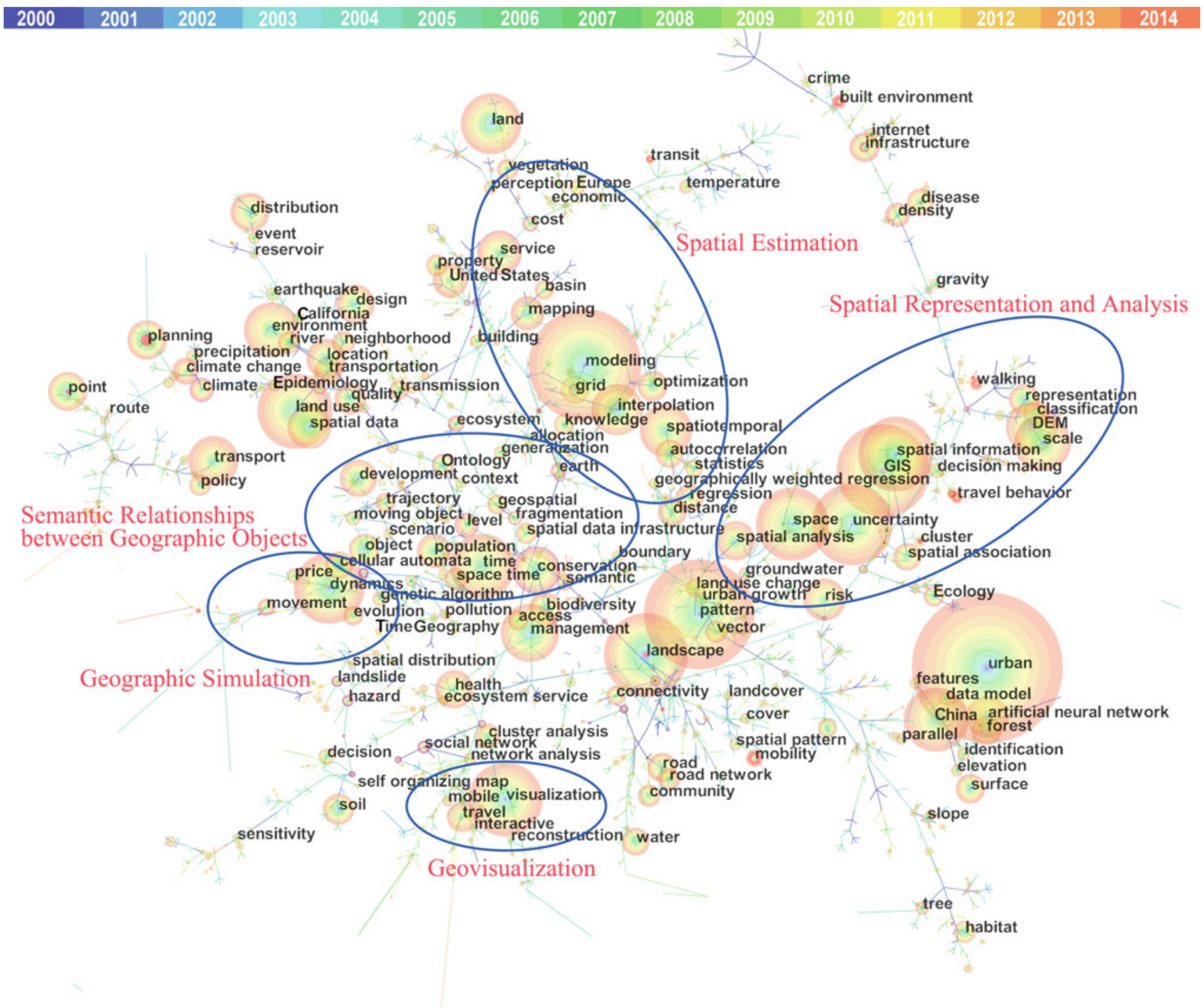

Fig. 15.1 Co-occurrence network of SCI/SSCI-indexed article keywords on "Spatial Analysis and Simulation" during the period 2000–2014

Table 15.2 NSFC-funded projects and SCI/SSCI-indexed articles on "Spatial Analysis and Simulation" during the period 2000–2014

SCI/SSCI-indexed articles					NSFC-funded projects			
Periods	Number of articles	% of articles by Chinese authors	% of articles with NSFC funding by Chinese authors	% of articles funded by MOST among those with NSFC funding	Number of projects	Funding (10,000 yuan)	Number of PIs	Number of institutions
2000–2004	656	9.6	41.3	0.0	43	1,356.0	40	20
2005–2009	1,417	10.3	32.2	21.3	100	3,369.0	95	50
2010–2014	2,847	13.8	66.9	44.5	280	15,791.0	262	105
2000–2014	4,920	12.2	55.8	37.8	423	2,0516.0	349	124

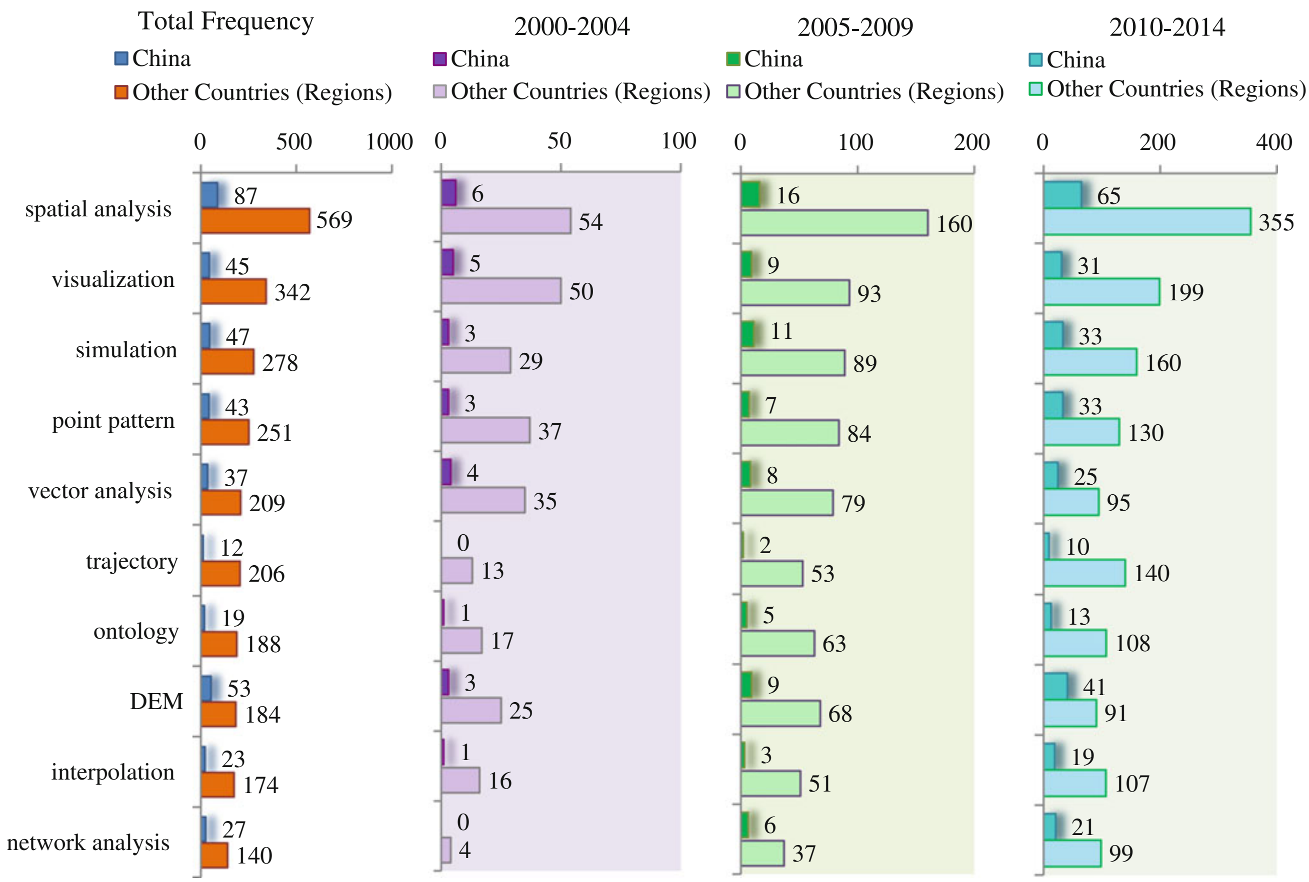

Fig. 15.2 Keyword temporal trajectory graph for SCI/SSCI-indexed articles on "Spatial Analysis and Simulation" during the period 2000–2014

"terrain analysis", "spatial data mining", "spatiotemporal process simulation", "spatial analysis", "geovisualization", "virtual geographical environment", "space-time optimization", "path analysis", "network analysis", "spatial interpolation", "location-based service", "spatiotemporal reasoning", "vector analysis" and "geo-ontology". Figure 15.3 shows the temporal variation of funding for different subtopics in spatial analysis and simulation from 2000 to 2014, where each column represents the number of projects funded by NSFC. Note that the names of subtopics in Fig. 15.3 may not match those in Fig. 15.2 because they are collected from NSFC-funded projects. From 2000 to 2004, subtopics of the "data representation model" and "geovisualization" and the analysis of different types of data received the large proportion of funding compared with other topics. From 2005 to 2009, the pattern changed to some extent. The proportion of "data representation model" decreased while those of "DEM" and "spatial data mining" increased. In addition, "network analysis" and "location-based service" were newly supported subtopics. In the past 5 years, new subtopics were funded by NSFC, including "path analysis" and "geographic ontology".

Table 15.2 lists the statistics for spatial analysis and simulation. From 2000 to 2014, 423 projects were funded by NSFC. The number in the latest 5-year period was 2.8 and 6.51 times more than during the first and the second 5-year periods, respectively. The total amount of funding was more than 200 million RMB. Specifically, the funding in 2010–2014 was more than ten times that in 2000–2004. In the last 15 years, 124 organizations and 349 individuals were supported by NSFC. The percentage of articles supported by NSFC increased from 41.3 % in 2005–2009 to 66.9 % in 2010–2014. The numbers of articles supported by NSFC in these periods showed a similar incremental rise. Over the last 15 years, 55.8 % of the SCI/SSCI-indexed articles were funded by NSFC, showing the significant effect of NSFC support on the research.

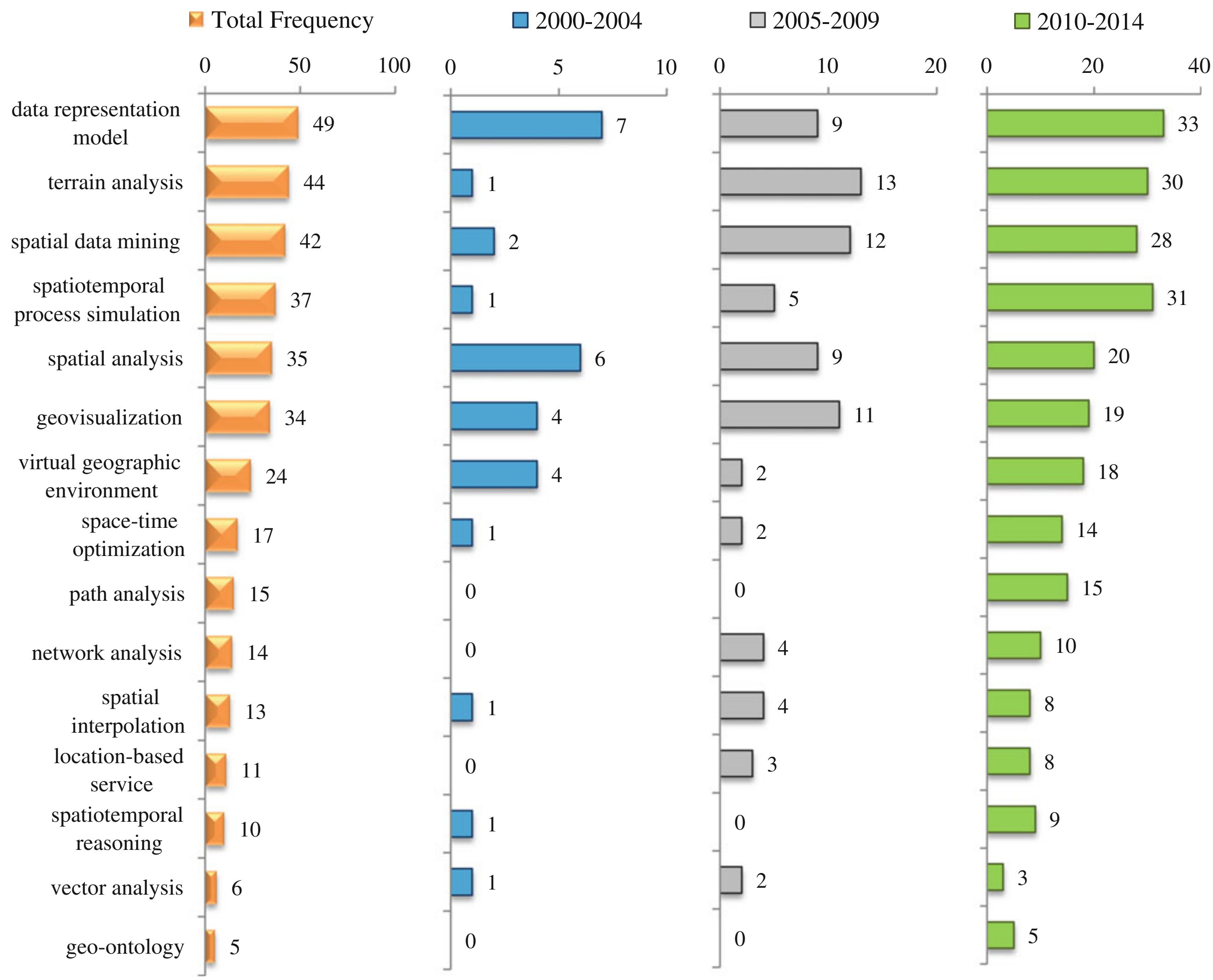

Fig. 15.3 Keyword temporal trajectory graph for NSFC-funded projects on "Spatial Analysis and Simulation" during the period 2000–2014

15.2 Questions and Research Progress

Five topics in the research of spatial analysis and simulation have been identified from Fig. 15.1. The developments connected with these five topics are described in an orderly fashion following the logic of research in spatial analysis and simulation below. The first is "What is the essence of geo-objects and their relationships?" corresponding to the cluster of "semantic relationships between geographic objects" in Fig. 15.1. The second is "How to express and analyze the spatial relationships between geographic features?", corresponding to the cluster of "spatial representation and analysis". The third is "How to make a more accurate spatial estimation?", corresponding to the cluster of "spatial estimation". The fourth is "How to simulate evolutionary geographical systems?", corresponding to the cluster of "geographic simulation". The fifth is "How to display spatial information and realize human-computer interaction?", corresponding to the cluster of "geovisualization".

15.2.1 What is the Essence of Geo-objects and Their Relationships?

The study of spatial analysis and simulation targets spatial aspects of the real-world located across large spatial regions. The first topic of spatial analysis and simulation should be geographical ontology, which helps to clarify the research objects of spatial analysis and simulation. A geographical ontology deals with the constituents of geographical reality and the relations between them, defines taxonomies of different types of geographical objects, geographical fields, spatial relations and processes, and builds their formal representations.

Contemporary Research

"Ontology" in the philosophical sense is often synonymous with Aristotle's "metaphysics", which is "the study of being qua being". There are two senses in which the term ontology is used. The first is in the philosophical tradition. The second is used in research on artificial intelligence and knowledge representation. As a philosophical discipline, Ontology (without the indeterminate article and with an uppercase initial) deals with the nature and organization of reality (Guarino and Giaretta 1995; Guarino 1998). In the artificial intelligence (AI) community, an ontology (with the indeterminate article and with a lowercase initial) refers to a particular determinate object (Guarino and Giaretta 1995; Guarino 1998). In the knowledge representation or AI application, it is usually not obvious what is to be represented, so an ontology of the concepts and principles of the particular subject has to be built (Lehmann 1992). Basically, an ontology describes a hierarchy of concepts linked by relationships; meaning axioms are added to infer more relationships between concepts and to constrain their interpretation (Guarino 1998). In this sense, Gruber (1993) defined an ontology as "an explicit specification of a conceptualization". More specifically, Studer et al. (1998) listed four characteristics of an ontology: conceptualization, explicit, formal, and shared. Since it has these characteristics, ontology has been widely used in many fields of computer science, such as natural language understanding, knowledge acquisition, and object-oriented database design (Guarino 1995).

Ontology was first introduced to geographic information science by Egenhofer and Mark (1995) in their paper about naïve geography. They argued that the design of intelligent GIS should incorporate the concepts and methods people use to infer information about geographic space, and the cognitive and epistemological differences among different domains or human groups must be treated appropriately, which makes research on geographical ontology increasingly important (Egenhofer and Mark 1995). An ontology of the geographical domain helps yield a better understanding of the structure of the geographical world. On the one hand, geographical ontology identifies the basic elements of commonsense conceptualizations of geographic space, entities, and processes from a theoretical perspective; and on the other, ontology built by integrating geospatial data and software standards make it possible for semantic interoperability and spatial data transfer (Mark et al. 2000). The two aspects of geographical ontology reveal that research on ontology in geography can occur either in the philosophical sense or in the sense of information systems and applications.

Research on geo-ontology in the philosophical sense focuses on geographical categories and their roles in cognition which clarifies human knowledge, beliefs and representation of geographical entities. Human subjects research for eliciting geographical knowledge, which is mentioned by Mark et al. (2000), could also be included in this area. The main scholars studying ontology in a philosophical sense are Barry Smith and David Mark. They proposed the objective, the importance and the content of geo-ontology research, indicating there are different types of properties, features, and entities in geographical reality which can be approached theoretically in various ways (Smith and Mark 1998, 2003). A series of experiments were conducted, which indicated that a difference exists between scientific geographers and ordinary people when conceptualizing geospatial phenomena, and basic ontology terms can carry different meanings when combined with different adjectives indicating geographical or mappable characteristics (Smith and Mark 2001; Mark et al. 2001). Geographical objects are not merely located in space, but also tied intrinsically to space, which means that their spatial boundaries are in many cases the most salient feature for categorization. Thus an adequate ontology of geographic objects must also contain a topology (Smith and Mark 1998). On this topic, Smith and Mark (2003) asked "Do mountains exist?" as objects, mountains are not among the most typical examples since mountains have no crisp boundary on the Earth's surface. Since then, more work has been conducted on the cognitive and language issues of geo-ontology. Some have studied the names and descriptions of geographical entities given by different languages (Mark and Turk 2003; Feng and Mark 2012). Others have studied the ontology of geomorphological landscapes, such as mountains, surface water, and bays, forming a cognitive perspective of views, and providing a method of extracting and modelling topographic features based on cognition (Sinha and Mark 2010; Sinha et al. 2014; Feng and Bittner 2010).

Much more work about geo-ontology has occurred in the sense of information systems, with research on the methods and tools for describing, assessing, comparing and integrating geo-ontologies for the purposes of interoperability and cross-system translation (Mark et al. 2000). Consistency constraints placed on a database are the foundation of Geographic Information Systems. Unfortunately, in real-world situations, rules for consistency constraints are not clear, and inconsistent ontologies are commonplace. Frank (2001) suggested five tiers of ontology for GIS: human-independent reality, observation of physical world, objects with properties, social reality, and subjective knowledge. Such an ontology can integrate different ontological approaches in a unified system. Based on the five tiers, Frank (2003) studied the ontology for spatiotemporal databases. Examining the fuzziness and uncertainty of some knowledge about geospatial categories, Sen (2008) presented a framework for encoding probabilistic information in geospatial ontologies based on the BayesOWL approach for rich references of similar concepts within and across ontologies. Within the application of domain ontologies, there are ways of integrating hydrological models and GIS for monitoring hydrological systems by modelling surface hydrological concepts with endurance and perdurance (Feng et al. 2004). This includes identifying components of various hydrological models for interoperable processes by using a concept lattice ontology method and semantic reference system (Bian and Hu 2007).

With the development of semantic webs and information retrieval, geo-ontology is used more and more in solving problems of context and semantic inference in information systems. Geo-ontology and semantics have been used in disambiguating place names in place ontology or digital gazetteers (Abdelmoty et al. 2007; Jones and Purves 2008), in the reasoning context of spatial data models (Cai 2007), in building reference rules for relational queries (Zhang et al. 2010), and in deriving ontologies and places from observation data and unstructured text (Janowicz 2012; Adams and Janowicz 2015). Other applications include context-aware geographical information retrieval and personalized recommendations for tourist attractions (Keßler et al. 2009; Huang and Bian 2009).

Different to the philosophers' way of building ontologies from the top down, for database and AI systems people tend to work from the bottom up, starting with limited ontologies or microworlds (Sowa 2000). An ontology can be formally represented with ontology languages, including frame-based, semantic web, and description logic languages. Currently there are more than ten ontology languages, which can be classified into traditional syntax ontology language and markup ontology language. Ontolingua, KIF, Loom, OKBC, OCML and FLogic belong to the former, and the latter include XML, RDF, RDF Schema, OIL, DAML, OWL, and DAML + OIL. Comparisons of several ontology languages in web environments lead to the conclusion that OWL is the more powerful language for semantic representation (Huang 2006).

Accompanying the study of the theoretical implications of ontology are software and tools for building ontologies, including Ontolingua developed by the Knowledge Systems and AI Laboratory at Stanford University, Protégé developed by the Stanford Center for Biomedical Informatics Research at the Stanford University School of Medicine, OILEd and OpenKnoME developed by the University of Manchester, and OntoEdit developed by the University of Karlsruhe, to name a few. Among these, Protégé, which is an open-source ontology editor written in Java, is the most popular. It is an expandable knowledge model, with different customized formats of output files and the provision of user APIs, which makes it a widely used ontology editor and knowledge acquisition system.

Bibliometric Analysis of Contemporary Research

From Fig. 15.2, we can see the trend of research in the topic of geo-ontology, which is represented by the subtopic of "ontology". The number of published papers in this topic increased during each 5-year period, especially in the last 5-year period during which the number was almost five times more than that in the first 5-year period. However, despite the increasing number, the proportion of papers by international scholars in this field did not increase, and even decreased over the period 2010–2014. Generally, the research output on the topic is not high compared with other topics, which suggests its non-dominant position in GIScience.

Bibliometric Analysis of Contemporary Research in China

The study of ontology in China started later than in Western Countries, but it has increased more rapidly than other fields. The proportion of papers by Chinese scholars on this topic compared with the total during the last 10 years (2005–2009 and 2010–2014) is higher than from 2000 to 2004 (Fig. 15.2), which indicates more attention has been paid to ontological research recently. The status of projects funded by NSFC for different topics is shown in Fig. 15.3. The topic includes the subtopics "geo-ontology" and "data representation model". The figure shows that geographical ontology research received funding from NSFC for the first time in the last 5 years while the number of funded projects for data representation models from 2010 to 2014 was almost five times that of the period 2000–2004.

Contemporary Research in China

Research on geographical ontology in China started at the beginning of this century, when He and other scholars used ontology in geographical information encoding (He et al. 2003). The first doctoral dissertation about geo-ontology was produced by Wei Cui in Wuhan University, in which the author discussed the socialization of geographical information, and explored methods of using ontology to integrate geographical information systems with other systems to realize semantic interoperation (Cui 2004). Later, in his book "Study on Key Issues and Application of Geo-ontologies", Huang analyzed the basic concepts of ontology, and emphasized the formal representation issues of geo-ontologies (Huang 2006).

In recent years, research on geo-ontology in China has mostly focused on semantic sharing, system integration and interoperability, knowledge inference, and geographic information query and retrieval. Such work includes spatial relation representation and reasoning based on ontology and SWRL (Wang and Cao 2007; Li and Li 2009), semantic integration and intelligent representation of spatial data (Wang et al. 2009a), and multiple representation in GIS based on description logic ontology, multi-scale and multi-application integration of geo-spatial data (Zheng et al. 2006). To improve the efficiency of spatial information queries, Li (2007) proposed an optimized query formula based on ontology and then developed intelligent queries based on knowledge and semantic levels. Other works focused on spatial information query and retrieval include building a context-aware and geographical knowledge-informed digital gazetteer service (Liu et al. 2009; Liang et al. 2010), and realizing natural-language queries of spatial relations based on geo-ontology and spatial relation semantics (Du et al. 2010a, b; Zhang and Xu 2011).

Contributions by Chinese Scholars and Subsequent Problems

Chinese scholars have made a strong contribution to ontological research in terms of formal representation, semantic integration and sharing, and spatial information queries, which are all addressed within the information system sense of ontology. However, little has been done within the philosophical sense of ontology. Working on the information system sense of ontology is practical and effective in solving the problems within geographic information systems at the current time. However, if intelligent GIS based on naïve geography is to be constructed, the study of the epistemological and cognitive aspects of geographical concepts, relations and processes is unavoidable. In addition, no ontology language or ontology tool has yet been developed in China.

Future Research

Currently, ubiquitous internet availability, and the wide use of personal communication and positioning equipment and sensor webs, provide us with large volumes of geographic data. This type of crowd-sourced data contains many inconsistencies, and much of the data are recorded in an unstructured way, which is semantically ambiguous. Knowing how to extract clear and formal representation from unstructured data and how we can infer meaningful descriptions of geographic events from observations are key problems in big data mining. The current data and text mining, statistical, and other analytical methods of finding correlations and patterns in big data should be combined with geo-ontology, spatial cognition and semantic content (Obrst et al. 2014; Devaraju et al. 2015). At the beginning of big data's emergence, it attracted interest in data mining. As research work progresses, people will find that ontology and semantic analysis are prerequisites for in-depth learning using big data.

Chinese has many differences to English in perceiving and describing spatial ontologies, which provides Chinese scholars with a good opportunity to research Chinese geo-ontological descriptions and information extraction. From the trends of publications and NSFC-funded projects (Figs. 15.2 and 15.3), we can see that the research of Chinese scholars into geo-ontology has rapidly increased, and the funding of ontology research is also increasing rapidly. Hopefully, Chinese scholars will take this opportunity to match the study of ontology in other countries, and even play a leading role.

15.2.2 How to Express and Analyze the Spatial Relationship Between Geographic Features?

The expression of spatial relationships between geographical features is a prerequisite for understanding geographical phenomena and semantics, and is the basis of spatial estimation. Therefore, this topic is at the core of the study of spatial analysis and simulation. The essence of modelling and analyzing spatial relationships is to reveal the spatial patterns of geographical phenomena, which can be deduced from the spatial relationships between geographic units, features and systems. Based on the modelling methods of geographical features, spatial data can be divided into five types: vector, grid, lattice, event and network. The diversity of geographical information leads to a variety of spatial relationships, and the review of the advancements in the field of "spatial representation and analysis" is organized according to the types of spatial data.

Contemporary Research

Formal Models for Semantic Analysis of Topological Relationships Recent developments in formalizing topological relationships have mainly focused on spatial cognition and linguistics. The goals are to present formal theories and models to transform geometric representations in databases into relational linguistics for human cognition, and to conduct spatial reasoning, geographic information retrieval and spatial knowledge representations. Five aspects are highlighted: formal models, uncertainty modelling, qualitative reasoning, scale issues, and qualitative locations.

Owing to the gap between geometric representations and cognitive concepts, the formal models aim to transform geometries into topological concepts. Two well-known models were presented for this purpose: the 9-intersection (Egenhofer and Herring 1991) and the region connection calculus (RCC, Cohn et al. 1997). The former can handle points, lines and polygons, while the latter was designed for regions. Since the 9-intersection model cannot distinguish between disjunct and adjacent relationships, Chen et al. (2001) presented a Voronoi-based model to classify topological relationships in more detail.

Geographic features are vague in semantics and uncertain in spatial extents, as are topological concepts. The two models mentioned above were extended to handle the vagueness and uncertainty. To account for the vagueness in semantics, the fuzzy 9-intersection (Shi and Liu 2007; Tang et al. 2010) and the fuzzy RCC (Schockaert et al. 2008) were presented to describe the degree of membership between geometries and relations. To handle the influence of uncertainty, uncertain objects were first modelled as regions with broad boundaries, then the extended 9-intersection (Clementini and Di Felice 2001) and Egg-yolk theory (Cohn and Gotts 1996) were used to model their topological relationships.

The formal models seek to transform geometries into relational semantics, while qualitative reasoning aims to investigate possible combinational constraints between different topological relationships and the consistency issues of qualitative relationship networks. Existing achievements in this field include topological reasoning with the 9-intersection model (Egenhofer 1994), RCC (Li and Ying 2004), and the extended 9-intersection for handling uncertain regions (Du et al. 2008).

Multi-scale abstractions of geometric representations and multi-granularity of cognitive concepts cause topological relationships to vary over different spatial scales. The contributions in this field mainly relate to multi-scale representations for multi-granularity concepts by considering different map generalization operators, such as region merging (Tryfona and Egenhofer 1997), collapse operations (Kang et al. 2004), attribute reduction (Du et al. 2010c), and generalization of topological invariants (Egenhofer et al. 1994).

Current models in GIScience regard Cartesian or spherical coordinate systems as the frames of reference to describe the absolute or geometric locations of geographic features in the coordinate systems. However, humans often use topological terms or natural languages to describe the relative or qualitative locations of geographic features, especially in geo-social media and text-based data. Unfortunately, current models cannot handle qualitative locations. Over the past decades, some interesting models have been investigated for modelling partial locations (Casati and Varzi 1999), rough locations (Bittner and Stell 2002) and multi-scale qualitative locations (Du et al. 2014). These new models bridge the gap between geometric locations and qualitative locations.

Digital Terrain Analysis Digital Terrain Analysis (DTA) aims to describe landforms quantitatively by deriving topographic attributes (e.g., slope gradient, curvature, and specific catchment area) and extracting terrain features (e.g., ridges and drainage network) from digital elevation models (Zhou and Liu 2006; Yang et al. 2009). Many geographical studies and applications are heavily reliant on DTA. With the rapid development of remote sensing and surveying techniques [e.g. Shuttle Radar Topography Mission (SRTM) and Light Detection and Ranging (LiDAR)], DEMs have been enhanced in terms of precision and resolution (Hengl and Reuter 2008), which prompted research on new algorithms, tools and applications of DTA.

Recent progress in DTA can be summarized from three main aspects. First, new topographic attribute algorithms (Gallant and Hutchinson 2011; Krebs et al. 2015) and even new topographic attributes (Gallant and Dowling 2003; Qin et al. 2009; Minár et al. 2013) were proposed to describe landforms more accurately or from a new angle. The second aspect of progress is on quantitative methods for evaluating DTA algorithms (Orlandini et al. 2012; Qin et al. 2013; Qin and Hu 2014). These methods were used to evaluate the performance of DTA algorithms, such as the scale effect (Gao et al. 2012), and uncertainty due to the data quality of DEMs (Hani et al. 2014). Third, the parallelization of DTA was proposed to speed up the data-intensive and compute-intensive DTA process (Tesfa et al. 2011; Qin and Zhan 2012), in which the key research issue is on the universal parallel strategy of DTA algorithms.

Compared with various kinds of widely-used topographic attributes, landform elements (e.g., summit, backslope, or saddle) are basic morphological units of the land surface and reflect the regional terrain context in a comprehensive way, which is important for geographical analysis (Deng 2007; Minár and Evans 2008). However, it is still difficult to automatically classify or map landform elements to aid terrain-related modelling. Existing methods adopt either a clustering strategy or a classifying strategy. The cluster-based methods (Burrough et al. 2000; Drăguţ and Blaschke 2006) apply a crisp or fuzzy cluster algorithm to a user-assigned set of topographic attributes and then each cluster is seen as a specific type of landform element. However, the cluster results do not always correctly match landform element types. The classification-based methods (MacMillan et al. 2000; Qin et al. 2009; Jasiewicz and Stepinski 2013) conduct classification under the supervision of a system of predefined landform elements, which can address the problem with the cluster-based methods. The question of how to classify the landform elements effectively is still open to debate, mainly because of the complexity of landform elements, including semantic fuzziness, multi-scale characteristics, and uncertain spatial support domains. Recent progress in mapping landform elements shows a new, promising direction for DTA research.

Anomaly Identification of Lattice Data Lattice data are referred to as the attribute values in polygon statistical units, such as the social and economic data in administrative units. The main approach to lattice data analysis was focused on anomaly identification. The key to this problem is the accurate identification of the location, size, shape and significance of a spatial anomaly. One of the solutions is the use of spatial scan statistics (Kulldorff 1997), which originated from the Geographical Analysis Machine (Openshaw et al. 1987). The early stage of spatial scan statistics is compatible with anomalies of simple shapes but the method becomes ineffective when facing complex anomalies due to the limitation of the window shape used for scanning, which is usually defined as a circle or ellipse. To overcome this limitation, a method for analyzing arbitrarily shaped anomalies was proposed. The concept is to look for an arbitrarily shaped anomaly by combining close polygons. Because there are potentially many combinations of polygons, the search process is a NP-hard problem. To solve this problem, evolutionary algorithms were employed to identify the spatial anomalies. Representative approaches are based on simulated annealing (SaScan) (Duczmal and Assuncao 2004), genetic algorithms (GaScan) (Duczmal et al. 2007) and ant colony methods (Pei et al. 2011; Wan et al. 2012).

Clustering Analysis for Geographical Events Geographical event data can be divided into two types. One is a spatial point process and the other is a spatiotemporal trajectory. The task for the analysis of point process data is to identify the spatiotemporal clustering pattern. Since the point process data are usually characterized by arbitrary shapes, spatiotemporal coupling and pattern mixtures, different clustering methods were constructed to deal with the difficulties existing in the identification of clusters. Clustering methods can be grouped into the following types: grid-, model-, density-, and graph-based clustering methods. The idea of a grid-based clustering method is to transfer discrete spatial objects onto a mesh grid and then cluster cells based on their statistical properties. Recent approaches include the Statistical Information Grid-based method (STING) (Wang et al. 1997) and clustering with Wavelets (Wave-Cluster) (Sheikholeslami et al. 1998). The idea of a model-based clustering method is to find the clusters that can best fit the predefined model (Banfield and Raftery 1993). Fraley and Raftery (2002) proposed the model-based clustering method, where the cluster is presumed to follow a Gaussian distribution and the number of clusters can be determined by the Bayesian Information Criterion (BIC). However, the model-based clustering method cannot adapt to arbitrarily shaped clusters. The strategy of a density-based method is to group points with high densities into clusters. DBSCAN, the most commonly used algorithm, is able to identify arbitrarily shaped clusters (Ester et al. 1996). However, the choice of the parameters in DBSCAN is difficult to define. Aiming to address this problem, OPTICS was proposed (Ankerst et al. 1999). Later, a more automatic strategy was designed using the EM algorithm (Pei et al. 2006). The graph-based method finds clusters from a graph that is constructed with regard to the links between points. The clusters are then generated by breaking up the longer links. The graph-based clustering method is divided into three types in light of the linkage strategies between points. The first is based on Delaunay Triangulation, such as TRICLUST (Liu et al. 2008a), the second is based on the *k*th nearest graph, such as Chameleon (Karypis et al. 1999), and the third is based on Minimum Spanning Trees (Wang et al. 2002). The graph-based method is easy to implement but has a disadvantage that the choice of parameters depends on the user's experience.

The approach to trajectory analysis is focused on representation models and pattern extraction methods. Trajectory data are usually stored in spatiotemporal index tree models (Li and Lin 2006). Miller (2006) and Shaw and Yu (2009) later realized the storage, representation and inquiry for trajectory data in GIS. Based on this, visualization and accessibility methods were also implemented. The task for the analysis of trajectory data is to mine spatiotemporal patterns. There are two different strategies for trajectory pattern identification. The first is to find the similarity between trajectories. One typical approach is the identification of the common T-pattern in the neighborhood (Giannotti et al. 2007) or finding predefined patterns in unknown trajectory data (Gudmundsson et al. 2007). The second strategy is to find the difference. One approach is to cluster trajectory data as a whole (Nanni and Pedreschi 2006) and another is to first separate trajectories into units and then group them into clusters (Lee et al. 2008).

Pattern Identification for Spatial Complex Networks In geography, the relationship between geographic objects can be simplified as a spatial network, where each node has its location and is at a distance from others. Recent research can be summarized into three aspects. The first is the study of the nature of spatial networks using traditional network theory, which is mainly focused on transportation problems (Sen et al. 2003; Bagler 2008; Crucitti et al. 2006; Jiang 2007, 2009). The second is concentrated on the relationship between distance and linkage strength. Research has shown that the existence of "good friends" in social networks is dependent on distance and follows the distance decay law (Lambiotte et al. 2008). The third concerns community mining in the network. Although traditional community methods can be used to discover groups, the distance factor is neglected. If distance is considered in community identification, then different patterns can be identified (Guimerá et al. 2005; Barber et al. 2011).

Bibliometric Analysis of Contemporary Research

The status of this topic can be represented by several subtopics: "spatial analysis", "vector analysis", "DEM", "point pattern", "trajectory", and "network analysis". From Fig. 15.2, we find the published papers on this topic dominated the research from 2000 to 2014, which corresponds to its central location in the research field of spatial analysis and simulation. Although the number of published papers on this topic in the second and the third 5-year periods is greater than in the first, the magnitude of the increase varied. Specifically, the numbers of papers on the classic spatial analysis models in the third 5-year period, such as "vector analysis", "DEM" and "point pattern", are three to four times more than those in the first 5 years. However, the numbers for "trajectory" and "network analysis" papers increased 10 times. All statistics indicate that the topic is central to the research field but that "trajectory" and "network analysis" are recent hotspots.

Bibliometric Analysis of Contemporary Research in China

For Chinese scholars, the total numbers of published papers on this topic increased dramatically in all three 5-year periods. The proportion for all subtopics dominates the whole research field, and some even increased significantly during last two 5-year periods, such as "trajectory" and "network analysis". In Fig. 15.3, the funded status on this topic is represented by "terrain analysis", "spatial data mining", "spatial analysis", "path analysis", "network analysis" and "vector analysis", where the number of funded projects on "terrain analysis", "spatial data mining", "spatial analysis", "path analysis", and "network analysis" increased dramatically. Specifically, the number for the third 5-year period was ten times more than that in the first 5 years although those for "vector analysis" and "spatial analysis" only increased by around three times. All statistics show that Chinese scholars have made remarkable progress in some subtopics, such as "DEM", "network analysis" and "trajectory", compared with those of classic subtopics, such as "vector analysis" and "spatial analysis". The support from NSFC has played an important role in this topic.

Contemporary Research in China

The progress made by Chinese scholars covers the majority of the themes. For example, for vector data, Du et al. (2008) constructed a framework for vector reasoning. Yuan et al. (2010) proposed a framework for geometry representation and analysis based on geometric algebra. Regarding DEM analysis, Qin et al. (2007) constructed a wetness index based on an adaptive multi-flow algorithm. In addition, the digital geomorphology mapping method at 1:1,000,000 was established and geomorphological maps were first produced in China (Zhou et al. 2009). Regarding lattice analysis, Pei et al. (2011) and Wan et al. (2012) proposed a spatial anomaly identification method by applying the ant colony strategy and expanded it to identify multiple spatial anomalies. Pei et al. (2009) developed the mixture density decomposed theory for identifying patterns in point process data, which is inspired by the concept of the Fourier transformation. Regarding the research of networks, the progress made by Chinese scholars is focused on applications in air transport networks (Wang et al. 2010), road networks (Duan and Lu 2012, 2013), and social networks (Liu et al. 2014; Gao et al. 2013).

Contributions by Chinese Scholars and Subsequent Problems

The contributions made by Chinese scholars focus on topological relationship descriptions and reasoning, multi-direction terrain analysis, evolutionary-algorithm-based anomaly identification, spatiotemporal point process decomposition, hierarchical clustering of trajectory data and spatial community detection. However, compared with the progress made by Western scholars, the original achievements in the key algorithms for spatial analysis made by Chinese scholars are still insufficient. There are two main reasons. The first is that transdisciplinary research is insufficient, which means that novel models, especially in spatial analysis, are relatively rare in the studies made by Chinese scholars. The second is that Chinese scholars do not regularly put their research into practice, which means that the quantity of new and novel results is not comparable with the published articles.

Future Research

Owing to the 4V characteristics, i.e., Volume, Variety, Velocity and Value, big data will bring complexity to spatial analysis in terms of data structure and spatial relationships. Future spatial analysis methods should adapt to the changes brought by big data. The review on this topic shows that compared with the research carried out by Western scholars, those by Chinese researchers are insufficient in terms of originality and applicability. To develop this research in China, Chinese scholars should take the opportunity offered by the big data era to develop more original methods for big spatial data. Further, there is a strong national requirement for spatial analysis methods. Specifically, China is undergoing a rapid process of urbanization, and meanwhile, facing serious problems with population growth, resource use and environmental degradation. This requires the development of more effective methods to solve practical problems.

15.2.3 How to Make a More Accurate Spatial Estimation?

Another important part of the study of "spatial analysis and simulation" is to estimate unknown attribute values based on known sampling information and thereby reconstruct the spatiotemporal distribution. Accurate estimation is dependent on the spatial relationship between spatial elements and is also the basis for geographical simulation. There are two strategies for spatial estimation. One is based on the first law of geography (i.e. near geographic phenomena are more similar than distant ones), which uses local information to reconstruct global spatial fields. Recent approaches have focused on how to use secondary information, adapt to different supports and make estimates with fewer assumptions. The second is based on the relationship between geographical elements and environmental covariates. Recent developments are concentrated on how to accurately describe the relationship between geographical elements and environmental covariates and how to improve estimate precision. The main achievements are summarized in the following sections.

Contemporary Research

Spatial Correlation Estimation Models Spatial Correlation Estimation Models (SCEM) are based on the assumption of Tobler's First Law in geography, i.e., "everything is related to everything else, but near things are more related than distant things" (Tobler 1970). The aim of SCEM can be described as: Given a set of discrete points with a geographical location and attributes, find a function that can best represent the whole surface or predict values at unknown points. Traditional SCEM includes k-nearest neighbor, inverse distance weighting, polynomial interpolation, spline and kriging. In the last two decades, much progress has been made in spatial interpolation methods, especially in kriging methods. The main approach to kriging can be summarized as support transformation, assumption relaxation and multi-source information utilization.

Support transformation has greatly expanded the range of applications of geostatistics. Ordinary kriging is a method for estimating unknown points with known point samples. In some cases, however, it is necessary to estimate the average value of a block with known points, or unknown points with known blocks. Block kriging (BK) was invented to estimate the average value of a block in light of known point samples, and is recognized as an upscaling method (Isaaks and Srivastava 1989). Conversely, estimating unknown points in light of the known block values is seen as a downscaling process. Kyriakidis (2004) proposed area-to-point kriging (ATPK) and area-to-area kriging (ATAK), where the support is transformed from area to point, and area to area in the interpolation models, respectively. Goovaerts (2006) developed ATP Poisson kriging, which is able to consider both the size and the shape of geographical units and produces smaller weights for data with low reliability. Later, area-and-point kriging (AAPK) was built to couple categorical secondary data with primary variables to improve the precision of estimation (Goovaerts 2009).

To estimate covariance and semi-variograms, a second-order stationarity assumption is required in geostatistical models, but, in many cases, variables fail to meet the assumption. Up to now, there were two approaches to this issue. One is non-stationary estimation and the other is spatial heterogeneity estimation. In non-stationary estimation, a random variable can be seen as a summation of different spatial components. If a random variable can be decomposed into a deterministic trend and a stochastic residual, universal kriging (UK) can be used to model spatial non-stationarity (Stein and Corsten 1991). If the drift and residuals can be separated, kriging with external drift (KED) and regression kriging (RK) (Hengl et al. 2007) can be adopted to model them separately. In spatial heterogeneity estimation, a spatial variable can be seen as a set of spatially homogenous units. Spatial stratification has been seen as a spatial heterogeneity estimation method. Wang et al. (2009b) extended the kriging concept to estimate means across space with stratified non-homogeneity (MSN) by taking both spatial autocorrelation and spatial stratified non-homogeneity into account. After that, a B-SHADE (Biased Sample Hospital-based Area Disease Estimation) method was developed to deal with biased estimates in samples (Wang et al. 2011).

Linear kriging assumes an estimate is the linear combination of the nearest neighboring sample observations, requiring that the random variable is normally distributed. For this reason, it may fail to provide unbiased estimates for non-normal distributions, which may result in a smoothing effect where high values are underestimated and low values are overestimated. Non-linear kriging methods were hence investigated to reduce this effect. Disjunctive kriging was constructed to estimate target variables within which the distribution of samples is known but is unable to be represented by a simple model, say, normal distribution (Armstrong and Matheron 1986; Emery 2006). In addition, lognormal kriging was developed to take advantage of transformed data distributions to reduce the influence of a few high values of observations following a lognormal distribution (Yamamoto 2007).

When auxiliary variables are available, cokriging that can incorporate auxiliary variables can be used to improve estimation. As auxiliary information has changed in terms of structure and form, cokriging has been improved to adapt to different situations. Regarding exhausted auxiliary information that covers the entire area, collocated cokriging can be used to incorporate collocated auxiliary information into estimation at any location (Rivoirard 2001). When multiple variables coexist and can be decomposed at different spatial scales, factorial cokriging can be employed to improve estimation (Goovaerts 1992). If the target and auxiliary variables do not meet the stationarity assumption, universal cokriging may be used (Stein and Corsten 1991). Ge et al. (2015) developed a universal cokriging (UCK) model for multivariate sampling design optimization. In addition to universal cokriging, geographically weighted regression kriging (GWRK) was also developed for the utilization of auxiliary variables, e.g., Imran et al. (2015) adopted GWRK for the regional-scale mapping of crop yields in West Africa. Apart from traditional variables, temporal information also can be incorporated into interpolation models as an auxiliary variable, which extends spatial geostatistics into spatiotemporal geostatistics (Cox and Isham 1988). Kyriakidis and Journel (1999) proposed a framework for spatiotemporal geostatistics, which has been widely used in environmental monitoring (Liu and Koike 2007), soil moisture monitoring (Snepvangers et al. 2003) and geographical environment change (Heuvelink and Griffith 2010).

Estimation Based on the Relationship between Geographical Elements and Environmental Covariates The spatial distribution of geographical elements cannot only be derived based on the spatial autocorrelation of geographical elements in the spatial domain, but it may be also determined by their environmental covariates in the feature domain. The approach to spatial estimation was summarized in the previous section while in this section prediction with the assistance of environmental covariates will be summarized. The improvement of spatial information acquisition techniques reduces the cost of obtaining environmental covariate data, which facilitates spatial prediction based on the relationship between geographical elements and their environmental covariates. Current predictive mapping methods based on the relationship can be divided into the following two types.

The first type is a knowledge-based expert system. In an expert system, the relationship between geographical elements and environmental covariates can be acquired from field experts by using techniques such as artificial intelligence (AI). A typical approach is the Soil-land Inference Model (SoLIM) developed by Zhu et al. (2001). The expert system is suitable for areas with prior knowledge that can be acquired from local experts or extracted from relevant thematic maps (Qi and Zhu 2003; Yang et al. 2011). The expert system method is able to maintain the continuity and the consistency of knowledge in that experts' knowledge on the spatial distribution of geographic elements can be recorded and formulated into an explicit knowledge set. However, because of the lack of experienced experts and the limitations of existing thematic maps in terms of accuracy and spatial detail, the quality of the derived knowledge set is not guaranteed, and thereby limits the application of knowledge-based systems over large areas. To address the issue of subjectivity in experts' knowledge (Van Den Eeckhaut et al. 2005), researchers have started to integrate knowledge from multiple sources in predictive mapping (Aitkenhead and Aalders 2011). Meanwhile, artificial intelligence, fuzzy logic and expert knowledge were also combined to improve mapping accuracy (Vahidnia et al. 2010).

The second type uses data mining methods. These methods aim to extract quantified relationships between geographical elements and their environmental covariates using statistical analysis and data mining techniques (McBratney et al. 2003; Bucas et al. 2013). Those approaches have been popular over the past 20 years and most were developed by mathematical and statistical experts. Examples of methods include regression analysis (Guo et al. 2007; Razakamanarivo et al. 2011), discriminant analysis (Qiu et al. 2012; Zhang et al. 2015), Bayesian approaches (Porwal et al. 2006; Dlamini 2011), regression tree/decision tree models (Coimbra et al. 2014; Henderson et al. 2005), geographically weighted regression (Zhang et al. 2011; Kumar et al. 2012; Liu et al. 2013), neural network models (Maier and Dandy 2000; Erzin et al. 2008; Li et al. 2012), support vector machine (SVM) models (Yang et al. 2007; Petropoulos et al. 2012), and random forest models (Heung et al. 2014; Carranza and Laborte 2015). The advantages of these types of methods are twofold. First, the relationships between geographical elements and environmental covariates can be extracted adequately. Second, there is no restriction on the knowledge background of researchers. However, the limitations are obvious. The quantified relationship relies on the representativeness of the training sample set, which means that the sample data should accurately represent the relationships throughout a study area. This requires that samples are collected through a well-defined field sampling scheme (McBratney et al. 2000; Zhu 2000). Moreover, the extracted relationships are usually fixed at a certain scale. Therefore, when the mapping scale changes, the relationships may lose their effectiveness. As data mining methods have been extensively applied in fields such as minerals distribution, marine mapping, and soil distribution predictive mapping, much work has been done to compare different data mining methods for mapping accuracy, the required quantity of the training sample set, and model sensitivity (Park and Vlek 2002; Zhao et al. 2005; Cracknell and Reading 2014). To improve mapping accuracy, attempts to combine several methods have been made (Kumar et al. 2012; Guo et al. 2015).

Bibliometric Analysis of Contemporary Research

The research status of this topic is represented by the subtopic "interpolation" in Fig. 15.2. The number of published papers on the topic has increased steadily in all three periods. Specifically, the number for the third 5-year period increased five times compared with the first 5-year period. However, compared with other topics, the proportion for "interpolation" is small, and little change has been found across all periods. The statistics indicate that although the number of published papers has increased, the topic is not seen as the center of the whole research field. This does not mean the topic attracts less attention from scholars. On the contrary, in areas such as soil science and geology the core models for spatial estimation, including autocorrelation and kriging, have been extensively used. However, since these papers are published in different areas, the share of "interpolation" is not as high in GIScience research.

Bibliometric Analysis of Contemporary Research in China

From 2000 to 2014, the papers published by Chinese scholars increased dramatically, with papers in 2010–2014 almost 20 times the number of those in 2000–2004. More importantly, the share of this topic has increased substantially. Both show that Chinese scholars have made remarkable progress regarding this type of research. In Fig. 15.3, subtopics "spatial interpolation" and "spatiotemporal reasoning" can be seen as an indicator of the support of NSFC on this topic. The numbers of funded projects during the period 2010–2014 are respectively eight and nine times those during the period 2000–2004, while the incremental change for both subtopics is much larger than the average increment in the same periods. All statistics demonstrate a different trend to that for international scholars.

Contemporary Research in China

The main contributions of Chinese scholars are the estimation of heterogeneous surfaces, high accuracy surface modelling and geographical elements-environmental covariate modelling. Heterogeneous surface estimation includes four aspects: the MSN model for heterogeneous surface sampling, the B-SHADE model for bias sampling, single point assessment (SPA), and the ground-sampling-reasoning Trinity model (Wang et al. 2009a, 2011). Based on the weaknesses of classic surface modelling methods, Yue (2011) simplified the Earth's surface and environmental element grid as a mathematical surface. Based on differential geometry, a High Accuracy Surface Model (HASM) was built on the condition that global data were used as an initial field and local high accuracy data were used as optimization conditions. The HASM effectively solved the problem that has hindered surface modelling for about half a century. Zhu et al. (2001) constructed a spatial gradual change similarity model under a high resolution grid, which not only solved the problem of expressing geographical phenomena with categorical polygons, but also provided a feasible way for saving and expressing geographical information in a GIS. Centering on the soil pedogenics model, SoLIM achieved high-resolution soil mapping by integrating case-based reasoning, prototype theory and artificial intelligence. The efficiency was improved while the cost was decreased.

Contributions by Chinese Scholars and Subsequent Problems

In all, Chinese scholars have made substantial progress on three aspects. First, the sampling, interpolation and uncertainty estimation are firmly combined in the estimation model, and thus estimation precision can be controlled and improved. Second, geographical element-environmental covariate models have been realized at high-resolution scales. Third, the HASM has been built to generate higher precision than that achieved with traditional methods. Regarding the estimation method, although the estimation precision has been improved in previous research, the utilization of ancillary information is insufficient both in spatial estimation and the geographical element-environmental covariate model. This leaves opportunities for subsequent research, especially in the era of data enrichment.

Future Research

The development of spatial estimation in recent years focused on the extension of support, the relaxation of assumptions and the inclusion of more covariates. From Figs. 15.2 and 15.3, we can see that research conducted by Chinese scholars has made remarkable progress on this topic while the support from NSFC also increased faster than for most other topics. The big data era has brought unprecedented volumes of samples and additional information, and at the same time, new challenges for spatial estimation research. On the one hand, as the number of samples increases, the estimation variance tends to decrease. On the other hand, the increase in samples may also bring noise. Both influences are still not paid sufficient attention to solve the problem, so it is necessary to study how to design spatial sampling schemes, control sample bias and estimate earth surface parameters accurately using big data. As a result, we need to develop spatial sampling and statistical reasoning methods based on existing methods. If Chinese scholars can take this opportunity to catch up with future research, more original achievements can be generated for the topic.

15.2.4 How to Simulate Evolutionary Geographical Systems?

For a long time, the formation of diverse spatiotemporal patterns was regarded as the static equilibrium state of geographical systems. The development of modern geography has provided new understandings of geographical systems. They are now recognized as dynamic spatiotemporal systems composed of various natural and socioeconomic elements with complex interactions across different scales. Geographical phenomena are characterized by non-equilibrium, hierarchy, stochasticity, self-similarity and uncertainty. Besides the descriptions of the phenomena themselves, an understanding of how they evolve over time is also crucial. To this end, a framework of geographic simulations was established with the aim of exploring the evolution of complex geographical systems. Under this framework, a variety of geographic simulation models were developed to model, replicate and predict the dynamics of many spatiotemporal phenomena with respect to their composition, patterns or distributions (Li et al. 2009).

Contemporary Research

Geographical Cellular Automata Cellular automata (CA) are bottom-up simulation models which have been widely used to simulate land-use dynamics and ecological processes. CA are discrete in that space is modeled through a lattice composed of regular cells with equal sizes, while time is represented using discrete steps. In a CA model, the states of the cells belong to a finite set, and can change over time according to a pre-defined set of transition rules as well as neighborhood interactions (Zhou et al. 1999). Several features make CA successful in solving geographical problems: (1) CA are simple and easily implemented, complex patterns and system behaviors are modeled as the result of local interactions through a set of simple transition rules (Batty and Xie 1994); (2) CA can be integrated with GIS analysis tools, remote sensing images and other data sources to retrieve spatial constraints for simulating realistic urban phenomena; (3) CA are convenient for addressing the intrinsic complexity of geographical systems in combination with other models, such as spatial optimization models; and (4) CA are promising for many recent studies (e.g., global climate change) that take into account the impacts of long-term land-use change at large-scales.

The utilization of CA in urban studies dates back to the 1980s. Tobler (1979) suggested the use of CA to solve geographical problems. Subsequent work by many researchers includes: Couclelis (1988) who theoretically examined the problem of individual behaviors and change at a global scale; Batty and Xie (1994) who integrated GIS with CA to simulate urban growth processes; White et al. (1997) who used a constrained CA model to replicate land-use conversions in Cincinnati; and Clarke et al. (1997) who proposed the SLEUTH model that aimed to simulate urban expansion in Santa Barbara. Over the past 15 years, remarkable progress has been achieved in the development of CA-based urban simulation models. Many important models were developed and refined during this period, including Logistic-CA (Wu 2002), Decision-Tree CA (Li and Yeh 2004), ANN-CA (Li and Yeh 2002) and ACO-CA (Liu et al. 2008b). These CA models were applied to scenario simulations, providing support for real-world decisions in urban planning or resource management (He et al. 2006; Li and Liu 2006; Gong et al. 2009; Li et al. 2011, 2013b; Chen et al. 2013).

Multi-Agent System (MAS) A multi-agent system (MAS) is formulated by the integration of complex adaptive system theories, distributed artificial intelligence and artificial life techniques. At present, it has been an important method in complex system analysis and simulation. Its core idea is to generate macro patterns from the interactions of micro individuals with a view to exploring how local detailed variations reflect global complex behaviors. MAS consists of multiple interacting intelligent agents, which can move, communicate, interact and cooperate with other agents. Through the interactions and collaborations among multi-agents, MAS is able to analyze and simulate most macro complex systems. A geographical system is a typical complex system, whose dynamic development is determined by the interactions between a series of individuals, as well as those between the individuals and the environment (Li et al. 2007). Therefore, MAS should be a more effective tool to reflect the human-environment relationship in a geographical spatial system than traditional CA. With these advantages, spatial multi-agent models have been increasingly used in the simulation of geographical systems, and subsequently a number of academic papers on urban simulation have been published. The start of spatial multi-agent modelling designed to simulate urban dynamics was Schelling's segregation model (Krugman 1996), in which a chessboard is used to represent the city. Although the model is quite simple, it can reflect the self-organizing process of interactive individuals in a city, fully embodying the principle of "instability produces order". Subsequently, many scholars have extended the multi-agent model to simulate urban dynamic or geographic phenomena. For example, Benenson et al. (2002) used a multi-agent model to simulate the self-organization phenomena of urban dynamics, in which inhabitants can change their residential behavior depending on the residential economic conditions, property prices, and culture identification. However, the model is relatively simple since it only takes the resident agents into consideration. In another study on urban dynamics, Ligtenberg et al. (2001) developed a spatial planning model based on MAS. The most significant advantage of the model is that factors of government planning are introduced into agent behaviors. In addition, Epstein et al. (2007) established an epidemic model based on MAS. He simulated human activities and interpersonal interrelations within the geographic space and network topology, and tried to find the impacts of social relationships on the propagating processes of epidemic diseases.

Conversion of Land Use and its Effects at a Small Region Extent (CLUE-S) CLUE-S is an improved empirical statistical model based on the CLUE model. It was developed to simulate and visualize multiple land-use changes in a small region. An advantage of CLUE-S is the ability to simulate multiple land-use types simultaneously and reflect the competition among land-use types. Moreover, it is capable of achieving the optimal allocation of land patterns under a given condition or limited land resources. At present, the CLUE-S model has been widely used in the simulation of multi-scale land use/cover changes and the decision-making of land use policies. For instance, Wassenaar et al. (2007) used the CLUE-S model to simulate vegetation changes in the tropics of Central and South America and Trisurat et al. (2010) applied the CLUE-S model to analyze the influences of land-use change on the biological diversity in northern Thailand. Britz et al. (2011) predicted the changes of European agriculture landscapes in 2025 using a combination of CLUE-S and the CAPRI-Spat model.

Geographical Simulation and Optimization System (GeoSOS) GeoSOS, proposed by Li et al. (2009), is a computer-based system capable of simulating, predicting, optimizing, and displaying geographical patterns and processes. As a bottom-up approach, GeoSOS consists of three major integrated components, including cellular automata (CA), multi-agent systems (MAS), and swarm intelligence (SI). The integration of CA with MAS allows the system to address social and human factors to handle more complex simulation tasks. Another novelty of this proposed system is its ability to couple simulation models with optimization models. This proposed system can provide a new kind of functionality, which is complementary to that of existing GIS. GeoSOS can be used to simulate, predict, and optimize a variety of geographical phenomena, such as land development, land use changes, landscape and ecological evolution.

Bibliometric Analysis of Contemporary Research

In Fig. 15.2, the topic is represented by the subtopic "simulation", which includes keywords "dynamics", "cellular automata", "evolution", and "urban growth". During the three periods from 2000 to 2014, there was a steady increase in the number of published papers on this topic. The number during the third period is five-fold more than that during the first period. However, compared with other topics, the proportions for the simulation topic have not significantly changed in any period. The above observations demonstrate that studies on "geographical simulation" have made considerable progress in the last 15 years, but its development is relatively stable compared with that of other topics.

Bibliometric Analysis of Contemporary Research in China

Figure 15.2 shows that, similar to the topic of "spatial estimation", not only the quantity but also the proportion of the SCI/SSCI-indexed papers published by Chinese scholars on "simulation" increased. As illustrated in Fig. 15.3, the number of projects funded by NSFC on spatiotemporal process simulation grew dramatically during the last 15 years, from only one project in 2000–2004 to five projects in 2005–2009 and 31 projects in 2010–2014. The number in the last 5 years is 30 times more than in the first 5 years.

Contemporary Research in China

Since the end of the last century, Chinese scholars began to pay more attention to theoretical exploration and applied research on spatial-temporal geographical simulation. Such efforts mainly focused on three aspects: geographical process simulation based on cellular automata (CA), interactive modelling based on multi-agent systems (MAS), and the fusing of urban development simulation and spatial optimization. Zhou et al. (1999) put forward the concept of Geographical Cellular Automata (GeoCA) and proposed the first GeoCA model for spatial analysis and geographical simulation. Li and Yeh (2000) carried out extensive exploratory research on CA's transition rules, which has been applied to the Pearl River Delta (PRD) region for the simulation of urban expansion and land use changes. The simulation results under various scenarios are valuable for providing important references for urban planning in the PRD region (Li and Yeh 2000). Li and Liu made the first attempt to carry out studies on the CA model's configuration, including parameter calibration, simulation rules and data mining. They proposed to use the Artificial Neural Network (ANN), Ant Colony Optimization (ACO), Artificial Immune System (AIS) and other artificial intelligence-based data mining methods to automatically discover transition rules and adaptively calibrate model parameters (Li et al. 2007; Liu et al. 2008b, 2010b). Liu proposed a land use simulation model based on MAS, which was applied to the simulation of residential location selection and dynamic changes of land price (Liu et al. 2010a). In addition, Li et al. proposed a simulation framework for population dynamics by coupling Labor economics and MAS, and successfully simulating the spatiotemporal evolution of population under various scenarios (Li et al. 2013a). In 2009, Li et al. proposed to integrate the CA models, MAS and swarm intelligence models (SIMs) into a unified framework for solving geographical process simulation and optimization problems. This framework not only equipped various models to explore the patterns, dynamics and evolution of geographic phenomena, but also provided powerful virtual tools for spatial optimization and urban land use planning. Meanwhile, a universal software platform based on this framework, the Geographical Simulation and Optimization System (GeoSOS), was developed to support regional development analysis and urban planning decision-making (Li et al. 2009).

Contributions by Chinese Scholars and Subsequent Problems

In general, Western scholars started investigation on geospatial simulation theory earlier than the Chinese, but they did not establish a comprehensive theoretical framework and powerful tools of geographic simulation systems. Over the last decade, Chinese researchers have caught up and achieved remarkable progress, and received widespread approval from their international counterparts, especially in the field of complex geographical system simulation and spatial optimization. Moreover, Chinese scholars have developed various modelling tools and platforms with independent intellectual property rights (IIPRs), which have been widely applied to the study of typical rapid urbanization regions in China. The work of Chinese scholars has been widely cited. For example, Li, Yeh and Liu are among the top cited authors in IJGIS.

Yet deficiencies still exist in precise descriptions of a city's macroscopic physical space and microscopic behavior of individuals, as well as accurate simulations of complex human-land interactive processes. Existing models have been widely used for the simulation and optimization of small-scale urban regions, but deficiencies still exist regarding the simulation of large-scale metropolitan areas and investigation of macrogeographical mechanisms, as well as elaborate simulations based on social big data.

Future Research

In the future, the main objective of research on geographical simulation will be the accurate prediction of the development trends of geographical systems. Supported by social big data, geographers will mainly focus on solving the following problems: generalization and integration of geographical features from social big data; accurate description of the micro and macro geographical mechanisms and integration of various advanced methodologies, such as evolution methodology and artificial intelligence. As illustrated in Figs. 15.2 and 15.3, Chinese scholars have made rapid advances in geographical simulation in recent years, both in terms of academic publications and funding from NSFC. Meanwhile, with growing support from NSFC, Chinese scholars have made important international contributions in the field of CA-based urban LUCC simulation and MAS-based modelling.

Future research is expected to focus on establishing original geographical process models in the field of physical geography (e.g., soil erosion modelling, and watershed management), investigating social big data elaborated simulation models and high-performance large-scale geographical simulation models as well as global-scale LUCC simulation models, and strengthening the key role of geographical simulation in global and environmental perspectives such as ecological modelling and climate change studies.

15.2.5 How to Display Spatial Information and Realize Human-Computer Interaction?

Geographical visualization refers a set of tools to display large amounts of multi-dimensional information. The virtual geographical environment uses virtual reality technologies to realize multi-sense representations of geographical information and processes, collaborative analysis and computing, and virtual experience. Both provide human-computer interactions in multi-sensory ways based on spatiotemporal analysis and geo-simulation, to achieve the purpose of data exploration and decision making.

Contemporary Research

Geographical visualization is the transformation of data or information into pictures. NSF defined the term as "a method of computing … a tool both for interpreting image data fed into a computer, and for generating images from complex multi-dimensional data sets" in a report on visualization in 1987 (McCormick et al. 1987).

The combination of geography and visualization forms geographical visualization. Geographical visualization represents a set of cartographic technologies and practices that take advantage of the ability of modern microprocessors to render changes on a map in real time, allowing users to adjust mapped data on the fly (MacEachren and Kraak 1997). It combines methods of cartography, image analysis, explorative data analysis and GIS for analysis, exploring and representing spatial data and information (DiBiase 1990; MacEachren 1994). Taylor (1994) concluded the information transmission mode of mapping was a triangle composed of formalization, cognition and transmission modes, where visualization is located at the center of the triangle. Cognition and transmission modes are important components of visualization, while computer and multi-media techniques are the basic means of visual manipulation.

It is known that humans can reason and learn more effectively in the visual environment than in the textual or numerical environment. Therefore, using visual stimuli by converting large amounts of data or information into pictures can be an effective method of communication (Turner and McDerby 2008). Geographical data often have a varied range of different data and are thus complex to display and understand. A traditional single view of a display is hard to use for high-dimensional datasets. However, geovisualization can display multiple views of data, by use of coordinated multiple view techniques (CMV). With CMV, each of the views is linked together such that any user manipulation in one view is automatically coordinated to that of any other view. According to Roberts (2008), there are many types of geovisualization displays, which can be divided into seven categories: maps/cartograms, networks, charts/graphs, tables, symbols, diagrams and pictures. There are several tools to develop CMV, such as CommonGIS (Andrienko and Andrienko 1999), GeoVISTA studio (Takatuska and Gahegan 2002) and Improvise (Weaver 2004).

Since multifarious data sets of unprecedented size and complexity are rapidly accumulating, Andrienko et al. (2008) pointed out that traditional visualization approaches involving the direct depiction of each record in a data set are not effective. Data summaries such as aggregation, generalization and samples, and computationally extracted patterns are increasingly used (Andrienko et al. 2007; Guo et al. 2005; Guo and Zhu 2014; Slingsby et al. 2008). Geovisualization has been a combination of knowledge discovery, data mining and visualization.

Adaptive geographical information visualization is the ability of the visualization technique to adapt to a specific user, his or her tasks, and his or her current context. It is an important branch of geovisualization. Reichenbacher (2001, 2004) illustrated the process of adaptive and dynamic generation of visualizations for mobile users, and pointed out some key research fields involved. The aim of geovisualization is to improve the ability of human-computer interactions and reduce the load of cognition during those interactions. Research on adaptive visualization has developed in two directions: data-oriented adaptive processes and user-oriented adaptive services. The former means the intelligent processing of multi-source, heterogeneous and multi-scale data, and deals with data matching and integration issues for proper visual representation. For example, in order to keep the details of 3D objects in limited rendering space, Lu and Hammersley (2000) presented an adaptive visualization solution for interactively building large high resolution geometric models; Cignoni et al. (2003) used the technique called Batched Dynamic Adaptive Meshes (BDAM) for out-of-core rendering and management of large textured terrain. The latter direction aims to provide a customized map service for different people. For example, Zipf (2002) realized a prototype of MapAgent that can use the spatial and personal context as reference to generate personalized maps.

Virtual geographical environments are built on the foundations of geographic information systems and geographic information science in which considerable attention is paid to the user in terms of the manner in which they interact with the software (Lin and Zhu 2005b). It is extended from Michael Batty's virtual geography theory (Batty et al. 1998). Batty et al. (1998) implemented the "Virtual London" plan which planned the city in a virtual environment, and developed the concept of virtual geography. From the perspective of geovisualization, virtual reality, collaborative decision-making and GIS, MacEachren (2001) proposed the concept of the "Geo-Collaborative Virtual Environment", and developed a prototype. Hudson-Smith and Crooks (2009) tried to explore Neogeography in a virtual urban environment. They proposed that there would be a "Second Earth" with the integration of the technologies of digital earth and "Second Life".

Based on the theory of virtual geography, Gong and Lin (2001) proposed the concept of the virtual geographical environment (Gong and Lin 2001). It is a web- and computer-based geographical environment built for geographical understanding and problem solving by merging geographical knowledge, computer technology, virtual reality technology, network technology, and geographical multi-dimensional interpretations (Gong and Lin 2001; Lü 2011; Lin et al. 2013). The virtual geographical environment provides virtual environments that correspond to the real world to allow the conduct of open CAGEs, in which human–environment interactions can be represented, simulated, and analyzed (Gong and Lin 2001; Lin et al. 2009).

Bibliometric Analysis of Contemporary Research

The topic "visualization", including the keywords "visualization", "mapping", "representation" and "virtual geographic environment", in Fig. 15.2 shows the trend of research in geovisualization and virtual geographic environments. The number of SCI/SSCI-indexed papers in this field kept increasing during each 5-year period so that the number of papers in the last 5-year period is almost three times more than in the first 5-year period. Compared with other topics, it formed a relatively high proportion of spatial analysis and simulation research from 2000 to 2004, and the proportion has remained almost unchanged ever since. This illustrates that research on geovisualization and virtual geographic environments which are rooted in traditional maps continue to play an important role in the study of spatial analysis and simulation.

Bibliometric Analysis of Contemporary Research in China

Figure 15.2 shows that the number of papers concerned with visualization by Chinese scholars has steadily increased. The number of articles from 2010 to 2014 is six and three times more than that in the previous two periods, respectively. The proportion of papers on this topic during the period 2010–2014 is almost the same compared with the previous two periods. There are also more projects funded by NSFC on this topic in recent years (Fig. 15.3). From 2000 to 2004, there were only four projects each on "geovisualization" and "virtual geographic environment" funded by NSFC, while the numbers came to 19 and 18, respectively, in the period from 2010 to 2014.

Contemporary Research in China

Chinese scholars have conducted substantial work in the field of adaptive map visualization. Wang et al. (2012) wrote a book to introduce the concept of adaptive map visualization and its theoretical framework and methodologies. Ai and Liang (2007) and Yang and Sun (2008) explored the methods of designing variable scales, which can display detailed objects at short range in navigation systems. Li and Chen (2012) introduced an adaptive levels model for web maps, and illuminated the key research contents and techniques of each level. Zhang et al. (2004) and Yan et al. (2006) proposed service models for mobile maps from the perspectives of adaptive elements and adaptive policy, respectively.

The virtual geographical environment was first proposed by Chinese scholars based on the concepts of geographical visualization, virtual reality and distributed networks (Gong and Lin 2001). It has been paid increasing attention since its emergence, and has become a frontier of GIScience. In China, the work in VGE pays most attention to human needs and human-land relationships. Gong and Lin (2006) and Lü (2011) discussed the research framework of VGE, then suggested some virtual geographical experiments, putting forward the ideas of collaborative VGE and human-oriented GIS. Lin et al. (2009), Lin and Zhu (2005a) and Lin and Xu (2007) regarded the VGE as a type of geographical language, and explained the development of geographical language in the stages of maps, GIS and VGE. In addition, Zhu and Lin (2004) studied techniques related to the "digital city". Other researchers studied VGE on aspects of 3D GIS and virtual reality, such as virtual landforms and virtual battlefields (Gao et al. 1999), 3D underground models and virtual mines (Wu et al. 2002), virtual forest and fire simulation (Lin et al. 2006), and 3D virtual geo-environments (Meng 2006).

At the end of the last century, Chinese cartographer Chen Shupeng put forward the idea of using graphical methodology to represent geographical information, which is called the geo-information map. The geo-information map uses a series of multiple views of maps or diagrams to describe phenomena. It aims to illustrate the spatial and temporal distributions of geographical objects (Chen 1998, Chen et al. 2000). Geo-information maps have the function of visualized representation, which is helpful for discovering patterns with visual thinking, and they are computational maps which can be analyzed quantitatively. Since then, many scholars have studied geo-information maps and their applications in a number of fields including vegetation, hydrology, and land cover/land use (Zhou and Li 1998; Liao 2001; Ye et al. 2004; Luo et al. 2009; Tang et al. 2001; Zhang 2008; Chen et al. 2004).

Contributions by Chinese Scholars and Subsequent Problems

There are two aspects of the contribution of Chinese scholars in geovisualization and virtual geographical environments. One aspect is their proposal and work on geo-information maps. This is an original representation of knowledge in computable graphics to disclose geographical patterns. However, research in this field has not progressed far yet. Along with the rise of big data, there are a number of visualized methods of representing knowledge, such as knowledge maps or knowledge graphs. With the help of these new methods, research should progress in this field. The other aspect is that Chinese scholars have put forward the idea of taking human-land relationships into the virtual geographical environment to achieve real human-computer interaction with real-world geographical process simulation and computation. Currently, this is still at the stage of system design and platform building. To realize the human-land relationship in VGE, collaborations with physical and human geographers are needed.

Future Research

In the future, geovisualization research will attempt to solve key problems of massive data processing, multi-factor interactions, and fine-scale display using spatiotemporal big data, while the virtual geographical environment research should emphasise spatiotemporal integration of human-land relationships, and human-computer interaction on multiple scales. The statistical results of published papers and NSFC-funded projects (Figs. 15.2 and 15.3) shows that research on this topic in China is steadily developing.

Currently, China has advantages in the scene simulation of urban virtual environments based on the concept of the smart city. The development of the virtual geographical environment will front geospatial big data and focus on a multi-dimensional visualized analysis model within the framework of geo-information maps. Meanwhile, virtual geographical environment research should seek a breakthrough in urban geography and urban (social) computing. For this purpose, the performance of traditional geographical experiments in VGEs is encouraged. By doing so, VGE will potentially contribute to traditional geographical research. With geovisualization, the virtual geographical environment, and combining virtual and real experiments of human-land relationships, we hope that our understanding of human-land interaction at data, information, knowledge, and intelligence levels will improve.

15.3 Roadmap for Further Research

The study of spatial analysis and simulation, as the requisite analysis tool, has witnessed the progress of geographical science from qualitative to quantitative. In recent years, geographical science has stepped into the big data era driven by a number of factors. First, geographical research now extends to more micro and macro scales, forcing research to go further into examining suitable mechanisms. Second, the development of Earth observation sensor technology has substantially changed spatial information in terms of origin, coverage, formation and resolution. Third, the development of big data, the internet, and cloud computing technology has greatly enhanced the ability of information processing. Future studies for spatial analysis and simulation will show the following trends.

(1) Expansion of the Research Scope for Spatial Analysis

As the technology of earth observation develops, the information that describes geo-objects and their evolutionary processes provides geographical research with an unprecedented new angle of view. The change will make geographical sciences pay much attention to research at a larger scale, synthesis of different elements and spatiotemporal dynamics. Observation at the larger scale will cause the assumption of homogeneity, stationarity and linearity to lose their effectiveness, and instead, boost development of analysis methods for larger scales. The synthesis of elements can be seen as a higher level analysis which is associated with spatial data of different sources, formations and modes, and thus may promote methods of synthesis, correlation and simulation. Since Earth observation technology has enriched spatial information, it is possible to reconstruct micro- and macro-scale dynamic geographical processes. This will greatly promote methods for spatiotemporal visualization and dynamic simulation.

(2) Closer Combination of Spatial Analysis Methods and Geocomputation Technologies

In the big data era, data quantities have exceeded the processing ability of personal computers due to their volume and the rapid updating. Moreover, the characteristics of geographical big data (multi-source, heterogeneity and coupling of multi-elements) make traditional computational methods unequal to the task of spatial analysis and simulation. At the same time, the rapid development of high performance and cloud computation along with deep learning has provided a solution for big spatial data handling while the technologies of NoSQL and cloud storage serve as powerful storage and index tools for multiple data representation structures and multi-element coupling. As a result, future research should link spatial analysis and simulation methods and advanced computational technology. By improving the existing methods, we can realize more robust, parallel and synthetic computational models and thereby break through the bottleneck caused by big data.

(3) **Closer Combination of Spatial Analysis and Simulation Methods and Specialized Models**

Spatial analysis and simulation methods have played an important role in geographical research and boosted the qualitative to quantitative transformation of geographical science. However, from the development history for spatial analysis and simulation, we find insufficient links with specialized models and knowledge, which causes a disjunct between analysis methods for geographical problems. The reasons for this can be attributed to the over-strict assumptions, simplistic models and ignorance of the interactions between geographical elements that exists in spatial analysis and simulation methods. As geographical research develops in terms of coupling of multi-elements, synthetic study at multi-scales, research into mechanisms, dynamic simulation and spatiotemporal analysis, the dependency on observed data and models will grow stronger. This requires that a specialized model should be incorporated with spatial analysis and simulation methods. To make a breakthrough in terms of pattern analysis, mechanism models and spatiotemporal predictions, Chinese scholars should link their research to national requirements and incorporate their work with specialized models regarding urbanization, globalization, ecological environment protection and disaster prevention and control.

15.4 Summary

Spatial analysis and simulation is an important tool for the analysis of geographical problems. Analysis shows that its development is guided by two fundamental principles—those related to spatiotemporal correlation and regional heterogeneity. The research in spatial analysis and simulation includes five topics: “semantic relationships between geographic objects”, “spatial representation and analysis”, “spatial estimation”, “geographic simulation” and “geovisualization”. These five topics represent the inner logic for spatial analysis and simulation. Geographical information science grew with the quantitative revolution and developed because of its combination with GIS. Future development is found in three aspects. The first is from the demand for further investigation into mechanisms, the second is because of the enrichment of Earth observation information and the third is from interdisciplinary research. The past 30 years have seen international research make remarkable progress in terms of ontology for geographical objects, multi-factor spatial relationship analysis, multi-element spatial estimation, dynamic simulation, and geographical environment visualization and modelling. Chinese scholars have matched the pace of international research in many branches, and even led in fields such as geographical system simulation, non-homogeneous estimation and reasoning models, spatial point process decomposition, geographical virtual environments, and fuzzy expression for spatial relationships. However, generally speaking, there is insufficient original work from Chinese scholars compared with Western Countries. The reason could be that not enough effort has been made to combine spatial analysis and simulation with specialized models and interdisciplinary research. The arrival of the big data era provides a chance to study geographical phenomena comprehensively, systematically and accurately, and also brings challenges for the development of spatial analysis and simulation. Chinese scholars should develop their studies of spatial data cognition, spatial relationship analysis and spatial information mechanism modelling to provide methodological and technical support for understanding Earth surface systems.

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16 Tempo-Spatial Processes and Modelling of Environmental Pollutants

Yuanming Zheng and Chunye Lin

Abstract

The research on the tempo-spatial processes and modelling of environmental pollutants is an important area of environmental science. The hotspots include the modelling, tempo-spatial distribution, emission inventories, source identification, species and bioavailability, and exposure and risk of aerosols, POPs, PAHs, toxic elements, and nutrients. In this chapter, the contributions to this study area by different countries are discussed. The achievements by Chinese scholars, mainly sponsored by NSFC, are further indicated. Chinese scientists have developed global high-resolution fuel combustion inventory (PKU-FUEL-2007) and modelled and then tested global-scale transports of PAHs and black carbon.

Keywords

Spatial and temporal variations • Source apportionment • Bioavailability • Fate • Risk

A total of 37,107 SCI/SSCI-indexed articles are analyzed in the research area of tempo-spatial processes and modelling of environmental pollutants. Articles were identified from 284 international journals from 2000 to 2014. The number of journals that have published more than 15 of the relevant articles is 196 (Appendix M). The search query is as follows: (“background” OR “baseline” OR “emissions inventory” OR “form” OR “species” OR “fractionation” OR “bioavailability” OR “interface” OR “transport” OR “transformation” OR “degradation” OR “environmental behavior” OR “source apportionment” OR “regional” OR “scale” OR “watershed” OR “spatial pattern” OR “environmental capacity” OR “fate” OR “migration” OR “transmission” OR “multi-media” OR “toxicity” OR “environmental risk” OR “ecological risk” OR “risk screening” OR “risk characterization” OR “early warning”) AND (“heavy metal” OR “POPs” OR “PAHs” OR “PFCs” OR “BFRs” OR “pesticides” OR “PPCPs” OR “eutrophication” OR “atmospheric particulate matter” OR “aerosol” OR “antibiotics” OR “non-point source pollution”).

16.1 Overview

16.1.1 Development of Research Questions

Among the many consequences of industrialization, urbanization, and rapid development of economics and society, humans are confronted with a series of environmental issues, such as continuing escalation of pollution and degradation of ecosystems. The contradiction of human-land relationship is becoming increasingly serious, which is threatening the sustainable development of human society and wellbeing. These problems have been experienced around the globe during the development processes of many countries. Under these circumstances, problem-orientated environmental science has emerged. Heralded by the Stockholm conference and “only one earth” publishing, environmental science has been evolving for more than 40 years, and now is faced with challenges arising from complex systems emerging with modern-day social and economic development. Through the

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ongoing interface with biology, chemistry, and the geosciences, etc., environmental science, the study of the environment, and the solution of environmental problems, has integrated the theories, techniques, and methods from these disciplines, forming an increasingly vital interdisciplinary academic field combining basic and applied research.

The problem-orientated attribution of environmental science has led to this subject being characterized by distinct geoscience features. For example, environmental problems always occur from specific tempo-spatial areas (sites), and they may differ in their regional characteristics. Therefore, solutions to more general problems may be achieved using the basic geographic theory of regional differentiation and regional comprehension. Consequently, the development of environmental science is closely related to the geosciences. In 1994, environmental geographer JS Chen noted that environmental science, geography, and ecology should be further integrated and developed towards more comprehensive research aimed at the "interaction of humans and their environment", calling for a "balanced development of economics and environment" (Chen 1994). Noted Chinese geographer BW Huang observed that geography, ecology, and pollution should be placed together under the topic of "environment" belong to "earth surface sciences". This, he believed, would help geography and ecology play more important roles in propelling environmental science research (Huang 2003).

The above suggests that research of a multi-scale and multi-disciplinary nature will be essential for the effectiveness of environmental science under the framework of the Earth Surface System; that responses, interconnections, adaption, and feedback among environmental factors and processes will be key features of scientific questions; and that increasing attention will be paid to comprehensive and long-term research (NSFC and CAS 2012). In "National Developing and Planning Outlines in Mid and Long Term for Science and Technology (2006–2020)", "Environment" has been recognized as an important field, as exemplified by four prior studies on "integrated pollution management and waste cycling; ecological function restoration and reconstruction in vulnerable areas; oceanic ecology and environmental protection; and global environmental change monitoring and countermeasures". It was also recognized that "Earth system processes and resources, environment and disaster effects" represents one of the frontiers of basic research.

Environmental research has become increasingly complex, triggered in part by its incorporation of computer technology, molecular biological technology, analytical chemistry technology, etc. It is becoming a comprehensive study of multi-dimensional problems encompassing different mediums—air, water, soil—and manifest at different scales, interactions among which are wrought with complexity in the following ways.

(a) Complexity of research objects (i.e., particular foci): From single to multiple combined pollution elements; from conventional to secondary or emerging pollutants.
(b) Complexity of observation approaches: Establishing a dimensional monitoring network including regular detection protocols combined with remote sensing and ground calibration; conducting integrated research on formation processes of environmental pollutants and their controlling factors.
(c) Diversity of migration media: Expansion of research from environmental behavior in a single medium to distribution, transport, and interaction between multi-media, especially at media interfaces.
(d) Diversity of research scale: Environmental behavior of pollutants and their effects are characterized by distinct tempo-spatial features. Thus, scale effects including temporal and spatial scales have been important foci of environmental research.

The foregoing has touched upon the scope of current environmental research. Within this, studies of tempo-spatial processes and modelling of pollutants are important components of research on environmental pollution and remediation. These studies essentially seek to better understand and summarize pollutant migration and transformation patterns, including multi-media processes and tempo-spatial evolution of pollutants, formation mechanisms, and modelling of regional pollution. The basis of these studies is the further exploration of the environmental behavior of pollutants via the use of models and GIS. The key challenge is the combination and matching of microscopic mechanisms and macroscopic processes, which is still a common problem in the geosciences.

16.1.2 Contributions by Scholars from Different Countries

In the past 15 years, along with the serious situation regarding environmental pollution, scholars worldwide have conducted extensive research on the tempo-spatial processes and modelling of environmental pollutants. Through investigating the literature from 2000 to 2014, the top 20 countries for SCI/SSCI articles on this subject are listed in Table 16.1. The 15-year time frame is divided into three periods—2000–2004 (P1), 2005–2009 (P2) and 2010–2014 (P3)—to compare the progress in terms of publications across different stages.

The quantity of SCI/SSCI publications has increased greatly over the past 15 years. With respect to total publications, the USA and China ranked 1st and 2nd, respectively. In 2000, only one country, the USA, published more than 100 papers. By 2014, there were 8 countries with more

Table 16.1 Top 20 countries (regions) with the number and citations of SCI/SSCI-indexed articles on "Tempo-Spatial Processes and Modelling of Environmental Pollutants" during the period 2000–2014

	Number of Articles						Cited Frequency						Number of Highly Cited Articles					
	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014
Rank	World	1,028	3,433	7,012	12,324	17,771	World	52,738	1506	319,150	352,307	132,192	World	157	0	967	985	948
1	China	24	820	340	1,528	3,585	USA	21,973	355	123,468	112,275	36,177	USA	63	0	392	381	338
2	USA	343	601	2,170	3,061	3,461	China	981	263	14,624	37,039	20,741	China	3	0	51	91	120
3	Spain	38	144	242	605	851	UK	3,336	51	20,952	19,103	6,479	UK	15	0	80	65	54
4	France	41	143	302	520	742	Germany	2,588	79	21,835	20,382	6,342	Germany	9	0	73	62	48
5	Germany	62	115	442	623	714	Spain	1,490	83	10,053	16,778	6,229	France	7	0	28	35	37
6	India	13	126	143	434	673	France	1,712	82	11,225	13,661	5,218	Canada	11	0	49	49	34
7	Italy	38	120	244	413	586	Canada	4,453	44	15,606	13,525	4,696	Italy	3	0	29	23	32
8	UK	59	95	399	539	584	Italy	1,490	50	9,952	9,822	4,387	Spain	3	0	33	42	30
9	Canada	54	104	336	435	561	India	467	43	4,398	9,836	3,699	Switzerland	2	0	20	29	26
10	Japan	30	78	256	384	425	Japan	1,165	29	9,091	8,524	2,790	India	2	0	11	23	23
11	South Korea	9	85	120	251	395	Australia	1,138	29	5,054	4,435	2,783	Netherlands	5	0	22	12	20
12	Australia	34	54	147	183	321	South Korea	246	38	3,740	5,257	2,681	South Korea	0	0	12	12	18
13	Brazil	6	62	71	165	298	Switzerland	518	30	5,134	9,685	2,644	Norway	0	0	5	12	18
14	Poland	11	53	92	179	257	Netherlands	1,277	18	7,709	5,089	2,447	Japan	4	0	20	17	17
15	Taiwan, China	13	39	113	198	244	Sweden	1,480	26	5,864	6,326	1,730	Australia	4	0	12	17	17
16	Netherlands	34	40	163	181	243	Denmark	1,270	28	5,224	3,793	1,527	Finland	1	0	8	7	14
17	Sweden	22	50	131	210	231	Finland	1,022	11	4,851	3,663	1,508	Denmark	3	0	14	8	10
18	Switzerland	11	43	90	206	229	Greece	493	18	4,333	6,140	1,380	Sweden	4	0	16	16	8
19	Turkey	11	47	85	217	223	Taiwan, China	384	11	3,666	3,776	1,214	Taiwan, China	1	0	8	6	8
20	Greece	11	30	97	190	195	Turkey	323	4	3,601	4,331	932	Greece	3	0	15	17	7

Note Countries (regions) ranked by the number of articles, cited frequency and number of highly cited articles during the period 2010–2014

than 100 annual publications. The quantity of publications in P3 increased by a factor of 1.5 over P1; and the proportion by the USA decreased from 30.9 to 19.5 %, whereas that by China increased from 4.8 to 20.2 %, with the quantity of publications increasing by a factor of more than 10. During P2, China reached the 2nd position in terms of total number of articles, and in P3 surpassed the USA to become No. 1.

With regard to citations and most frequently cited papers, for the USA the trend was that the proportion of total citations decreased gradually, and the extent of the decrease was not as obvious as that for the quantity of published papers. This indicated that the papers by the USA were high-quality publications, and its leading role in world scientific research was prominent. The progress of China in paper citations was significant: from below the top 10 in 2000 to No. 2 in 2014, surpassing many developed countries such as the UK and Germany. However, there was a large gap between China and the USA in terms of paper citations. The number by the USA was four times that of China. In general, the number of citations of an article receives is affected by the time that has elapsed since its publication. The earlier a paper is published, the more it is cited. For most-cited papers, China showed a similar trend to that of overall citations: significant progress was observed, and a large gap also existed with the USA. Most papers by the USA were cited three times as much as those of China. Thus annual variation could not reflect the variation in quality of publications for a country. Only a comparison between countries should be appropriate.

In summary, progress of Chinese scholars was distinguished and far exceeded the average level of the world. Meanwhile, two indexes reflecting paper quality—citations and most-cited papers—indicated that the USA plays a dominant role in this field. Moreover, comprehensive multi-index comparison in Table 16.1 suggests that scientific publishing is a very important index to reflect the level of science and technology in a country. The quantity of papers is basic and cannot be ignored, but quality is the goal and is an inevitable result after the accumulation of published papers reaches a certain level. This is a process of change from quantity to quality.

16.1.3 Key Research Topics

The keyword clusters in Fig. 16.1 reveal that the research objects (i.e. environmental pollutants) could be classified into heavy metals; organic pollutants (including PCBs and pesticides); PAHs (listed independently given the broad research); atmospheric particulate matter, and aerosols; nitrogen-/phosphorus-related with eutrophication; black carbon; and antibiotics, which cover conventional and emerging pollutants. This figure presents some clusters of keywords describing these objects.

Topic keywords expressing research contents were contained within each cluster, and these differed for each type of pollutant. Topics expressed in keywords could be summarized as follows: pollutant source; pollutant environmental behavior (adsorption/desorption, redox, precipitation/dissolution, degradation); pollutant fate (long-distance migration); pollutant spatial process (scale effect); environmental effects (bioavailability, toxicity, exposure assessment, risk assessment); and pollution remediation. Meanwhile, in each cluster, some specific environmental media were connected with the research objects (individual foci), and then keyword combinations of "object + medium + topic" appeared together to form several large clusters.

In Fig. 16.1, atmospheric particulate matter (ATM) and aerosols are typical air pollutants, which form an independent cluster. This cluster contains the keywords related to ATM characteristics, such as size and composition, as well as keywords related to optical properties, remote sensing identification, observation methods, and data analysis. Research on pollution sources, emissions, source apportionment, and models within this cluster was distinctly different from the others.

Pollutants, such as POPs, PAHs, and heavy metals, form another large cluster. This cluster was composed of 5 small clusters—i.e., organic pollutants, PAHs, heavy metals,

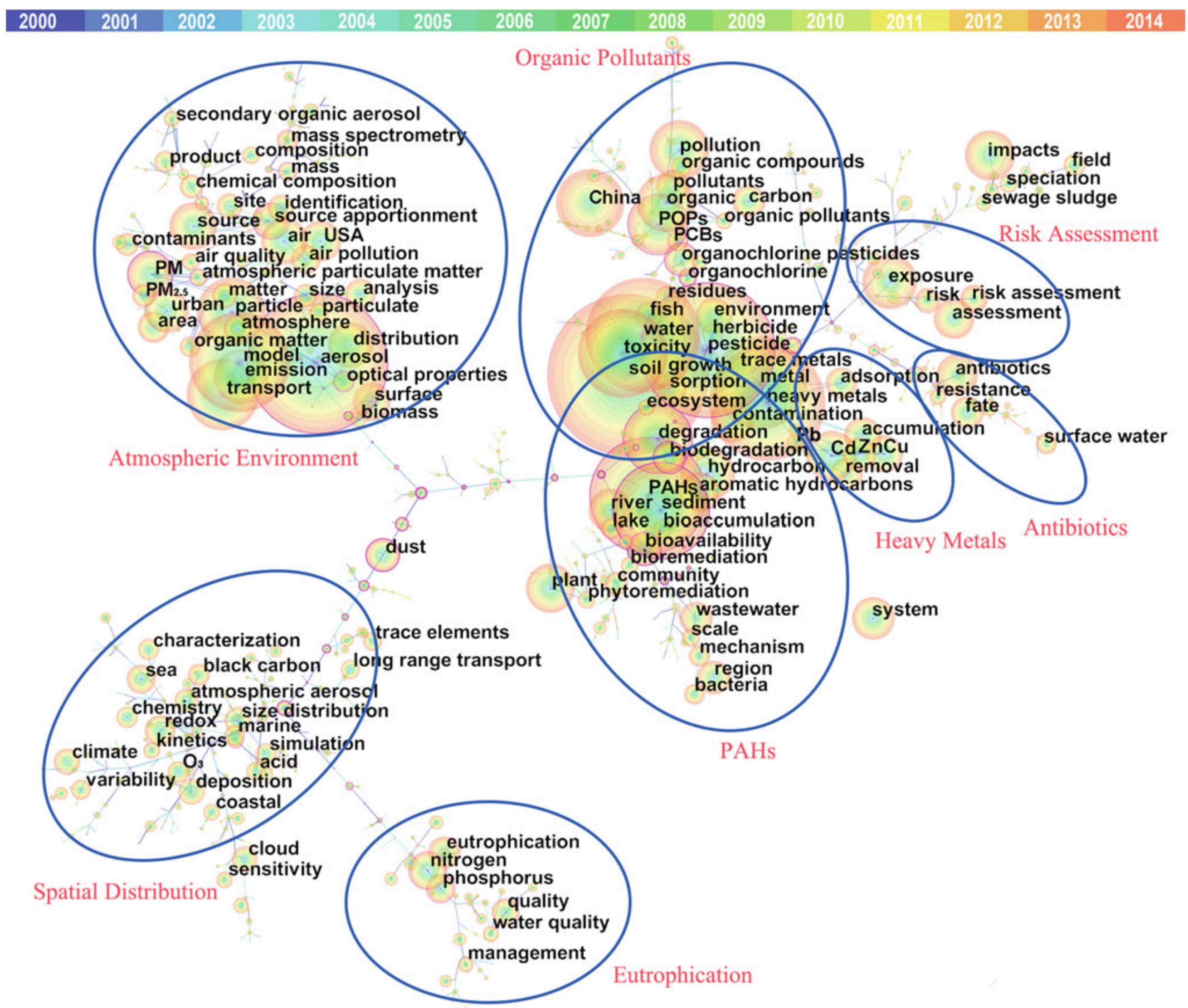

Fig. 16.1 Co-occurrence network of SCI/SSCI-indexed article keywords on "Tempo-Spatial Processes and Modelling of Environmental Pollutants" during the period 2000–2014

antibiotics, and risk assessment—which were linked across the words soil, water, and ecosystem. Except for toxicity, sorption, etc., every small cluster contains specific individual studies. Accumulation and removal are related to heavy metals and are typical pollution remediation words. Words related to residues and degradation (biodegradation) are linked with organic pollutants, especially PAHs, which are closely related to biodegradation and phytoremediation. PAHs in rivers, lakes, and sediments are foci of scientific research. Moreover, research on PAHs is linked with region and scale, showing the spatial perspective in these studies.

Although the cluster of risk assessment was relatively independent, it was still an extension of heavy metals and organic pollutant research, basically focused on exposure risk caused by these two types of pollutants.

Antibiotics and emerging pollutants were related to resistance and fate, especially in surface water. This was consistent with the current situation.

The cluster of eutrophication indicated that nitrogen and phosphorus were the core substances in this type of research. Their transport and transformation were research foci mainly in the water environment. Meanwhile, environmental management is becoming an important topic in this field.

The keyword "distribution" was linked with sea, aerosols, black carbon, trace elements, long-range transport, deposition, dynamics, variability, and simulation to form a cluster. This is related to pollutant distribution and long-distance transport, especially in oceanic areas.

Based on statistics for keywords in SCI/SSCI articles from 2000–2014 on the environmental behavior, fate, migration, and modeling of pollutants, the cumulative frequency of each keyword is presented in Fig. 16.2. The 15-year time frame is again divided into 3 periods—for 2000–2004 (P1); 2005–2009 (P2); and 2010–2014 (P3)—to compare the temporal progression of keywords across different periods. Meanwhile, comparison was also conducted between Chinese scholars and those from other countries (regions). According to the expression of keywords, three classes of keywords were obtained including environmental media, pollutant and research topic.

There were obvious changes over time for the keywords with high rankings in Fig. 16.2. For keywords in other countries (regions), the frequencies increased rapidly from P1 to P2 and then slowed down from P2 to P3. For China, there was a rapid increase in the last 10 years compared with P1. The rate of increase for China was much greater than that for other countries (regions). As the rate of increase slowed in P3, Chinese scholars shared an increasingly larger overall proportion of keywords in these scientific research fields.

In Fig. 16.2, water, soil, and air are three typical media in conventional research. Studies focusing on water and soil were much more frequent, than those of air globally. Compared with scholars from other countries (regions), Chinese scholars had much more similar quantities of studies about water and soil, while studies on air were relatively weaker.

With regard to the pollutant types, aerosols, pesticides, and heavy metals were given more attention by researchers from other countries (regions). High-frequency keywords were concentrated to some extent, and research on these pollutants was much more voluminous than that on other pollutants. The interest of Chinese scholars was focused mainly on heavy metals, PAHs, and pesticides. Concerns about aerosols and atmospheric particulate matter lagged behind their international counterparts, which was coincident with the lag in research on air in China. Therefore, atmospheric environmental research, which is much more urgent in terms of Chinese environmental issues, is greatly needed in the future. For emerging pollutants such as PPCPs, studies in China were consistent with those across the world. In the future, environmental research in China will likely continue to feature simultaneous work on both conventional and emerging pollutants.

Keyword frequencies for research topics varied greatly and a total of 11 high-frequency keywords cover tempo-spatial processes and modelling of environmental pollutants. The results of these highlighted word rankings between China and other countries were similar, but the number of Chinese scholars contributing to these various topics differed greatly. Among them, Chinese scholars paid more attention to environmental behavior and accounted for a relatively high proportion of overall articles; while for modeling research, the trend was opposite. Therefore, model research and its scaling require more input in future studies.

16.1.4 The Role of NSFC in Supporting the Research on Tempo-spatial Processes and Modelling of Environmental Pollutants

Keywords were searched in titles, abstracts and keywords of articles from 2000 to 2014 arising from NSFC-funded projects. Comparisons of the cumulative frequencies of keywords were conducted among different periods (Fig. 16.3). Keywords in NSFC programs can reflect trends in environmental science in China, where NSFC represents the frontier of related research. Altogether, frequencies of pollutant types and ranking of keywords are very different from the results of SCI papers. Keywords on heavy metals, as the main research objects of the programs, have the highest frequency during each period and increase steadily. POPs, including PAHs and pesticides, rank behind heavy metals as the second most important pollutant focus and show a trend similar to that of heavy metals. Moreover, nutrients, non-point source pollution, and eutrophication are also foci of research in NSFC D01 (geography) sponsorships, especially studies

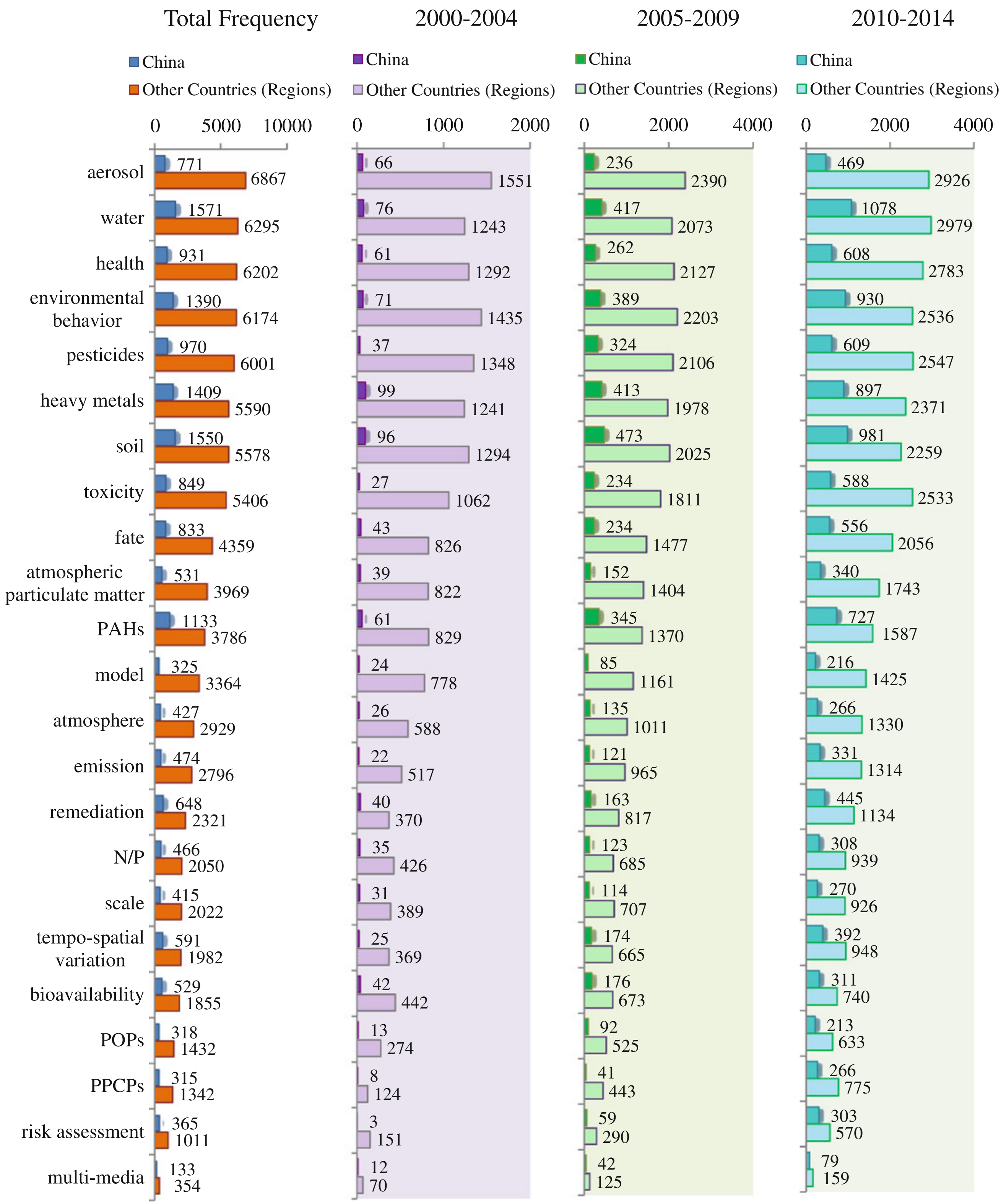

Fig. 16.2 Keyword temporal trajectory graph for SCI/SSCI-indexed articles on "Tempo-Spatial Processes and Modelling of Environmental Pollutants" during the period 2000–2014

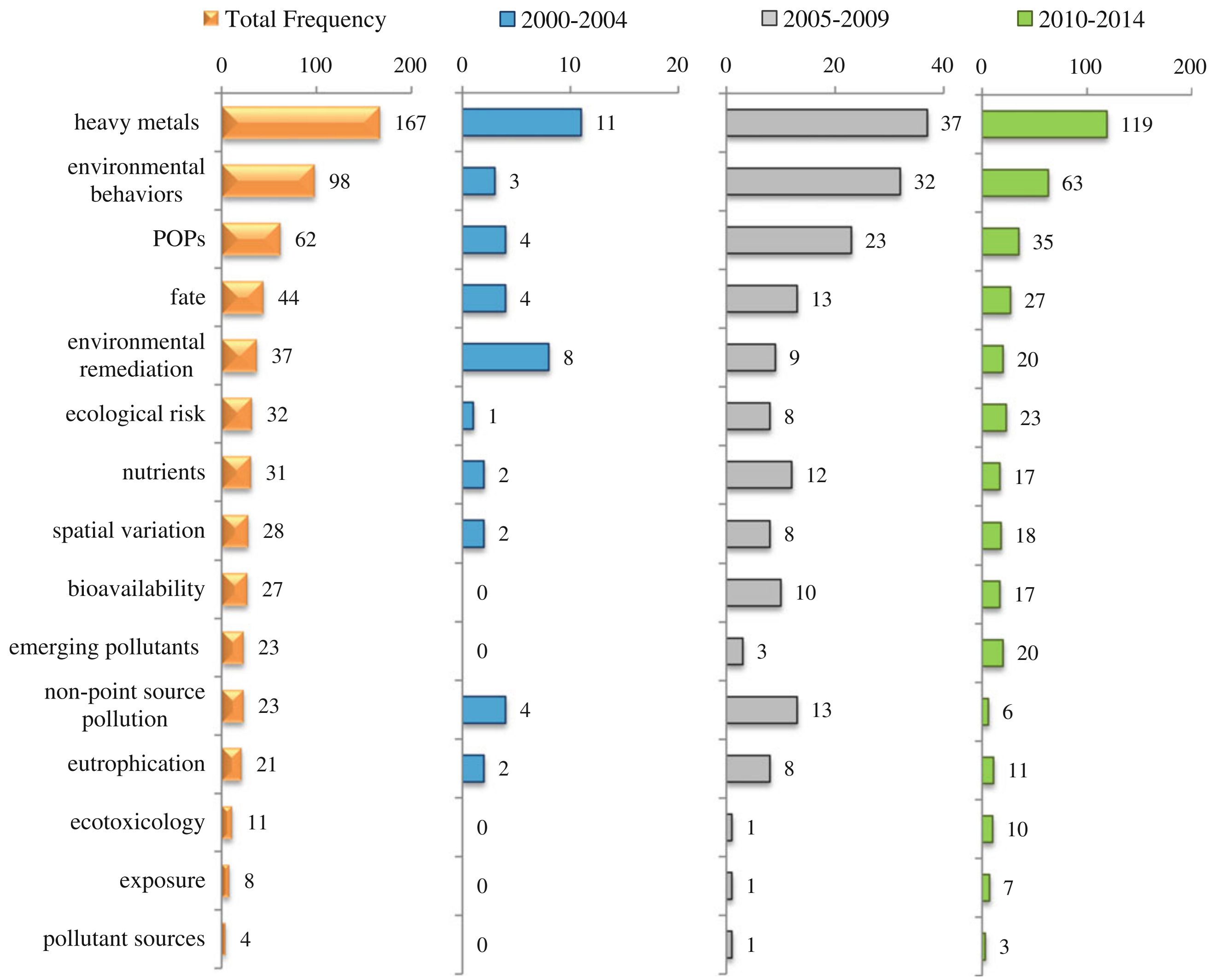

Fig. 16.3 Keyword temporal trajectory graph for NSFC-funded projects on “Tempo-Spatial Processes and Modelling of Environmental Pollutants” during the period 2000–2014

conducted in typical eutrophic lakes such as Taihu Lake. After the period of 2005–2009, these latter types of research increased slowly or decreased. This may be related with research expansion in recent years—for example, expansion into research on newly emerged pollutants. Although such expansion could still fall within the scope of non-point source pollution or eutrophication, no visible links between keywords of newly emerged pollutants and non-point source pollution are observed. Concern with emerging pollutants, represented by antibiotics and related resistant genes, varied over the course of the 15-year study period. At the beginning of this century, there were no efforts to study emerging pollutants. In the last 5 years, this type of research has increased greatly and ranks third, clearly reflecting the developmental trends of environmental science. Atmospheric pollutants account for a fairly small percentage of D01 sponsorships.

With regard to the research content, environmental behavior is a key focus of research, including migration, transformation, sorption, speciation, and degradation of pollutants, which is similar with statistical results of SCI papers. This is mainly because NSFC programs emphasize mechanism research, and researchers generally choose this type of research to initiate their scientific careers. Tempo-spatial pattern research, representing geo-scientific features including fate and spatial variation of pollutants, is an important pathway to funding, and shows an increasing trend year by year and should continue to strengthen.

Table 16.2 NSFC-funded projects and SCI/SSCI-indexed articles on “Tempo-Spatial Processes and Modelling of Environmental Pollutants” during the period 2000–2014

SCI/SSCI-indexed articles					NSFC-funded projects			
Periods	Number of articles	% of articles by Chinese authors	% of articles with NSFC funding by Chinese authors	% of articles funded by MOST among those with NSFC funding	Number of projects	Funding (10,000 yuan)	Number of PIs	Number of institutions
2000–2004	7,012	4.8	13.8	0.0	40	2,113.4	39	17
2005–2009	12,324	12.4	32.0	32.0	100	3,734.7	94	46
2010–2014	17,771	20.2	70.2	37.6	111	7,989.0	105	61
2000–2014	37,107	14.7	56.0	36.1	251	13,937.1	215	90

Research related to the interaction of organisms and pollutants is moderately funded by NSFC. Bioavailability research accounts for a moderate proportion of NSFC-funded articles, whereas the proportions of exposure and ecotoxicology are relatively low. A geographical disciplinary foundation might lead to a weak basis in these fields because related research was nonexistent at the beginning of this century. Source apportionment of pollutants is a particularly pressing research need at the moment.

Among the SCI/SSCI papers related with this tempo-spatial processes and modelling of environmental pollutants, 14.7 % were published by Chinese scholars (Table 16.2); and this proportion is increasing steadily year by year. Among these, 56 % were funded by NSFC, and in the last 5 years this number has increased to 70 %. This indicates that NSFC occupies a prominent status in basic research on Chinese environmental geography. Among the papers funded by NSFC, 36 % were also funded by the Ministry of Science and Technology (MOST). Compared with the quantity of published papers and sponsorships, the average scientific paper output for each NSFC-funded program has spectacularly increased substantially: from 1.2 papers for each program in 2000–2004 to 22.7 papers for each program from 2010–2014. On an overall basis, every program has produced 12.2 papers in the last 15 years. Meanwhile, underlying these numbers is a tremendous increase in research grants; approximately 0.22 papers are published per ten thousand yuan invested.

These sponsorships pertain primarily to 251 NSFC programs with 140,000 thousand yuan in grant funding. In total, 215 principal investigators (PIs) from 90 organizations have been funded. NSFC has continued to extend the scope of funding during recent decades regardless of recipient research organizations and PIs. In this way, research teams on Chinese geography have grown from a few dozen people to hundreds of participants. Currently, several important research organizations and research teams have been formed and are playing important roles in the development of Chinese geography, including such institutions as Peking University and Beijing Normal University.

16.2 Questions and Research Progress

16.2.1 How to Identify and Apportion Sources of Environmental Pollutants

Source identification and apportionment of environmental pollutants are critical to environmental protection and management. On the one hand, source-oriented models (transport or diffusion) have often been used to model the transport, transformation, fate, and spatiotemporal distribution of pollutants. For example, Wang et al. (2015) modeled the transport and fate of phosphorus and then estimated the global atmospheric deposition of phosphorus using global emission inventories. At the same time, receptor-oriented models have been used to identify the sources of environmental pollutants; e.g., lead concentration and isotope profiles of ombrotrophic peat were used to quantitatively identify the anthropogenic sources of lead and reconstruct the history of atmospheric lead deposition (Shotyk et al. 1998). In addition, the relationships between environmental pollutants and their sources have been investigated based on their tempo-spatial distribution. For example, spatial variation of deposition fluxes of PAHs has been related to PAH emission sources, local population density, and air concentration of PAHs. The PAH emission sources alone can explain 36, 49, 21, and 30 % of the spatial variation in spring, summer, fall, and winter, respectively (Wang et al. 2011).

Bibliometric Analysis of Contemporary Research

There have been 11,826 papers on pollutant source apportionment, modeling, and transport published since 2000 (excluding those published by Chinese scholars). Figure 16.1 shows that some keywords that are closely related to pollutant source apportionment, model, and transport include emission, distribution, particle, PM, urban, air, and the USA. These keywords show that aerosol, particle, and PM source apportionments are closely related linked to model, emission, transport, and distribution. The ten top most frequently utilized 10 keywords in this sub-field (excluding the papers published by Chinese scholars) are "aerosol" (2136), "PAHs" (999), "model" (897), "soil" (872), "particle" (818), "source apportionment" (789), "heavy metal" (763), "source" (716), "pesticide" (715), and "impact" (694). The number of papers published in this sub-field by non-Chinese scholars increased from 276 in 2000 to 1269 in 2014, indicating that atmospheric pollutant transport, distribution, modelling, and source apportionment are becoming key research fields.

Contemporary Research

Pollutant Background Content or Baseline Environmental pollutants generally originate from both natural and anthropogenic sources. Since the onset of human civilization, man has impacted the environment. Not surprisingly, therefore, the current surface environments show combined natural and anthropogenic footprints. A considerable rise in the concentration of heavy metals and organic compounds in different environmental media have been observed, compared to the "pre-industrial" period. The critical question is —what concentration is natural (geologic and/or biologic) and what concentration is unnatural (anthropogenic)? The pollutant background content or baseline is often used to differentiate the anthropogenic sources from the natural sources. The establishment of background concentrations in earth surface materials is important for at least two reasons: (1) it facilitates the distinction of contaminated or polluted areas (or concentrations of elements and organic compounds that are regarded as pollutants) from uncontaminated or unpolluted ones; and (2) it enables modelling of the anthropogenic influences on the mobilization, migration, and deposition/uptake of substances in the environment (Gałuszka 2007). In the 1980s, elemental background contents in the mainland soils of the USA were identified and published (Shacklette and Boerngen 1984). China conducted a survey of elemental background content in soils in the 1980s and also published the results (CNEMC 1990; Wei et al. 1991). The Global Geochemical Mapping Project has promoted the worldwide investigation and survey of elemental background contents or baselines in the earth's surface materials. This project is critical to understanding the past and forecasting the future (Chen and Yin 1991; Wang 2012). The China Geochemical Baselines Project (CGB) was launched in 2008, and sampling was completed in 2012 (Wang 2015). Its purpose is to document the abundance and spatial distribution of chemical elements covering all of China. The database and accompanying element distribution maps represent a geochemical baseline against which future human-induced or natural chemical changes can be quantified. Recognizing that the earth's surface materials (soils and sediments) are characterized by high heterogeneity, high-density surveys of elemental background content or baselines have been widely conducted around the world (Darnley 1997; Zhang et al. 2007; Jiang et al. 2013).

Source Identification and Apportionment of Pollutants In Fig. 16.1, the keywords "source apportionment" and "identification" cluster together with the keywords "aerosol", "model", "particle", "transport", "emission" etc., indicating that source apportionment and/or identification of aerosols and particles, especially in urban areas, have been the focal point of analyses and modelling of pollutant tempo-spatial processes. Figure 16.1 also shows that the USA has played an important role in the research area of aerosol source apportionment. In general, two types of approaches have been used in source identification and apportionment in Europe: (1) source-oriented (chemical transport or diffusion) models based upon pollutant emission rates and meteorological data; and (2) receptor-oriented models, especially for airborne particulate matter, based on statistical analysis of pollutant concentrations measured at a sampling sites (receptor sites) to infer the source types and estimate their contributions to the measured site concentrations. For the receptor-oriented models, there are generally three types of data input: ambient pollutant mass concentrations, source profiles, and meteorological data. In addition, there are extended models, which can process other types of information such as season, day of the week, and precipitation. In the 1960s, the USA initiated studies on aerosol source apportionment and identification and developed the receptor-oriented models such as factor analysis and chemical mass balance. Afterwards, Europe began studying source apportionment by employing receptor models. Over the period from 2000 to 2012, a shift was observed in the use of receptor-oriented models from principal component analysis, enrichment factors, and classical factor analysis to Positive Matrix Factorization, whereas Chemical Mass Balance is still employed for certain topics (Belis et al. 2013). In the past 30 years, acceptor-oriented models have been widely used and greatly improved and thus have become a major methodological tool for source apportionment and identification.

Tempo-spatial Distributions of Pollutants and Sources Pollution sources are generally classified into point sources and non-point sources. Currently, studies on pollution sources are focused mainly on the tempo-spatial distributions of atmospheric emissions and non-point sources. An accurate emission inventory could provide fundamental information for exploring pollution formation mechanisms and guide decision-making with respect to pollution control strategies. Hence, emission inventories of different types of pollutants at various tempo-spatial scales have been created and published. Streets et al. (2003) developed an inventory of air pollutant emissions in Asia in 2000 to support atmospheric modelling and analysis of observations taken during the TRACE-P experiment funded by the National Aeronautics and Space Administration (NASA) and the ACE-Asia experiment funded by the National Science Foundation (NSF) and the National Oceanic and Atmospheric Administration (NOAA). Bond et al. (2004) created a technology-based global inventory of black and organic carbon emissions from combustion. Atmospheric emission inventories of trace metals from anthropogenic sources and natural sources have also been developed (Nriagu and Pacyna 1988; Nriagu 1989). Pacyna et al. (2006) reviewed the state of knowledge regarding global emissions of mercury and presented a new inventory of global emissions of mercury to the atmosphere from anthropogenic sources for 2000. Pacyna et al. (2007) presented estimates of atmospheric emissions of As, Cd, Cr, Ni, and Pb from anthropogenic sources in Europe in 2000. These emissions were then compared with emissions of these elements in the past. In addition, emission estimates from 2000 were then used as the basis for development of emission scenarios for As, Cd, Cr, Ni, and Pb in 2010. In Fig. 16.1, the keywords "eutrophication", "nitrogen", "phosphorus", "quality", and "water quality" cluster together, representing a prominent research area of non-point source and eutrophication. Agriculture and urban activities are major sources of phosphorus and nitrogen in aquatic ecosystems. Atmospheric deposition further contributes as a source of N (Carpenter et al. 1998). These non-point inputs of nutrients are difficult to measure and regulate because they derive from activities dispersed over wide areas of land and are variable in time due to effects of weather. Mayorga et al. (2010) estimated the globally spatial distribution of nitrogen, phosphorus, and carbon export from watersheds for 2000. The spatial distribution of phosphorus export loading at the watershed scale was estimated by using the Soil and Water Assessment Tool (SWAT) (Ouyang et al. 2012).

Bibliometric Analysis of Contemporary Research in China

Since 2000, Chinese scholars have published 1846 academic papers on pollutant source apportionment, modeling, and transport, accounting for 13.5 % of all articles globally in this sub-field, most of which concentrated on sources of PAHs and heavy metals in soils and sediments. In China, pollutant source apportionment research has paid more attention to PAHs and heavy metals in soils and sediments. The top 10 keywords in this sub-field (for the papers published by Chinese scholars) are "China" (809), "PAHs" (300), "source" (257), "soil" (238), "sediment" (230), "heavy metal" (226), "source apportionment" (212), "aerosol" (193), "region" (155), and "distribution" (144). Whereas the number of papers published in this sub-field by Chinese scholars increased from 9 in 2000 to 370 in 2014, the studies on atmospheric emissions and modeling of pollutants are still limited in China.

Contemporary Research in China

Pollutant Background Content or Baseline In the period from 1986 to 2014, NSFC funded three projects on the survey of elemental background contents and baselines. Whereas NSFC funding on this topic is very limited, Chinese scientists have achieved some milestones and published some papers. Tao (1995a, b, 1998) collected 83 soil samples from the Shenzhen area and determined the contents of copper, lead, zinc, nickel, chromium, cobalt, mercury, vanadium, and manganese in collected soil samples. Two-dimensional ordinary block kriging as an optimal interpolation technique was then applied to produce regular grids of predicted estimates of copper, lead, and mercury contents in surface soil in the Shenzhen area for mapping purposes. The kriging analysis was based on theoretical variograms calculated from measured data for 83 top soil samples. Finally, the elemental background contents in the soils of the Shenzhen area were mapped. Geochemical baselines of trace elements and phosphorus in watershed sediments of the Liao River were developed using statistical and geochemical methodologies (Lin et al. 2012, 2013; Liu et al. 2013; Jiang et al. 2013). Tao et al. (2011a) investigated the spatial distribution and sources of PAHs in the surface soils of the Tibetan Plateau and found that PAHs in those soils may represent the background levels for East Asia and the entire world.

Source Identification and Apportionment of Pollutants Serious environmental pollution in China now poses threats to environmental quality as well as human health. Accurate identification and quantification of sources play an important role in establishing effective policies, laws, and control measures. The titles of 15 projects funded by NSFC prior to 2015 include the word "source identification". These projects investigated the sources of organic pollutants, heavy metals, and nitrogen in air, water, soils, and sediments. Whereas Chinese scholars have conducted a number of studies on pollutant source apportionment and identification, studies on methodologies have been relatively weak. Cao et al. (2005) apportioned the sources of atmospheric organic and elemental carbon during fall and winter of 2003 in Xi'an, employing absolute principal component analysis. Source apportionment of ambient non-methane hydrocarbons in Hong Kong was accomplished through application of a principal component analysis/absolute principal component scores (PCA/APCS) receptor model (Guo et al. 2004). Principal component analysis and multiple linear regression were applied to apportion sources of PAHs in surface soils of Tianjin, based on the measured PAH concentrations of 188 surface soil samples (Zuo et al. 2007). The source of PAHs contamination in rivers in Tianjin was diagnosed by using a PAH isomer ratios acceptor model (Shi et al. 2007).

Tempo-spatial Distributions of Pollutants and Sources Air pollution has been one of the most serious environmental concerns because of its negative impact on the air quality, public health, and economic development, and therefore requires much attention to devising effective controls. Funded by NSFC, Chinese scholars have widely studied the tempo-spatial distribution of atmospheric emissions and non-point export loadings. The research group from Peking University, led by Dr. Shu Tao, has compiled a series of global scale high-resolution data products on fuel consumption and emissions of greenhouse gases and air pollutants from all combustion sources. The inventories are high resolution both spatially (0.1 degree by 0.1 degree) and sectorially (at least 64 fuel sub-types in 5 categories and 6 sectors for CO_2 and Hg; and 7 fuel categories for BC, OC, PM and PAHs). The products that have been uploaded include PKU-CO_2 2007/08 (carbon dioxide), PKU-BC 2002/07/08/11/13 (black carbon), PKU-PAHs 2007/08 (polycyclic aromatic hydrocarbons), PKU-Hg 2007/08 (mercury), PKU-CO 2007/08 (carbon monoxide), PKU-OC 2002/07/08/11/13 (organic carbon), and PKU-PM 2002/07/08/11/13 ($PM_{2.5}$, PM_{10} and TSP) (http://inventory.pku.edu.cn) (Shen et al. 2013; Wang et al. 2014a). On the basis of the above inventories, the large scale tempo-spatial distributions and transports have been investigated (Shen et al. 2011; Zhu et al. 2013; Huang et al. 2014). The sources of PAHs in environmental media can often be identified by comparing the ratios of concentrations of selected pairs of PAHs congeners in the source emissions to the ratios in the contaminated environmental media. However, PAH ratios change remarkably from the source emissions to various environmental media (Zhang et al. 2005). Therefore, Zhang et al. (2005) suggested and tested a new multi-media fugacity fate model to identify the sources of PAHs in multi-media. A steady state fate model was established and applied to quantify the source-receptor relationship in a coking industry city in Northern China, successfully applying this multi-media fate model to predict the concentration, distribution, and transferring flux of PAH components in different bulk media. Soil and sediment were the dominant sinks for the local emissions of PAHs, and exchanging fluxes between air and underlying surfaces (dominated by soil) played an import role.

Contributions by Chinese Scholars and Subsequent Problems

Comparison of the ten most frequently utilized keywords published by Chinese scientists—"China"(809), "PAHs" (300), "source" (257), "soil" (238), "sediment"(230), "heavy metal" (226), "source apportionment" (212), "aerosol" (193), "region" (155), and "distribution" (144)—with those employed by non-Chinese scientists—"aerosol" (2136), "PAHs" (999), "model" (897), "soil (872)", "particle" (818), "source apportionment"(789), "heavy metal" (763), "source" (716), "pesticide" (715), and "impact" (694)—reveals that more attention has been given to the source apportionment of PAHs and heavy metals in soils and sediments by Chinese scholars, while non-Chinese scholars have been more interested in the modelling and source apportionment of aerosols and PAHs in the atmosphere and pedosphere.

Chinese scholars need to enhance their work in the field of aerosol modeling and apportionment. Given the serious levels of soil and water pollution in China, source identification of pollutants in soils and waters remains a pressing need.

Future Research

To solve environmental pollution problems, pollutant source identification and apportionment at different tempo-spatial scales will still be the major focus of future research. At the same time, further development and improvement of source identification and apportionment methods will be a challenge. The developed countries will be more interested in high-resolution emission inventories and modelling of greenhouse gases, whereas the developing countries will pay more attention to high-resolution emission inventories and modelling of toxic materials in the coming decade.

Whereas the source apportionment and identification of POPs, toxic heavy metals, and non-point pollutants will still be studied widely, emerging pollutant sources will also be a prominent focus of research. Pollutants emitted from biomass burning—e.g., black carbon (BC) and organic carbon (OC)—may have affected the light absorption capacity and altered the climate system. The emitted active trace gases, such as volatile organic compounds (VOCs) and NOx, are precursors of O_3, which poses a threat to human and ecosystem health. Whereas considerable efforts have been made worldwide to obtain and improve estimates of biomass burning emissions, these continue to be associated with large information gaps and uncertainties, especially for regions in the developing world. Carbonaceous aerosols play an important role in environmental issues—e.g., air quality, human health, and global climate change (Huang et al. 2006). Therefore, source apportionment and identification of carbonaceous aerosols, their formation mechanisms, and their atmospheric transformation and transport must be further understood. In addition, increasing attention should be paid to volatile organic compounds, particularly to polycyclic aromatic compounds (PAC) and especially, owing to their carcinogenic character, to PAHs. With respect to environmental media, more attention will likely be paid to the source identification and apportionment of atmospheric pollution compared to soil pollution and water pollution. In particular, the source apportionment and identification of aerosols and $PM_{2.5}$ will be a key focus of future research. The isotope receptor model, reactive receptor model, and reactive diffusion model will be further improved and widely used to identify aerosol and $PM_{2.5}$ sources.

Modelling of non-point pollutant export loadings and nitrogen and oxygen isotope source identification methods will be the key areas of research on non-point source pollution. In addition, the modelling and source identification of non-point pollutants such as agrochemicals and toxic heavy metals will be critical tools for the protection of water resources. Non-point source contamination of China's surface water and groundwater has emerged as a major environmental problem over the past decades. Whereas significant advances have been made in controlling point source pollution, the overall improvement of water quality in China has been limited. Nitrogen and phosphorus pollution will remain serious environmental problems. Pesticide contamination of groundwater and surface water from agricultural land uses has been well documented. Therefore, Chinese scientists should further study and identify the underlying causes of water pollution and eutrophication in the process of developing technologies for controlling non-point source pollution.

A thorough understanding of air pollution concentrations and fluxes at various spatial scales requires emission inventories of pollutants at high tempo-spatial resolution. In addition, tempo-spatial characteristics of emission inventories are critical for environmental decision makers in developing effective air pollution abatement strategies. The accuracy of the emission inventories can significantly affect that modelling results and the effectiveness of air quality management decisions. Consequently, a detailed emission inventory with high resolution is the key source of information for understanding and solving complex air pollution problems. Although atmospheric emission inventories of various pollutants have been built, they must be improved in terms of emission factors, spatiotemporal resolution, natural sources, and so on. Chinese scientists have developed a multi-resolution emissions inventory for China (MEIC database) and a globe-scale $0.1*0.1°$ emissions inventory (PKU Inventory). These must be further improved in order to better understand the reasons behind urban haze fog in China.

16.2.2 How to Determine the Behaviors of Environmental Pollutants

The environmental behavior of pollutants generally depends on the environmental conditions and pollutant properties. Once introduced into environments such as the atmosphere, hydrosphere, and pedosphere, pollutants will experience a series of transports and transformation. In Fig. 16.1, keywords relating to the environmental behavior of pollutants include "adsorption", "sorption", "degradation", "biodegradation", "accumulation", "bioaccumulation", "bioavailability", "fate", "resistance", and "exposure". These keywords generally cluster together with pollutants such as POPs, PCBs, herbicides, pesticides, heavy metals, and PAHs in soils, water, and sediments. In addition, the keyword "China" is in this cluster, likely indicating that Chinese scientists have widely studied the environmental behavior of pollutants. Keywords such as "model", "transport", "distribution", and "long-range transport" represent the tempo-spatial behavior of pollutants. These keywords cluster together with aerosols.

Bibliometric Analysis of Contemporary Research

There have been 25,873 papers on the environmental behavior of pollutants published since 2000 (excluding those published by Chinese scholars). Figure 16.1 also shows that some topics closely related to the environmental behavior of pollutants include exposure, adsorption, toxicity, accumulation, bioaccumulation, bioavailability, degradation, biodegradation, speciation, and China. These keywords show that pollutant speciation, bioavailability, adsorption, degradation, exposure, and toxicity are closely related to POPs, herbicides, pesticides, heavy metals, and PAHs in soils, water, and sediments. The ten most utilized keywords in this sub-field (excluding the papers published by Chinese scholars) are "soil" (3436), "aerosol" (2625), "pesticide" (2585), "PAHs" (2546), "heavy metal" (2430), "sediment" (1626), "toxicity" (1604), "water" (1593), "transport" (1548), and "POPs" (1387). The number of papers published in this sub-field by non-Chinese scholars increased from 856 in 2000 to 2514 in 2014. In the sub-field of environmental behavior of pollutants, non-Chinese scholars were most interested in pesticides, PAHs, and heavy metals in soils and aerosols.

Contemporary Research

Atmospheric Transports of Pollutants In general, source-oriented atmospheric chemical transport models are able to simulate meteorological, physical, and chemical processes. Thus they can provide estimates of the concentration and deposition of atmospheric pollutants. In the past, source-oriented atmospheric chemical transport models have been widely used to model atmospheric transports of pollutants and provide advice to policymakers. The advantages of these models generally include the following: (1) estimation of the tempo-spatial concentrations and deposition of atmospheric pollutants at different scales with high resolution; (2) forecasts of future tempo-spatial changes of atmospheric pollutants; and (3) identification of source apportionment of atmospheric pollutants. In contrast, the monitoring of atmospheric pollutants is both spatially and temporally limited by the number of sites and their periods of operation. The selection of models depends on data availability and modelling purposes. The use of both simpler and more complex models can provide complementary benefits (Dore et al. 2015). The advantages of more complex models include a more detailed representation of meteorology and its influence on concentrations of air pollutants; high temporal resolution of pollutant concentrations; more detailed parameterization of nonlinear atmospheric chemical reactions; and simultaneous multi-pollutant simulation. In contrast, simpler models benefit from a rapid simulation time that allows multiple simulation applications, including source–receptor and integrated assessment studies, uncertainty studies, high spatial resolution studies, detailed vertical resolution, etc. (Dore et al. 2015). Atmospheric transport of aerosols, secondary organic aerosols, PM, $PM_{2.5}$, black carbon, dust, trace elements, ozone, and other elements has been widely modeled in the last 15 years (Fig. 16.1).

Speciation, Bioavailability, and Bioaccumulation Speciation of pollutants in environments generally determines their bioavailability and bioaccumulation. The speciation and bioavailability of POPs, PCBs, herbicides, pesticides, heavy metals, PAHs, etc. in soils, water, and sediments, as well as their accumulation and bioaccumulation in fishes and plants, have been widely studied in the past 15 years (Fig. 16.1). The increasing concern for assessing the bioavailable fraction and the mobility of pollutants in the environment is reflected by a considerable increase in the frequency of soil and sediment analyses based on operationally defined extraction procedures over the past decades. Single and selectively sequential extraction schemes have been widely used to assess the speciation and bioavailability of inorganic (e.g., heavy metals) and organic pollutants (Kelsey et al. 1997). The in vitro gastrointestinal method has been used to investigate the oral bioaccessibility of pollutants (Rodriguez et al. 1999; Tao et al. 2009). The chemical assessment of bioavailability has been further tested by biological accumulation experiments. In addition, spectrum methods have been employed to identify the speciation of pollutants at the surface of environmental colloids.

Pollutant Sorption/Desorption The sorption of pollutants on environmental colloids has been widely studied. In Fig. 16.1, the keywords "adsorption" and "sorption" cluster together with the environmental medium keywords "soil", "sediment", and "water" and pollutant keywords "heavy metal", "herbicide", "pesticide", "PAHs", etc. This shows that the adsorption and sorption of pollutants such as heavy metals, herbicides, pesticides, and PAHs on the surface of soil, sediment, and water colloids have been a key research area in the last 15 years. The effects of environmental conditions such as pH, Eh, ionic strength, and competition ions on the colloid surfaces have been extensively investigated. The manner in which an element is bound to the solid components of environmental solids, such as soils or sediments, influences the mobility and, ultimately, the bioavailability and toxicity of the element to organisms. As a result, there is considerable interest in improving the understanding of element–solid phase associations in natural and polluted systems. Spectroscopy and microscopy have been increasingly used to understand the adsorption mechanisms of different pollutants on various environmental colloids. Sparks and his research team (2003) extensively studied the molecular-scale adsorption mechanisms of toxic elements on environmental colloids, employing X-ray absorption spectroscopy (XAS), micro X-ray absorption fine structure (micro(u)-XAFS), and u-synchrotron-X-ray fluorescence spectroscopy (u-SXRF). In recent years, there has been considerable interest in understanding adsorptive interactions between organic contaminants and carbon nanotubes, since they are critical to both the environmental application of carbon nanotubes as special adsorbents and the assessment of the potential impact of carbon nanotubes on the fate and transport of organic contaminants in the environment. Xing and his research team have studied the adsorption mechanisms of different organic pollutants on soil organic matter, biomass carbon, and carbon nanotubes (Chun et al. 2004; Kang and Xing 2005; Pan and Xing 2008; Chefetz and Xing 2009).

Pollutant Degradation and Biodegradation Degradation and biodegradation are major removal methods for environmental organic pollutants. Therefore, they represent a key research area in environmental remediation. In Fig. 16.1, the keywords "degradation" and "biodegradation" cluster together with pollutants "PAHs", "pesticide", "herbicide", etc. in soil, sediment, and water, indicating that the degradation and biodegradation of PAHs, pesticides, and herbicides in soils, sediments, and water have been investigated in the last 15 years. In view of the extensive contamination of the environment by persistent and toxic chemical pollutants originating from human activities, it is necessary to develop cost effective and efficient methods for their remediation. Bioremediation is a popular and attractive technology that utilizes the metabolic or co-metabolic potential of microorganisms to clean up the environment. There are considerable interests in identifying microorganisms that are able to efficiently degrade xenobiotics and recalcitrant pollutants. White rot fungi, in light of their high tolerance of toxic substances in the environment, are considered to be robust organisms with enormous potential for oxidative bioremediation of a variety of toxic chemical pollutants. In recent years, significant work has been undertaken on the development and optimization of bioremediation processes using white rot fungi, with emphasis on the study of their enzyme systems (Asgher et al. 2008). In addition, heterogeneous photocatalytic degradation using photocatalysts continues to represent a viable alternative for the degradation of organic contaminants in both air and water.

Pollutant Toxicity, Exposure, and Risk In Fig. 16.1, the keyword "toxicity" clusters closely together with the keywords "water" and "fish"; thus, the toxicity of pollutants in aquatic environments has been an important research area in the last 15 years. In addition, the keywords "exposure", "risk", "risk assessment", and "assessment" cluster together as a relatively independent group, indicating that exposure and risk assessment of pollutants have become a relatively independent research area in the environmental sciences. Persistent organic pollutants are a significant concern due to their potential toxicity and prevalence in arrangements of environmental media, even at remote geographical locations. Persistent organic pollutants are found not only in environmental media but also in living organisms such as plants, animals, and humans. Public concern about contamination by POPs has increased because several of these compounds have been identified as hormone disrupters that can alter normal functions of endocrine and reproductive systems in humans and wildlife. Various organisms and biomarkers have been used for toxicity assessments. A comprehensive exposure assessment is part of a risk assessment that evaluates the relationship between the source of a pollutant and its health effects. Several countries have published guidelines in the form of exposure assessment and exposure factor handbooks. Health risk assessment is generally classified into categories of non-carcinogenic and carcinogenic risks.

Bibliometric Analysis of Contemporary Research in China

Since 2000, Chinese scholars have published 4441 academic papers on environmental behavior of pollutants, accounting for 14.7 % of article globally in this sub-field, most of which concentrate on environmental behavior of heavy metals and PAHs in soils and sediments. The ten most utilized keywords in this sub-field (for the papers published by Chinese scholars) are China" (1058), "soil" (784), "heavy metal" (631), "PAHs" (611), "sediment" (476), "distribution" (314), "POPs" (290), "aerosol" (269), "source" (265), and "water" (264). The number of papers published in this sub-field by Chinese scholars increased from 17 (1.9 % of the articles globally) in 2000 to 777 (23.6 % of the articles globally) in 2014, demonstrating that the Chinese contribution to research in this sub-field has increased rapidly over the past 15 years.

Contemporary Research in China

Atmospheric Transport of Pollutants Funded by NSFC, Chinese scientists have conducted a number of studies in the area of atmospheric transport of pollutants. The research group from Peking University, led by academician Shu Tao, has studied long-range atmospheric transport of some pollutants by employing self-developed models (Lang et al. 2008a; Zhang et al. 2011a, b; Shen et al. 2014; Zhu et al. 2014). This research group developed a potential receptor influence function (PRIF) model based on calculations of air mass forward trajectory and then simulated atmospheric transport and outflow of PAHs emitted from China (Lang et al. 2008a). Their results indicated that most neighboring countries and regions, as well as remote regions, were influenced by PAH emissions from China within a 10-day atmospheric transport period. This research group also developed a probabilistic function (integrated source contribution function: ISCF) based on calculations of backward air mass trajectory to track sources and atmospheric pathways of PAHs to the Canadian High Arctic station of Alert (Wang et al. 2010a). In addition to the movement of air masses, the emission intensities at the sources and the major processes of partition, indirect photolysis, and deposition occurring on the way to the Arctic were incorporated into the ISCF. The predicted temporal trend of PAHs at Alert was validated by measured PAHs concentrations throughout 2004. The PAHs levels in the summer are orders of magnitude lower than those in the winter and spring, when long-range atmospheric transport events occur more frequently (Wang et al. 2010a). To investigate the possible sources of OCPs, air mass backward trajectories were calculated using the HYSPLIT model (Hybrid Single-Particle Lagrangian Integrated Trajectory, Version 4.7), indicating that the unusually high DDT levels in the atmosphere of Guangzhou and Hong Kong in summer could be related to the seasonal usage of DDT-containing antifouling paints for fishing ships in the upwind seaports of the region (Li et al. 2007). However, the high concentrations of α–endosulfan in winter in the atmosphere of Guangzhou and Hong Kong suggested an atmospheric transport by the winter monsoon from East China, where endosulfan is being used as an insecticide in cotton fields (Li et al. 2007). Backward air trajectory analysis suggested that the high concentrations of g-HCH, DDTs and PBDEs in the atmosphere of Waliguan Baseline Observatory in northwest China during the spring period were related primarily to air masses passing over the neighboring countries (e.g., Russia, Kazakhstan) (Cheng et al. 2007).

Speciation, Bioavailability, and Bioaccumulation The titles of 136 projects funded by NSFC in the period from 1986 to 2014 include the words "speciation", "bioavailability", or "bioaccumulation", indicating that Chinese scholars have paid increasing attention to this study area. These projects investigated the speciation and bioavailability of various inorganic and organic pollutants in aerosols, soils, sediments, water, and organisms. The funding instrument of these projects includes the Key Programme (KP), the National Science Fund for Distinguished Young Scholars (DYS Fund), the General Program, International Cooperation and Exchange, and the Joint Research Fund for Overseas Chinese Scholars and Scholars in Hong Kong and Macao. This demonstrates that Chinese distinguished scholars are interested in the study of pollutant speciation, bioavailability, and bioaccumulation.

Tao et al. (2000a) observed that the secretion of mucus from fish (*Carassius auratus*) proceeded at a constant rate that could be accelerated through exposure to lead. Mucus is an organic ligand for lead, and its interaction with lead can be characterized using a single-site model. Pb-mucus complexation is not bioavailable for fish uptake. Because of the influence of mucus complexation and pH change, bioavailable copper speciation in the fish gill microenvironment was significantly lower than that in the bulk solution, especially under acidic conditions (Tao et al. 2001). When differences in pH and alkalinity between the fish gill microenvironment and the bulk solution and the presence of free mucus are considered, the predicted binding-site concentration and conditional stability constants differ from calculations based on the properties of the bulk solution (Tao et al. 2002). A fragment constant method was established to predict the fish bioconcentration factor of non-polar organic compounds from nine classes (chlorinated aliphatic hydrocarbons, monocyclic aromatic hydrocarbons, chlorinated benzene, brominated benzene, polychlorinated biphenyls, polybrominated biphenyls, chlorinated naphthalenes, polycyclic aromatic hydrocarbons, and others) (Tao et al. 2000b). A bioconcentration factor estimation model for a wide range of nonionic organic compounds was developed on the basis of molecular connectivity indices and polarity correction factors (Lu et al. 2000).

Chemical forms of copper in the rhizosphere and bulk soil of maize were investigated using rhizobox cultivation and sequential extraction techniques, revealing that the amount of accumulated copper absorbed in the plant material exceeded the initial quantity of the exchangeable copper in the soil (Tao et al. 2003). This suggested a transformation from less bioavailable to more bioavailable fractions. The change in copper speciation may result from root-induced changes in DOC, redox potential, and microbial activity in the rhizosphere. Tao et al. (2004) investigated the root-induced changes of copper fractionation in the rhizosphere of a calcareous soil, showing that the resulting significant influence of root exudates on copper fractionation appears to have been produced through complexation rather than acidification or alkalization. In addition, the increase in exchangeable copper in the rhizosphere was strengthened by microorganisms. Huang et al. (2005) studied the role of mycorrhiza on change in heavy metal speciation in maize rhizosphere. This study found that mycorrhiza could protect its host plants from the phytotoxicity of excessive copper, zinc, and lead by changing the speciation from the bioavailable to the non-bioavailable form. Speciation differences were observed for the elements Cr, Ni, Zn, Cu, Pb, and Cd between the rhizosphere and bulk soils (Wang et al. 2002).

A static in vitro gastrointestinal model was used to investigate the oral bioaccessibility of organochlorine pesticides, revealing that 8–38 % of the mobilized OCPs were sorbed on the residue and remained in the solid phase after the separation (Tao et al. 2011b). The sorption of the mobilized PAHs on the digestive residue of the in vitro gastrointestinal test was positively correlated with both soil organic carbon (SOC) and molecular weight of PAHs; and a regression model was developed so that the sorption of different PAHs on soils with different SOCs could be estimated (Tao et al. 2010). In addition, the bound residues of OCPs and PAHs were mobilized to a certain extent during digestion. The ratios of the mobilized bound residues over the total quantities extracted after digestion varied from 0 to 0.96. The mobilization process followed typical first-order kinetics. The calculated rate constants suggest that rapid mobilization occurred (Tao et al. 2011b).

Pollutant Sorption/Desorption Pollutant adsorption/desorption on environmental colloids has a significant effect on pollutant bioavailability and mobility. The titles of 53 projects funded by NSFC in the period of 1986 to 2014 include the words “adsorption” or “desorption”, indicating that Chinese scholars have been interested in this study area. Chen et al. (2007) proposed that the strong adsorptive interaction between carbon nanotubes and nitroaromatics was due to the π-π electron donor–acceptor interaction between nitroaromatic molecules (electron acceptors) and the highly polarizable graphene sheets (electron donors) of carbon nanotubes. In addition, the stronger adsorption of nonpolar aromatics relative to that of nonpolar aliphatics is attributed to the π-electron coupling between the flat surfaces of both aromatic molecules and carbon nanotubes. Wang et al. (2009) studied the sorption of humic acid (HA) and aromatic compounds by multiwalled carbon nanotubes (MWCNTs) and their competition on MWCNTs. They observed that HA sorption by MWCNTs was regulated by their surface area (SA). Hydrophobic and π- attractions of HA with MWCNTs were the main driving forces for their interactions. The results of this study highlight the significance of MWCNTSA for HA sorption and the associated influence on the sorption of aromatic compounds. In addition, the molecular size and hydrophobicity of aromatic compounds strongly affected their competition with HA on MWCNTs. The sorption of hydrophobic organic compounds (HOCs)—phenanthrene, lindane and atrazine—by original and OH-functionalized multiwalled carbon nanotubes (F-MWCNTs) has been examined (Wang et al. 2010b). This study showed that the surface area and sum of meso- and macropore volumes of MWCNTs were governing characteristics that influenced their affinity and capacity for sorption of HOCs. The molecular size of HOCs markedly influenced their volume sorption capacity by the original MWCNTs. The introduced hydroxyl groups may have reduced the accessibility of a large portion of sites in meso- and macropores of MWCNTs that were originally available for smaller HOCs but not for those with larger molecular sizes. Guo et al. (2012) examined the sorption behavior of four hydrophobic organic contaminants (HOCs) by three types of polymers—polyethylene, polystyrene, and polyphenylene oxide—and found that the mobility and abundance of rubbery domains in polymers regulated HOC sorption.

Pollutant Degradation and Biodegradation The titles of 103 projects funded by NSFC from 1986 to 2014 include the words “degradation” or “biodegradation”, indicating that this is a prominent research area in China. NSFC also funded 73 projects on pollutant degradation and biodegradation in the five years from 2010 to 2014. This interest among Chinese scholars in pollutant degradation and biodegradation may be attributed to the strong demand for environmental measures such as soil and water remediation. In recent years, more attention has been given to photo-assisted and electrochemical degradation of organic pollutants. The TiO_2-photoassisted (photocatalytic) degradation of the cationic dye rhodamine B (RhB) was examined in aqueous dispersions under visible light irradiation (Zhao et al. 1998), demonstrating that pre-adsorption on the surface of TiO_2 particles is a prerequisite for efficient photodegradation of RhB under visible light irradiation. Moreover, the data imply that degradation occurs at the particle surface and not in the solution bulk. 2-mercaptobenzothiazole (MBT) degradation is enhanced by cerium ion-doped titanium dioxide (Ce^{3+}–TiO_2) (Li et al. 2005a). The overall photocatalytic activity of Ce^{3+}–TiO_2 catalysts in MBT degradation was significantly enhanced due to the higher adsorption capacity and better separation of electron–hole pairs. The separation efficiency of electron-hole pairs at first increased with increasing cerium ion content at first and then decreased when the cerium ion content exceeded its optimal value. Li et al. (2005b) studied the kinetics and pathways of the electrochemical degradation of phenol at three different types of anodes: Ti/SnO_2–Sb, Ti/RuO_2, and Pt. Although phenol was oxidized by all the anodes, there was a considerable difference among the three anode types in terms of the effectiveness and performance of electrochemical organic degradation.

It is argued that the anodic property not only affects the reaction kinetics of various steps of electrochemical organic oxidation, but also alters the pathway of phenol electrolysis.

Pollutant Toxicity, Exposure, and Risk The titles of 43 projects funded by NSFC from 1986 to 2014 include the word "toxicity", indicating that Chinese scholars have been interested in the toxicity of pollutants in contaminated soils. Most of these projects used earthworms to perform the toxicity assessment. Tested pollutants included heavy metals, persistent organic pollutants, pesticides, PAHs, antibiotics, and nano-materials. Zhang et al. (2009) investigated inhalation exposure to ambient PAHs and lung cancer risk among the Chinese population. This study indicated that the risk of lung cancer was greater in eastern China than in western China, and that populations in major cities had a higher risk of lung cancer than did those in rural areas. Wang et al. (2014b) estimated exposure to ambient black carbon derived from a unique inventory and high-resolution model. The estimated global population-weighted BC exposure concentration constrained by observations is 2.14 μg m^{-3}, 130 % higher than that obtained using less detailed inventories and low-resolution models. The association between dietary intakes and human milk concentrations of DDTs and metabolites of two populations from Beijing and Shenyang were investigated by Tao et al. (2008), showing that the exposure of infants to DDTs through breastfeeding would be a public health concern for years to come, although breastfeeding is still recommended. In addition, residues of hexachlorocyclohexane isomers (HCHs) in human milk of two populations from Beijing and Shenyang were estimated, and a nonlinear model was developed to predict the residues of HCHs in human milk using both dietary intake and body mass index as independent variables (Yu et al. 2009). PAH residues in human milk, placenta, and umbilical cord blood in Beijing have been studied, indicating selective transfer potential of individual PAHs from mother to fetus (Yu et al. 2011). Concentrations of HCHs in placenta and umbilical cord blood in urban populations were higher than those of the rural group owing to enhanced consumption of fish, meat, and milk (Yu et al. 2013a). The estimated dietary intakes of DDTs and HCHs in 2005/2007 were almost one and two orders of magnitude lower than those in 1992 and in the 1970s, respectively, revealing the historical decrease of DDT and HCH in Chinese foods after their use was banned (Yu et al. 2013b). Chen et al. (2008) studied the influence of humic acid (HA) on the bioavailability and toxicity of benzo [k]fluoranthene (BkF) to Japanese medaka. They observed that BkF bioaccumulation in medaka was generally reduced with an increase of HA concentration in the exposure medium. In addition, approximately 17–22 % and 13–18 % of the BkF-HA complex contributed to the bioaccumulation and/or to the induced toxic effect, respectively. The effects of pH and selected cations on the toxicity of trivalent chromium (Cr(III)) to barley root elongation were investigated to develop an appropriate biotic ligand model (BLM) (Song et al. 2014). It was observed that the toxicity of Cr(III) decreased with increasing activity of Ca^{2+} and Mg^{2+}, but not with K^{+} and Na^{+}. In addition, the effect of pH on Cr(III) toxicity to barley root elongation could be explained by H^{+} competition with Cr^{3+} bound to a biotic ligand as well as by the concomitant toxicity of $CrOH^{2+}$ in solution culture.

Contributions by Chinese Scholars and Subsequent Problems

A comparison of the ten most utilized keywords in articles by Chinese scientists from 2000–2014—"China" (1058), "soil" (784), "heavy metal" (631), "PAHs" (611), "sediment" (476), "distribution" (314), "POPs" (290), "aerosol" (269), "source" (265), and "water" (264)—with those employed by non-Chinese scientists over the same period—"soil" (3436), "aerosol" (2625), "pesticide" (2585), "PAHs" (2546), "heavy metal" (2430), "sediment" (1626), "toxicity" (1604), "water" (1593), "transport" (1548), "POPs" (1387)—reveals that in general more attention was given to the environmental behavior (e.g., distribution) of heavy metals and PAHs in soils and sediments by Chinese scholars; while non-Chinese scholars have focused more on the environmental behaviors of aerosols and soil pesticides, PAHs, and heavy metals. Chinese scholars should devote more attention to the environmental behaviors (e.g., toxicity and transport) of aerosols and pesticides in the future.

Future Research

The environmental behaviors of pollutants are characterized by high complexity and spatial heterogeneity. Thus studies on these behaviors will still face huge challenges in the future. With respect to the macro transport of atmospheric pollutants, modeling by Chinese researchers of long-range transports and environmental behaviors should be enhanced in China. Moreover, in light of extensive atmospheric pollution and the need for its control in China, more attention should be paid to the modelling and formative causes of fog-haze in the key urban and industrial areas of the country.

At the microscale of environmental behavior of pollutants, accurate characterization and modelling of the speciation and bioavailability of pollutants in the environment are critical to assess pollution exposure and its health risks to humans. Chinese scholars should further develop methods for assessing speciation and bioavailability, especially via employing local or native organisms.

To solve China's pollution problems, Chinese scientists should also develop and improve environmental remediation methods and technologies. In this regard, photo-assisted catalytic degradation and green bioremediation may be a key study area in the future.

16.2.3 How to Simulate the Spatial Processes of Environmental Pollutants at the Regional Scale

After entering the environment, pollutants will be subject to oxidation/reduction, adsorption/desorption, and precipitation/dissolution as affected by natural and human factors. Given the spatial variation of natural and human factors, environmental behavior and tempo-spatial processes of pollutants will also manifest spatial variation. In Fig. 16.1, atmospheric pollutants, PAHs, and trace elements are linked with words reflecting obvious scale effects and regional research characteristics. These pollutants may be adsorbed on the surface of particulate matter for long-distance transport. Alternatively, they could migrate between multimedia. Thus interface transport, fate, and modelling of environmental pollutants have been important research foci within this field.

Bibliometric Analysis of Contemporary Research

There are 15,605 papers in this sub-field of the spatial process simulation of environmental pollutants at regional scales (excluding those published by Chinese scholars). The related words shown in Fig. 16.1 mainly were "capacity", "fate", "simulation", "distribution", "risk", "fate", and "long-range transport". The ten keywords in this sub-field utilized most frequently are "pesticide" (1800), "soil" (1717), "aerosols" (1655), "toxicity" (1604), "heavy metals" and "PAHs" (1355), "sediment" (1048), "model" (951), "water" (898), and "POPs" (800). The number of publications by non-Chinese scholars increased from 459 in 2000 to 1654 in 2014.

Contemporary Research

Fate of pollutants The capacity for multi-media migration and long-distance transport of pollutants is the basis of their spatial distribution. This capacity in turn interacts with environmental factors to determine their fate, which has long been the focus of researchers, especially at regional and global scales. Heavy metals such as Hg, Pb and Cd, or POPs (such as HCH, DDT, PAHs, and dioxins) can be dispersed over large areas through atmospheric transport. Thus pollutants from human activities are no longer limited to areas with intensive anthropogenic activities. In Polar Regions (the South and North Poles, the Tibetan Plateau) and oceanic areas, pollutants have also been detected. Through the processes of transport and redistribution, these areas have become sources and sinks of different pollutants.

For example, Hg is a typical airborne heavy metal. In 2011, the EU initiated a GMOS project to observe the global cycle of Hg. This was triggered by the recognition that the polar bear, the primary predator and resident of the North Pole region, was displaying very special exposure characteristics that were inconsistent with the background concentration of Hg in this region (Sonne, 2010). Similarly, in some lakes located in remote areas of northern Europe and North America, Hg concentrations in fish at the top of food chains were found to be clearly beyond the recommended WHO standard. Many types of POPs also are amenable to long-distance transport. In Fig. 16.1, PAHs were clustered together with keywords such as scale and region, indicating that research on organic pollution across regions has been an important topic.

Sinks of POPs include Polar Regions, soils (sediments), and oceans. Sinks in Polar Regions are primarily related to temperature, whereas sinks in soils and oceans are related to rich organic matter. Among them, soil and sediment, having strong sequestration effects on PTS and affecting the biogeochemical processes of PTS, have been identified as the most important sinks in the environmental media (Dalla et al. 2005). For example, approximately half of PCDD/Fs are stored in soil (Lohmann et al. 2006: L12607). Chinese scholars have shown that organic matter in soil controls the concentrations of chemicals (Wang et al. 2012), and that soil pollution is closely related with human health (Tao et al. 2008).

Modelling of Regional Pollution Processes The contribution from Western scholars is dominant here. Through development and application of models, they occupy a leading role in advancing this research direction. Currently, modelling research is mainly conducted using the receptor model, fugacity model and diffusion model (Gordon 1988; MacLeod et al. 2010). Through chemical analysis of samples, the receptor model can be used to determine the contribution of individual pollution sources, identify sources affecting receptors, and then quantify the effects and contribution of the source.

The multimedia fugacity model summarizes the processes controlling the chemical behavior and fate of chemicals in or between phases of environmental media, and it is utilized to study and predict the behavior of chemicals in different environmental media. Mackay generalized this model to the natural environment and proposed a "unit world" concept. In this model, interface processes are given critical emphasis. A mass balance equation for each relevant phase, including fugacity, concentrations, fluxes and amounts, should be the first step of modeling. The fugacity model has been developed from steady-state closed systems in equilibrium to unsteady open systems in non-equilibrium and further to a model with a number of subunits in space (Tian et al. 2011). Depending on the number of phases and the complexity of processes, different level models are applied. In regional process research, the fugacity model has obvious shortcomings, especially in model validation of spatial variation characteristics, dynamic predictions under the unsteady assumptions, and uncertainty analysis. Using high-precision meteorological data as model input, the atmospheric diffusion model combines emissions data on pollution, physicochemical properties of pollutants, and environmental parameters to describe the atmospheric transport and migration in environmental media of pollutants and evaluate atmospheric tempo-spatial variation of pollutants quantitatively (MacLeod et al. 2010). This model is based on the meteorological model and has higher requirements for input parameters (Ma et al. 2003).

Ecological Risk of Environmental Pollution Regional ecological assessment is a branch of ecological risk assessment (ERA) that emphasizes the regional scale. The potential for novel or enhanced stresses on ecological components, structures, and functions has been evaluated as caused by pollution, anthropogenic activities, and/or natural hazards. The purpose is essentially to apply theoretical and technological support to risk management. According to the framework of USEPA, ecological assessment is divided into 4 stages: problem formulation, risk analysis, risk characterization, and risk management. Among these, risk management is based on risk analysis and characterization and is particularly emphasized. Because of the spatial heterogeneity of stresses on ecosystems, ERA should take into account great differences among geographical areas. Thus, uncertainties and their controlling factors should be given more attention in ERA (Bartolo et al. 2012; de Vries et al. 2013). Moreover, depending on differences in ecosystem components and structure, changes—from the quantity and structure of species and populations to the structure and functions, and ultimately the stability and sustainability, of the ecosystem—can be surveyed within the framework of risk assessment (de Laender et al. 2008). Current research in ERA is focused mainly on identification of stresses and assessment endpoints such as population or community. How to conduct risk assessment at the ecosystem level requires further and deeper consideration.

Bibliometric Analysis of Contemporary Research in China

There have been 2782 papers published in this sub-field of spatial process simulation of environmental pollutants at regional scales by Chinese scholars. The ten most frequently utilized keywords are "China" (780), "heavy metals" (445), "soil" (426), "sediment" (356), "PAHs" (319), "toxicity" (215), "distribution" (214), "source" (196), "POPs" (182), and "antibiotics" (170). Publications by Chinese scholars increased from 11 in 2000 to 554 in 2014, a factor of approximately 50, which was much higher than the rate of increase of articles by non-Chinese scholars. In 2014, publications from Chinese scholars accounted for 25 % of the articles globally. Pollutants addressed in Chinese articles also differed from those in non-Chinese publications. Antibiotics were a major focus in China, while pesticides and aerosols were major foci among non-Chinese scholars. Moreover, water as a medium was less important in China. Modelling was a weakness in Chinese research. At the same time, scholars from across the world shared common interests in heavy metals, PAHs, and POPs in soils or sediments, especially with regard to their toxicity.

Contemporary Research in China

Soil is the most important sink for POPs. In the Qinghai-Tibet Plateau, namely as Third Pole of the Earth, Chinese scholars have carried out a detailed investigation and provided a sketch map of POP distribution in plateau surface soils and explicated the contribution of soils to the cycle of POPs (Tao et al. 2011b; Wang et al. 2012). Moreover, Chinese scholars, represented by Shu Tao, carried out a series of research efforts on PAH transport and migration in Bohai Rim, North China (Lang et al. 2008b; Shi et al. 2007; Wang et al. 2011) and explored distributions and changes in concentration profiles of PAHs from emission sources to various environmental media (Lang et al. 2008b). In addition, they have modeled the transport and outflow of PAHs in China and Asia. These studies have enriched the spatial transport and simulation research of pollutants at the regional scale.

Contributions by Chinese Scholars and Subsequent Problems

In this sub-field, Chinese scholars have mainly followed the research progress of Western scholars. Chinese and Western scholars share a common interest in the causes and manifestations of world environmental pollution—for example, PAHs, heavy metals—but Chinese researchers have contributed less than their Western counterparts in terms of originality and novelty, particularly in the area of modelling. However, as described above, in some directions they have accomplished distinctive achievements, especially regarding pollutant transport in various environmental media or within long-distance transboundary scenarios. They have also attempted to analyze the uncertainty in modelling the fate and transport of pollutants (Wang et al. 2004).

Future Research

Future studies should focus on model mechanisms and explicit effects of spatial and environmental factors on pollutant behavior. More attention should also be given to parameter optimization and precision of predictions in modelling.

In addition, ecological risk assessment should be improved at different levels of biological organization, especially the ecosystem. Currently, related techniques and methodologies are insufficient.

Chinese research in this sub-field of spatial process simulation of environmental pollutants at regional scales has made great progress in the past 10 years, but most of it is based on Chinese data and western theories and methodologies. Such studies are more often extensions or applications of Western research achievements. China faces serious pollution problems and there is an urgent need for methodologies and technologies to effectively address them. It is very important for Chinese scholars to contribute original and novel scientific achievements to fulfill this national need, especially in via theoretical contributions to modelling, scaling, and scaling effects.

16.3 Roadmap for Further Research

The current development of the Chinese economy and society differs from any other time and any other country. The rapidity of social and economic development with all its accompanying achievements has also generated a serious combination of environmental effects driven by familiar and newly emerging pollutants. Research on the tempo-spatial processes and modelling of pollutants are confronted with the challenges of complex environmental issues characterized simultaneously by multiple factors, processes, scales and targets. There are underlying and multi-faceted scientific questions to explore not only in fundamental research on process/mechanisms and development policy, but also with respect to national decisions of macro-management. To integrate the demands of the discipline, society and the nation, Chinese scholars should make great efforts to achieve breakthroughs in the following areas.

(1) **Spatial Process Analysis of Pollutants**

Studies on the environmental behavior of pollutants are always confronted with substantial issues of high tempo-spatial complexity and heterogeneity. Approaches to cope with these issues are strongly needed to analyze data and summarize laws more efficiently, especially when addressing spatial sampling, investigation, analysis, and simulation of pollutant behaviors at regional scales. Scholars should consider the employment of new mathematical methods to assess the sampling efficiency and estimates of novel (i.e., heretofore unexamined) areas where pollution problems arise. Assisted with a GIS platform, researchers will then be able to better visualize sampling results, calibrate estimation procedures, and improve survey strategies. All such studies will greatly aid in supplying a solid foundation for the spatial process analysis of pollutants in the future.

(2) **Methodology of Spatial Process Modelling of Pollutants**

Explorations of many scientific questions, such as source apportionment, emission inventory, process simulation, and risk assessment, strongly depend on reliable tools and methods to effectively describe and model geographical space. These issues are crucial for breakthroughs in current macroscopic geographical research of China, which requires that geographers break down disciplinary barriers and exploit mathematical modelling methods to characterize the complicated relations among factors and simulate the virtual geographical environment. Spatial process analysis and modelling should utilize remote sensing and the Internet of Things to acquire high-resolution tempo-spatial data representing the gradients of natural and human factors. Meanwhile, data calibration may be fulfilled by relying on a long-term observational platform and position control system. A unified and effective observational platform will be helpful in comparing data from different observatories and upscaling research from the local to regional or global levels.

(3) **Improvement of Source Apportionment of Pollutants and Emissions Inventory**

The environmental problems in China are highly complicated. Interactions among environmental factors are multi-faceted and result in great uncertainty in source identification of pollutants, especially in macroscopic research. Moreover, China is responsible for fulfilling commitments to international conventions and should initiate and push forward the related research starting from prior controlled pollutants. The future focus must be to improve the high-resolution tempo-spatial emission inventory at a broad scale for recognized pollutants including aerosols, Hg, POPs, NOx, and sulfates.

(4) **Environmental Risk Assessment and Policy Scenario Simulation**

Development is an eternal topic in Chinese society, although the last four decades are undoubtedly unprecedented in history. For the purposes of science-based and effective ecosystem and environmental management and the attainment of optimal marginal benefits, scholars should devote themselves to better understanding data for different request, such as background content, baseline, and screening value, at regional scales through systematic analysis and investigation. Sustainable development should be the ultimate objective in the framework of environmental capacity to maintain the health of population and ecosystem. In such an eventuality, resolution of environmental problems cannot completely depend on environmental pollution control techniques. Such problems should concurrently be addressed through macroscopic decision-making and management, incorporating new ideas of management and novel scientific policy making. At the same time, progress in risk management will be achieved through reliable risk assessments. Great efforts should be made to establish a virtual policy simulation platform, one which can pose and then confirm the detailed effects of environmental management strategies.

16.4 Summary

Tempo-spatial processes and modelling of environmental pollutants is an important disciplinary frontier in environmental geography, one which can be even further developed into a robust research field based on geographical theory and methods. The main research contents include description of the migration, transformation, and fate of pollutants and the modelling of their tempo-spatial patterns, long-distance transmission, and ecotoxicology of pollutants under multiple environmental factors. The final purpose is to provide scientific support for risk management. The maturation of the research field is characterized by the expansion of the research focus from a single- to multi-dimensional character, the expansion and integration of that focus from patterns to processes and mechanisms, and the linking of the study scale from microscopic to macroscopic research. Over the past 15 years, comprehensive international studies on tempo-spatial processes and modelling of pollutants have been conducted, and achievements have been substantial and promising. Overall, Chinese scholars have mainly tended to follow international research. However, some distinct achievements have clearly represented the significant progress of scientific research in this field of China, including the establishment of a high-resolution tempo-spatial database of global combustion sources based on dynamic emission factors (PKU-Fuel-2007); analysis of the long-distance transport mechanism of PAHs across the Pacific; and high-resolution near-surface concentration field simulations of PAHs and BC. Moreover, at the regional scale, Chinese scholars have employed a multi-media fate model to identify pollutant sources and significantly reduce the uncertainties of source apportionment. In the future, Chinese researchers should conduct studies to simulate the transformation and transmission of pollutants and improve emissions inventories based on a thorough understanding of the interaction of environmental factors and pollutants. They should also strive to bring about the implementation of risk management and regulation as a central tenet in environmental management.

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Part IV

A Review and Outlook of Research Fields on the Geographical Sciences Regarding NSFC

Abstract

Part IV examines the developmental direction at a macro level of nine of the many sub-disciplines and research fields within the geographical sciences, by analysing the origin, connotation evolution, research progress and representative achievements, and challenges faced by Chinese scholars, along with perspectives for future research. The chapter also includes a detailed analysis of the research trends and the evolution of prominent topics based on statistics such as the number of academic articles published in journals cited in the SCI/SSCI-indexed database and the CSCD core journals database during the period of 2000–2014, as well as article citations, subjects or keywords in articles, and the research projects and articles sponsored by NSFC. The nine fields, which correspond to four branches of the geographical sciences and are interdisciplinary to certain degree, reflect various important foci of NSFC's sponsoring strategies. "Geomorphology" represents a traditional field which currently evolving at an established (i.e., steady but slow) pace. "Ecohydrology" and "Ecosystem Services" represent interdisciplinary studies on the international research frontier. "The Urbanization Process and Mechanism" and "International Rivers and Transboundary Environment and Resources" represent superior research fields driven by national strategies. "Medical and Health Geography", "Records of Environmental Changes in Physical Geography", and "Detection and Attribution of changes in Land Surface Sensitive Components" represent research fields with a pressing need for data enhancement and/or methodological breakthroughs. "Uncertainty of Spatial Information and Spatial Analysis" represents a research field with strong potential in which NSFC-sponsored explorations may play a leading role in international research. We believe that the analysis of research trends for the above fields will promote the optimal disciplinary system of geographical sciences and consolidate the basis of NSFC's sponsoring strategies.

Keywords

NSFC's sponsoring strategies • Sub-disciplines and research fields in the geographical sciences • Geomorphology and Quaternary environmental change • Ecohydrology • Ecosystem services • The urbanization process and mechanism • Medical and health geography • International river • Detection and attribution • Uncertainty of spatial information and spatial analysis

17 Geomorphology

Liping Zhu, Jinliang Feng, Fangen Hu, Xiaoping Yang, Jiongxin Xu, and Changxing Shi

Abstract

During recent 30 years, the international hot spots of Geomorphology have been focusing landform evolution histories based upon sedimentation, fluvial landforms and disaster occurrences due to sediments transportation and land surface erosion, landform evolution mechanism based upon modeling simulations. The main achievements of Geomorphology in China include long time scale landform evolution under tectonic and sedimentary controls; engineering landform studies relating with reservoirs, ports and soil and water conservations; past climatic changes based upon sediments' proxies; loess, karst and other types of landform with China regional features; and landform evolution mechanisms by modeling simulations. In the future, the basic theories, crossing and anastomosing, model simulations are required to be paid more attentions.

Keywords

Geomorphology development • Hot spot • China • Main achievements • Future

A total of 38,092 SCI/SSCI-indexed articles are analyzed in the research field of geomorphology. Articles were identified from 39 international journals from 2000 to 2014. The number of journals that have published more than 15 of the relevant articles is 39 (Appendix N). The search query is as follows: "geomorphology" OR "landform*" OR "weathering" OR "slope" OR "landslide" OR "debris flow" OR "sediment*" OR "deposit*" OR "fluvial" OR "river" OR "glacier*" OR "periglacial" OR "permafrost" OR "karst" OR "loess" OR "coast" OR "delta" OR "tectonic" OR "desert*".

17.1 Overview

17.1.1 Development of Research Questions

Geomorphology, the scientific study of the origin and evolution of land surface processes and morphology, seeks to understand the migration of materials and energy transforming/dissipating processes at the interfaces of the atmosphere, lithosphere and hydrosphere. Geomorphology is an important branch of physical geography that takes the land surface of the earth as the object of research.

The first theory of geomorphology was arguably devised by the Chinese scientist and statesman Shen Kuo (1031–1095 AD). He observed marine fossil shells in a geological stratum of mountain hundreds of miles from the Pacific Ocean. Noticing bivalve shells running in a horizontal span along the cut section of a cliff side, he theorized that the cliff was once the pre-historic location of a sea shore that had shifted hundreds of miles over the centuries. He theorized that the land had been reshaped and formed by soil erosion of the mountains and by deposition of silt, after observing strange natural erosions of the Taihang Mountains and the Yandang Mountain near Wenzhou (Sivin 1995; Needham 1959).

In the late 19th century, **F. Richthofen** systematized knowledge of land surface structure and landform genesis and attempted to construct a classification for landforms. In the books *River Evolution Cycle* and *Geomorphic Cycle*, American scientist W.M. Davis proposed some theories, in

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particular the theory that landform is a function of tectonic activity. Such forces, along with time, became the core theory of modern geomorphology. In the 1920s, German scientist **W. Penck** analyzed slope evolution, which he believed in many landscapes occurs by the wearing a way of rocks, via a mathematical method and explained crust movement in his book *Geomorphology Analysis*. The formation and development of modern geomorphology was inseparable from field observation and investigation. One of the significant features of geomorphology's development in this stage was to conduct theoretical summaries based on the analysis of massive data derived from observations. At the same time, concepts and technology from neighboring subjects was also a feature of the modern development of geomorphology. For example, Davis's geomorphology cycle theory was clearly influenced by Darwin's biological theory of evolution (Mo 1988).

The quantitative revolution in geomorphology during the late 1950s and middle 1960s greatly enhanced development of the discipline. During this stage, there were three distinguishing features in the growth of geomorphology: (i) substantial incorporation of advanced theory and technology from neighboring subjects (Embleton et al. 1978); (ii) application of new study methods and techniques, such as physical detection, remote sensing, dating, microfossils and sporo-pollen analysis (Hart 1986; Abrahams and Parsons 1994); and (iii) the rapid development of positioning experimental stations and indoor/outdoor simulation experiments (Allison 1996). The quantitative revolution in geomorphology also generated certain side effects. Some scholars who conducted modeling research have converted some models into mathematical games. In particular, with the rapid development of computer technology in recent years, a trend appeared involving excessive dependence on computer modeling while downplaying field observation and experiments.

The development of modern geomorphology effectively entered a new stage when the British Geomorphology Research Group (BGRG) was established in 1961. In 1976, the journal *Earth Surface Processes* began publication, which confirmed the maturity of a process-oriented focus in geomorphology. In 1981, this journal was renamed *Earth Surface Processes and Landforms*, reflecting a shift in outlook from an almost exclusive focus on processes of landform change to a broader perspective that also gave extensive attention to the outcomes of landform change. In 1984, **R.J. Chorley**, **S.A. Schumm and D.E. Sugden** coauthored a monograph *Geomorphology*, signifying the establishment of the dynamic geomorphology school (Chorley et al. 1984). Since 1985, the International Conference on Geomorphology, which is held every four years, reports on the latest developing trends in international geomorphology. The focal theme of the first conference in 1985 was that geomorphology was relevant to energy, environmental protection and management as well as hazard prevention. In 1989, the conference theme was geomorphology and geoecology, while in 1993 and 1997, themes centered on the diversity of geomorphology. In 2001, the focal theme was tectonic activity, climate, human activities and geomorphology, while in 2005, the conference covered various branches of geomorphology. This was followed in 2009 with a thematic focus on viewing the ancient landscape from modern perspectives. The most recent conference in 2013 addressed the theme of geomorphology and sustainability. From an international perspective, the science of geomorphology has evolved from process studies in its earliest stage through the integration of a focus on outcomes amenable to practical applications, and ultimately expanding into earth system science connecting multiple elements on the land surface.

17.1.2 Contributions by Scholars from Different Countries

Based on the literature of geomorphology studies published in international journals, we may objectively evaluate the overall situation of this field, both domestically and internationally, and China's position therein. To do so we searched the literature on geomorphology studies in the aforementioned 39 international journals and analyzed the quantity of articles, total citations, and number of highly cited articles in various countries during different time intervals over the period from 2000–2014. The search results for the geomorphology research field for the top 20 countries (regions) in terms of number of articles in this time period are presented in Table 17.1.

It is evident here that the main research groups and achievements in international geomorphology research have been from developed countries. China and India are two developing countries among the top 20, with China clearly at the forefront. Comparing the two periods 2000–2004 and 2010–2014, China's position in the geomorphology research field rose from 6th to 1st in terms of research scale (quantity of articles); from 6th to 2nd in academic influence of literature publications (total citations); from 5th to 3rd in the production of outstanding achievements (highly cited articles). On the basis of these results, along with the increase in scientific and technological investment, Chinese geomorphology studies have yielded significant academic achievements internationally. At the same time, the influence of these achievements has not kept pace with the rapid advances in productivity, as reflected in the slower advance over the same period in the quantity and overall ranking of highly cited articles. This suggests that the international academic influence of Chinese geomorphology research must be further promoted.

Table 17.1 Top 20 countries (regions) with the number and citations of SCI/SSCI-indexed articles on "Geomorphology" during the period 2000–2014

	Number of articles						Cited frequency						Number of highly cited articles					
	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014
Rank	World	1,429	4,199	8,172	11,781	18,139	World	50,895	2,469	256,366	229,448	93,080	World	159	0	690	684	1,010
1	China	44	883	352	743	3,102	USA	12,617	461	67,141	53,377	16,830	USA	39	0	198	171	206
2	USA	331	651	1,980	2,498	2,984	China	2,646	425	11,527	15,322	12,723	UK	26	0	105	107	129
3	UK	222	256	980	1,329	1,346	UK	8,715	195	36,302	30,728	9,789	China	11	0	30	47	120
4	Germany	101	231	538	740	1,118	Germany	3,487	195	16,693	16,644	7,397	Germany	11	0	49	60	91
5	Canada	122	192	597	783	929	France	1,595	110	12,541	11,078	5,709	France	5	0	35	37	80
6	France	50	198	359	568	924	Italy	1,530	111	7,917	9,380	4,336	Switzerland	7	0	25	29	42
7	Italy	54	175	286	534	832	Canada	2,851	114	15,691	13,368	4,264	Canada	6	0	28	33	39
8	Spain	45	157	274	466	708	Spain	1,222	94	7,785	8,499	3,476	Italy	2	0	14	19	36
9	India	13	148	147	227	535	Switzerland	1,698	90	8,053	7,793	3,055	Spain	2	0	19	17	32
10	Japan	42	92	277	365	440	Australia	1,919	42	9,925	8,084	2,241	Netherlands	11	0	24	22	26
11	Switzerland	41	87	190	296	428	Netherlands	2,086	50	7,960	5,965	2,181	Australia	7	0	30	27	23
12	Australia	50	96	289	378	414	Norway	1,462	32	6,008	3,579	1,726	Norway	6	0	21	14	19
13	Netherlands	41	61	225	270	309	Japan	1,342	31	5,232	5,390	1,710	Sweden	2	0	24	7	19
14	Norway	29	50	152	184	256	India	345	58	2,683	2,543	1,682	Japan	5	0	9	13	16
15	Poland	9	72	72	137	246	Sweden	1,020	24	6,867	4,040	1,293	Belgium	3	0	8	12	14
16	Belgium	17	33	102	190	187	New Zealand	437	16	2,776	3,062	1,185	Denmark	4	0	20	13	12
17	Sweden	28	39	184	195	183	Belgium	649	15	3,329	3,642	1,155	Austria	1	0	3	5	10
18	New Zealand	15	31	96	150	175	Denmark	773	19	4,852	2,764	979	New Zealand	0	0	7	6	9
19	Russia	14	40	77	115	160	Austria	407	51	1,479	1,792	878	Israel	0	0	5	2	8
20	Denmark	21	27	125	106	154	Finland	514	7	1,804	1,831	514	Finland	2	0	4	5	5

Note Countries (regions) ranked by the number of articles, cited frequency and the number of highly cited articles during the period 2010–2014

17.1.3 Key Research Topics

Based on a cluster analysis of the keywords of geomorphology articles published in SCI/SSCI journals during the past 15 years (Fig. 17.1), the most prominent topics in modern geomorphology may be described as follows: (1) The core content of geomorphology still centers on the utilization of sediments to study the formation processes and evolutionary history of landforms, in connection with which global climate change is a prominent topic; (2) Geomorphology has emphasized studies on application or engineering geomorphology, such as erosion processes of water and sediment, landslides and mud-rock flows and mountain disasters; (3) Geomorphology is continually incorporating methods and techniques from related disciplines and performing model simulation studies; and (4) Studies in geomorphology focus more on regional, as opposed to global issues. Studies on the formation and evolution of landforms in regions with various geomorphic types that have been poorly understood have become a major focus. Thus the keywords in international articles on geomorphology coincide exactly with the headings of international geomorphology conferences, mirroring their focus on surface-environmental changes from the perspectives of process, development of engineering applications, and earth system science.

From the keywords of geomorphology articles in the SCI/SSCI journals, the foci of geomorphology studies are as follows (Fig. 17.2): (1) "late Quaternary" has the highest word frequency, reflecting the historic processes of the period of geomorphologic change to which the most attention has been devoted; (2) Word frequencies of "climate" and "record" are 4394 and 4328, respectively, evidence that records on climate and environmental change are popular topics in investigating the historical processes of geomorphic change; (3) "model", with a word frequency of 4211, reflects the fact that model simulation is becoming an important tool for revealing the mechanisms underlying geomorphologic and environmental changes; (4) "sediment", "lacustrine", "glacier", "river", and "basin" rank within top 10 most employed keywords, indicating the main foci and contents of geomorphology research; (5) Keywords ranking below 10th include "soil", "flow", "erosion" and "water" relating to water and sediment processes of rivers, and "landslide" and "mountain" related closely to mountain hazard, indicating the related geomorphic processes are emphasized frequently, but to a slightly lesser degree; (6) The ranking of "China"—the only keyword related to a region has entered into the top

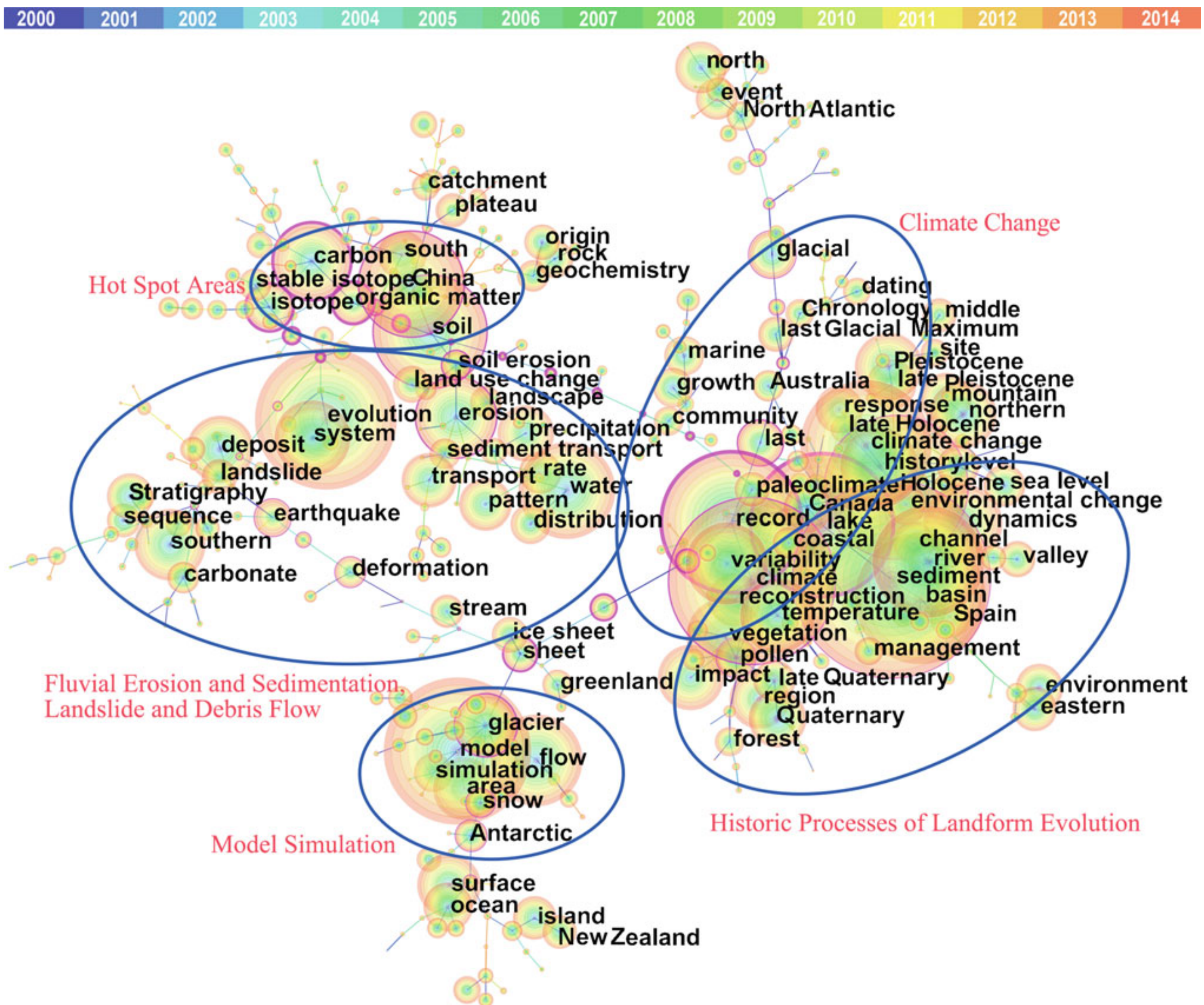

Fig. 17.1 Co-occurrence network of SCI/SSCI-indexed article keywords on "Geomorphology" during the period 2000–2014

20, indicating that China is becoming a popular region for the study of geomorphology.

According to the analysis of international articles on geomorphology contributed by Chinese scholars, "China" is the keyword with the highest frequency of appearance, followed by "sediment", "lake", "river" and "basin", indicating that Chinese scholars are focusing on the same geomorphologic objects as international researchers. However, "glacier" does not appear very frequently in international articles on geomorphology contributed by Chinese authors. The high frequency of "soil" may be related to weathering processes or loess studies. The frequency of "climate" and "record" is close to that of "late Quaternary", indicating that historical processes of geomorphologic change in which climate and environmental change are the main contents have been the foci of Chinese geomorphologic scholars. It should be noted that the keyword "model" appears with high frequency in international articles of geomorphology, but with relatively low frequency in articles contributed by Chinese scholars. This suggests that it is necessary for Chinese researchers to improve their modeling efforts regarding the mechanisms and quantitative description of geomorphologic processes.

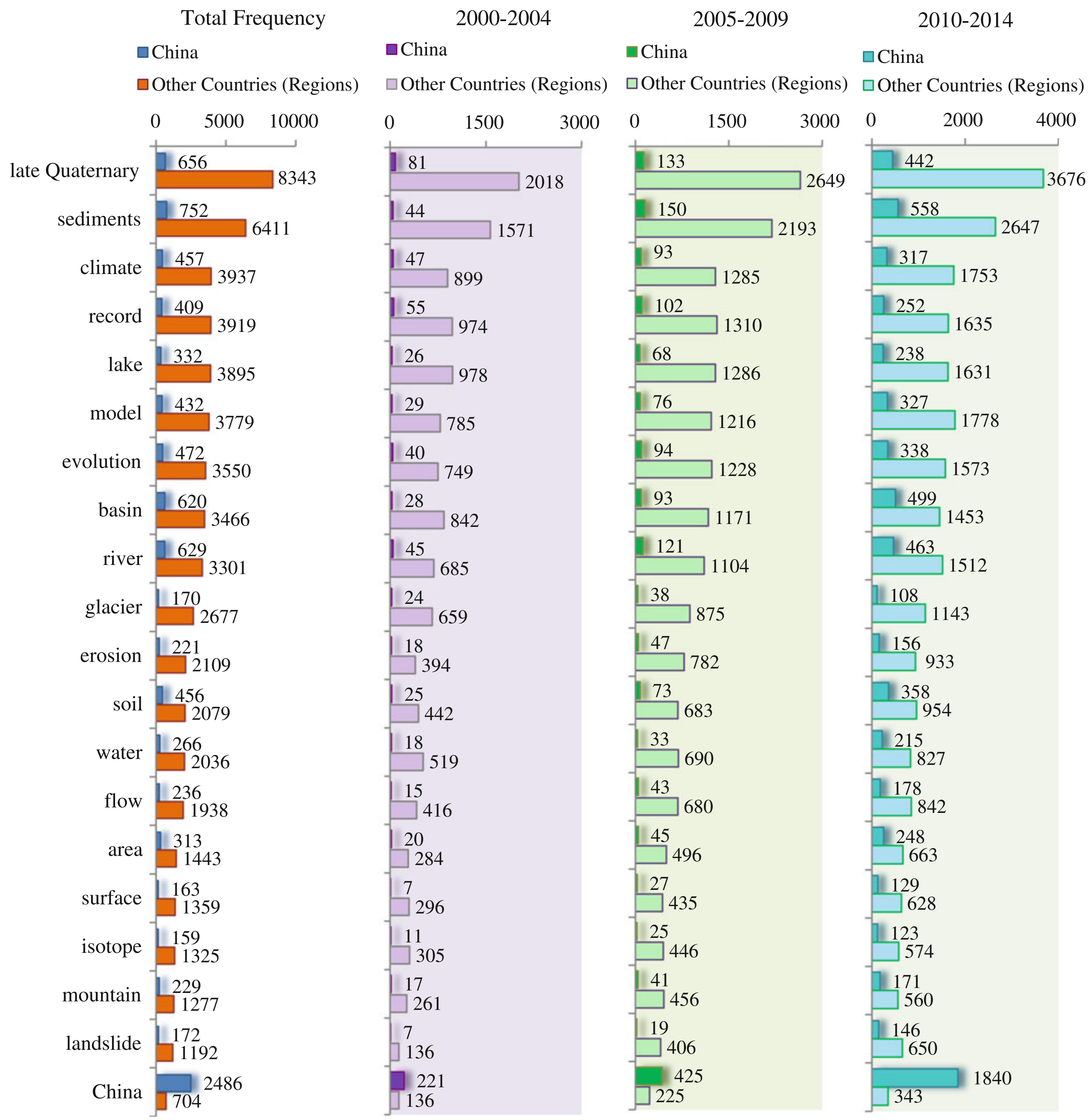

Fig. 17.2 Keyword temporal trajectory graph for SCI/SSCI-indexed articles on "Geomorphology" during the period 2000–2014

17.1.4 The Role of NSFC in Supporting the Research on Geomorphology

According to the classification code[1] of National Natural Science Foundation of China (NSFC), there were 738 projects that focused on geomorphology supported by NSFC from 2000–2014. The articles of Chinese scholars accounted for 11 % of the 38,092 articles on geomorphology published in international journals. For those articles contributed by Chinese scholars, 69.7 % were supported by NSFC, indicating that NSFC is the main funding channel to support Chinese geomorphology studies.

The number of geomorphology articles contributed by Chinese scholars to SCI/SSCI journals and supported by

[1]Including all projects of geomorphology (D010101), some projects of hydrology (D010102), cryosphere geography (D010105) and soil erosion and conservation (D010505).

Table 17.2 NSFC-funded projects and SCI/SSCI-indexed articles on "Geomorphology" during the period 2000–2014

SCI/SSCI-indexed articles					NSFC-funded projects			
Periods	Number of articles	% of articles by Chinese authors	% of articles with NSFC funding by Chinese authors	% of articles funded by MOST among those with NSFC funding	Number of projects	Funding (10,000 yuan)	Number of PIs	Number of institutions
2000– 2004	8,172	4.3	33.8	0.0	98	3,001.0	89	33
2005– 2009	11,781	6.3	45.0	22.5	211	9,944.5	191	61
2010– 2014	18,139	17.1	79.7	43.0	429	29,633.3	390	119
2000– 2014	38,092	11.0	69.7	38.9	738	42,578.8	533	136

NSFC reveals the relative contribution from NSFC in Geomorphology development (Table 17.2). During 2000–2004, 352 articles were contributed by Chinese scholars in SCI/SSCI journals, accounting for 4.3 % of all geomorphology articles; only one-third of these were supported by NSFC. One reason was that at that time NSFC gave relatively little support to the field of geomorphology; another was that NSFC did not emphasize the acknowledgement of articles it supported with funding. During 2005–2009, the number of geomorphology articles contributed by Chinese scholars in SCI/SSCI journals was 743, accounting for 6.3 % of all geomorphology articles. When NSFC began acknowledging funding of and providing much more support to geomorphology, 45 % of the geomorphology articles from Chinese scholars in SCI/SSCI journals were found to be supported by NSFC. From 2010–2014, the number of geomorphology articles by Chinese scholars in SCI/SSCI journals reached 3102, accounting for 17.1 %; among these articles, 79.7 % were funded by NSFC, confirming that NSFC played a crucial role in promoting Chinese geomorphology studies, transforming an earlier ebb into a gradual resurgence in the early 21st century. Comparing funding input to the number of articles as output, NSFC funding for geomorphology projects during 2010–2014 was 9.9 times that during 2000–2004, while the output (number of NSFC-sponsored articles) increased by a factor of 20.9. Thus the benefit of scientific research funding by NSFC to the field of geomorphology was high. Moreover, a large number of the geomorphology articles funded by NSFC were also supported by the Ministry of Science and Technology (MOST). During 2000–2004, no articles were exclusively supported by the MOST; however, the proportion of articles from 2000–2004 co-supported by NSFC and MOST was 22.5 % of those supported by NSFC; and this proportion increased to 43 % from 2010–2014. This shows that not only is NSFC increasing its support for geomorphology, but increasing funds are also being provided by the MOST.

The relationship between the development of Chinese geomorphology and the input of NSFC can be examined with respect to the main content of NSFC projects (Fig. 17.3). It can be seen from the keyword frequency distribution of projects that the historic processes of landform evolution ("glacier change", "environment change", "chronology", "geomorphic evolution", "spatial-temporal change" and "glacial-interglacial period"), along with soil erosion, water and sediment transport processes have been the common topics in the international literature and articles of the Chinese scholars, as well as NSFC projects. However, the historic process of landform evolution has been more important than soil erosion, water and sediment transport processes in both the international literature and the articles of Chinese scholars. This situation is reversed in NSFC projects. The reason for this is probably that part of the projects of the historic process of landform evolution, especially those linked with the environmental change of the Quaternary period, were funded by other discipline codes in NSFC system. At the same time, some keywords of international geomorphology articles and those contributed by Chinese scholars did not match well with the keywords of NSFC projects. For example, the keywords "glacial change", "model simulation" and "isotope" were prominent in both NSFC projects and the international articles on geomorphology; however, these were not primary keywords for the articles contributed by the Chinese scholars. Therefore, even though NSFC has supported certain popular studies of international geomorphology, the output from Chinese scholars was not always consistent with NSFC input. The keywords "permafrost" and "aeolian landform" have high frequency in NSFC projects; however, these keywords were not the main keywords of the international literature of

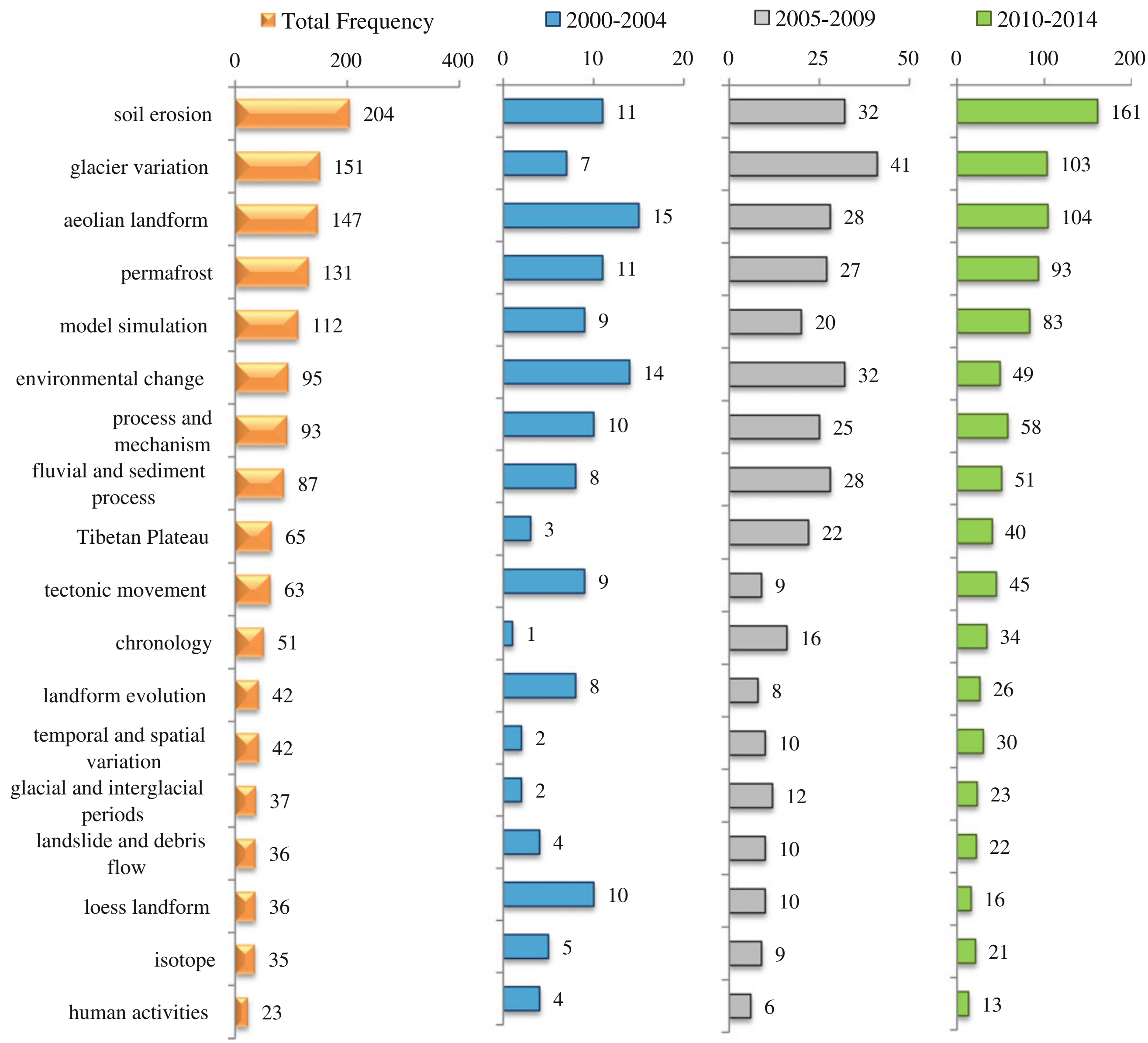

Fig. 17.3 Keyword temporal trajectory graph for NSFC-funded projects on "Geomorphology" during the period 2000–2014

geomorphology, indicating that permafrost and aeolian landform are more likely unique research foci of Chinese geomorphology.

17.2 Research Advances and Problems

17.2.1 Bibliometric Analysis of Contemporary Research

There have been 38,092 articles on geomorphologic research topics published since 2000, among which the topic "Holocene" ranked 1st in number of articles, with 1591 articles accounting for 4.0 % of the total (Fig. 17.4). The topics "paleoclimate" (806 articles) and "climate change" (775 articles), ranked 2nd and 3rd, respectively, accounting for 2.1 and 2.0 %, respectively, of all articles. Each of the subsequent 12 topics accounted for less than 2.0 % of the total number. These include: "paleoclimate", "climate change", "diatom", "landslide", "stable isotope", "pollen", "erosion", "paleoecology", "sediment", "lake sediment", "sediment transport", "climate", "soil erosion" and "Quaternary". According to the top 15 topics of the articles on geomorphology research, it can be observed that past environmental changes are the main focus, and these studies are based upon sedimentary processes. Moreover, "landslide" is an important landform hazard that also receives some attention. "Sediment transport" and "soil erosion" are closely

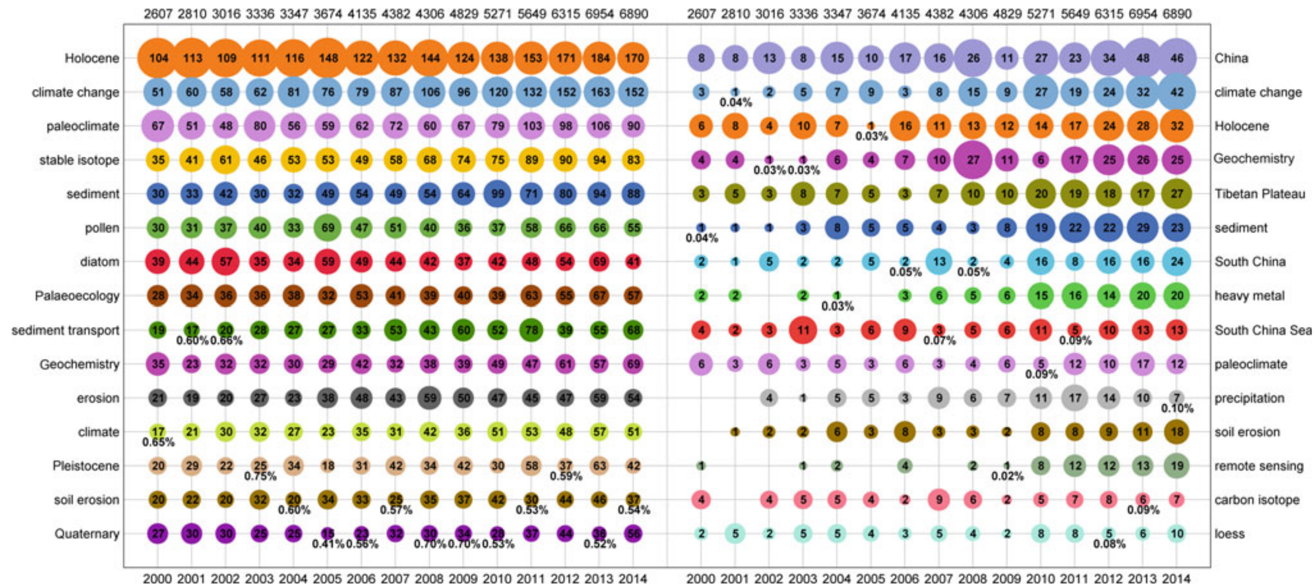

Fig. 17.4 Comparative diagram of prominent keywords on "Geomorphology" by Chinese authors and others in SCI/SSCI-indexed articles during the period 2000–2014. *Note* Right panel shows keywords used by Chinese authors and left panel shows those used by the authors from other countries (regions). Size of circles denotes the ratio of a certain keyword frequency to the total article number in a specific year. The annual total number of articles is shown at the *top* of the diagram. The frequency of the keyword is shown inside the circle. The size of circles in the diagram for Chinese authors are magnified for clear display

related to fluvial landform and processes. The number of articles on different topics also reveals that international geomorphology has focused on the historical processes of landforms, mainly through sediment studies, as well as the fluvial landform and related water and sediment transport processes, and landform disasters.

17.2.2 Contemporary Research

Geomorphology has made great progress in the world during the past 15 years. First, significant advances have been made in the aspect of landform response to environmental changes. These studies, including those on ice-sheet development and climatic changes, sea level fluctuations reflected by coast landform and marine sediments, sedimentation related to carbon burying, and others (Svendsen et al. 2004; Lambeck et al. 2004; Waelbroeck et al. 2002), have exerted wide influence. Second, studies of the Holocene environmental changes such as confirmation of special environmental events, reconstruction of paleo temperature and paleo hydrology, relationships between climatic changes and human activities, and integration of climatic change sequences, have been given great attention (Alley 2000; Gasse 2000; Davis et al. 2003; Magny 2004; Mayewski et al. 2004; Alley and Ágústsdóttir 2005). Third, the effects of tectonic movements on landform evolution have been a topic of interest, especially the functions of the North China platform in earth crust evolution (Kroner et al. 2005). Fourth, great progress has been achieved in the methodologies for studying sedimentary processes and amplitudes of environmental changes. These advances include chronologies of sediments and landforms; and physical, chemical and biological proxies indicating environmental changes (Blott and Pye 2001; McKnight et al. 2001; Leng and Marshall 2002; Balco et al. 2008). Fifth, modeling and simulation have gradually become important research methods for understanding mechanisms underlying landform evolution and environmental changes. Some studies have investigated the planet's evolutionary history with respect to landform patterns and plate movement. Environmental evolution at a regional scale has been simulated as driven by factors related to land, sea, and glaciers and snow (Mix et al. 2001; Hall 2002). Sixth, the modern processes of landforms have been given more attention in recent years. The most significant studies have been focused on ice and snow processes, lake distribution and variation, and erosion processes of channels and valleys (Poesen et al. 2003; Downing et al. 2006; Rignot et al. 2008).

In light of the aforementioned analyses, studies of environmental changes based on geomorphic processes are becoming popular topics in geomorphology. Articles focusing on methodology have also been given much attention, which may indicate that refining of methodological techniques is becoming the key to further developing the field of geomorphology.

International journals that have published frontier articles in the field of geomorphology provide valuable clues as to the future directions in which the discipline is heading. For example, many articles are concentrated in *Quaternary Science Reviews,* a journal focusing on environmental change studies and related reviews. Other journals focus on environmental change and sedimentary processes, such as *Limnology and Oceanography* and the *Journal of Paleolimnology*. There are also some frontier articles published in such journals as the *Journal of Asian Earth Sciences*, *Terra Nova*, and *Earth Surface Processes and Landforms*, which focus on tectonic movements and geomorphic processes.

17.2.3 Bibliometric Analysis of Contemporary Research in China

As shown in Table 17.1, since the turn of the century Chinese scholars have published 3102 academic articles on geomorphology, accounting for 8.1 % of the total. From the top 15 themes of these articles, excluding "China" as a regional indicator, the following themes rank from 2nd to 15th: "Holocene", "geochemistry", "climate change", "debris flow", "landslide", "permafrost", "Tibetan Plateau", "South China", "soil erosion", "Loess Plateau", "sediment", "South China Sea", "paleoclimate", loess", "precipitation", Among these themes, articles on "Holocene", "geochemistry", "climate change", "paleoclimate" and "sediment" account for 4.1, 3.6, 3.3, 1.6 and 1.8 %, respectively, of total articles on geomorphology published by Chinese scholars. The total percentage here reaches 14.4 %, indicating the historic processes of landform evolution constitutes the top key issue in geomorphologic research in China. Articles focusing on "debris flow" and "landslide" account for 2.9 and 2.7 % of total articles, respectively. This fact indicates that Chinese geomorphologic scholars are paying more attention to landform disasters than is the international geomorphologic community. Articles focusing on "soil erosion", "Loess Plateau" and "loess" account for 2.0, 2.0 and 1.5 %, respectively, of the total, suggesting that fluvial process in the loess area is important in Chinese geomorphologic research. It is noteworthy that articles on "permafrost", "Tibetan Plateau", "South China", and "South China Sea" account for 2.7, 2.6, 2.1, and 1.7 %, respectively, of all articles. Because permafrost is mainly distributed on the Tibetan Plateau, these keywords have clear regional significance. Compared with the main themes of articles from the international geomorphologic community, in addition to historical processes of landforms, fluvial landforms and related water and sediment transport processes, and landform disasters, landforms of the Tibetan Plateau and South China receive high attention in China as regional geomorphologic foci.

17.2.4 Contemporary Research in China

Chinese geomorphology developed rapidly from the 1980s to the end of the 20th century. Based on the studies dating sediments and terrace, Chinese scientists proposed a theory regarding the Tibetan Plateau uplift, attributing to it a significant influence on atmospheric circulation, subsequently affecting the surrounding environment and human activities (Li et al. 1979; Li 1991). In terms of fluvial landform and geographical distribution, scholars found that rivers with braided channels and middle bars had regularities of zonal distribution (Xu 1990). Some progress was also achieved in understanding lengthwise channel scouring and silting and plane deformation mechanisms; evolution of paleo-river channels; and the influence of reservoir construction and human activities on river evolution (Xu 1989; Ye et al. 1990; Wu 1991). The studies of aeolian (i.e., wind-driven) landform and desertification processes led to rules for the evolution of aeolian sand and topographic features as well as management measures (Wu 1987; Zhu 1989). Research was also conducted on ancient aeolian sand, including its distribution pattern, characteristics, chronology and evolutionary history (Dong et al. 1991). Based on the research on glacial debris, Chinese scholars dismissed the theory that a great ice sheet had ever existed on the Tibetan Plateau (Li 1988) and clarified the Quaternary glacier issue with respect to the eastern areas of China (Shi et al. 1989). In loess landform and hill-slope process research, Chinese scholars revealed the loess erosion mechanisms of different topographic features (Chen 1989) and quantified the relationship between loess plateau erosion and sediment runoff to the Yellow River (Jing et al. 1993). In research on river mouths and coastal landforms, extensive investigations were undertaken on the delta sediment transport rule for the large river mouth and silt beach, providing a scientific basis for sea port construction, channel and river mouth management (Chen et al. 1989; Ren 1993). The studies of karst landform research elucidated an evolutionary relationship between peak forest and peak cluster in karst areas of southern China; both comprise the karst landform that was formed in tropical climates since the Tertiary period (Yang 1993). Landscape protection and development of karst landform tourism resources were investigated based on the formation mechanisms of the karst landscape (Lin et al. 1993). The relationship between the carbon cycle of karst landscapes and global change began to attract the attention of scientists (Yuan 1993). In geomorphic experiments and simulation research, experiments on fluvial landforms led to a process response model based on systems theory (Jin et al. 1992). Aeolian landform experiments based on a random theory proved the logarithmic function of jumping sand grain distribution in the wind-sand flow structure; and based on this result, a theory was proposed regarding the formation mechanism of pyramid dunes (Zou et al. 1992). Through debris flow observations and experiments, the formation mechanisms for the Dongchuan debris flow in Yunnan Province were revealed, and an early warning and prediction protocol for debris flow disaster was developed (Wu et al. 1990). With respect to geomorphologic mapping, 15 geomorphologic maps with a scale of 1:1,000,000 and accompanying instruction books were completed by the 1:1,000,000 geomorphologic map editor committee of China in 1988. Thematic geomorphic maps were completed covering the entire nation with respect to glacier and frozen soil, landslide and debris flow disasters, and distribution of desertification; and regional geomorphologic maps were produced of Quaternary glacial remnants on the Tibetan Plateau and erosion distribution of the Loess Plateau (Shi 1988; Li and Li 1991; Li and Liu 1991; Tang et al. 1991).

From 1996 to 2005, Chinese geomorphology research experienced a lull. During this period, the challenging and controversial scientific issues of concern in some branches of geomorphology had to some extent been resolved. For example, substantial progress had been made in research on the Quaternary glacier in Lushan, the Quaternary ice sheet on the Tibetan Plateau, the formation age of the western desert, and the causes of formation and classification of the loess landform; and hence the development of some branches of geomorphology began to stagnate. In other areas the study of karst landforms focused on material (including carbon and calcium) migration and the climatic information revealed by cave stalagmites (Wang et al. 2001). At the same time, attention turned toward the development of cave tourism resources and the protection of the cave tourism environment (Song et al. 1994). Theoretical research on the evolution of the estuary delta and the prediction of coastal erosion prediction was incorporated within the study of estuarine and coastal geomorphology (Li et al. 2007b). Most of these studies were in combination with channel improvement, site selection of ports, silting-up management, and so on. New research foci, such as geochemistry and fluid physics, were introduced into some relevant studies due to the complex factors of environmental change affecting estuarine and coastal landforms (Wang et al. 2006). Some special landforms became tourism resources and also the study foci of geomorphic scholars. For example, studies on the Danxia and Zhangshiyan landforms (Peng 2000; Wu et al. 2002) have made some progress. In the study of experimental geomorphology, due to the ambiguity of scientific issues and application targets, together with higher cost for operations and maintenance, indoor and outdoor mechanical simulation experimental research has stagnated or disappeared. The observational studies of field stations that have been gradually established since the 1950s, such as the glacier station, permafrost station, desert station, debris flow station, landslide station, soil erosion observational test stations in small watersheds and so on, have not only continued to focus on geomorphic problems, but also have tended to diversify into observational studies related to environmental changes (Guo 2000).

During the most recent 10-year period, the development of earth system science as a discipline has focused on the man-land relationship, while maintaining geomorphology as its foundational core; and geography has attracted increasing attention as well. In the study of tectonic geomorphology, the uplift of the Tibetan Plateau remains the primary focus. In addition to the traditional study of land denudation, terrace studies of geomorphology, some methods of faulting chronology, seismic geology, and remote sensing and three dimensional terrains, have been introduced (Jia et al. 2007; Li et al. 2007a; Fu et al. 2008). The study of fluvial landforms now includes a complete series of drainage systems in slope, valley and riverbed development (Cai et al. 2006; Fang et al. 2007) and has further expanded applications in the loess erosion process, horizontal river bed evolution and sediment transport (Xu et al. 2006; Ni et al. 2008). The formation and evolution of slopes have been studied thoroughly, including the slope erosion process and its influencing factors (Sun et al. 2014), slope stability and its influencing factors (Chen et al. 2007), a quantitative description of the slope erosion process (Gong et al. 2011), and the prevention of slope geological hazards (Huang and Fan 2013). At the micro scale, an Aeolian landform has been achieved via the mechanisms of dune movements (Yang et al. 2011), and at the macro scale the relationship among climate changes, landform evolution and desertification has been investigated (Yang and Scuderi 2010). In the study of glacial geomorphology, the utilization of new dating methods in constraining the age of moraines has contributed to a better understanding of the scale of the last glacial period and the Little Ice Age (Yi et al. 2005; Zhou et al. 2007). In addition, great progress has been made in the study of glacier-dammed lakes and their disastrous influences (Wang and Liu 2007). In the study of estuarine and coastal geomorphology, a profile model of delta development has been established based on the study of river deltas and sea-level change histories (Dai et al. 2007), and the evolution of estuary coastal geomorphology has been simulated with the aid of experimental results from long-term observations (Gao 2007). In the research on karst geomorphology, utilizing GIS and geochemical approaches, studies on the classification and development processes of karst landscapes have been conducted (He et al. 2008), which have consequently stimulated some related research on such foci as karst rocky desertification (Zheng et al. 2008) and the chronology of the deposits in karst caves (Yuan et al. 2004).

17.2.5 Contributions by Chinese Scholars and Subsequent Problems

Seen from the three developing stages of geomorphology in China, the rapidly developing status of Chinese geomorphology has been closely linked to international geomorphology. It is reflected in the overall balanced development of all branch subjects of geomorphology, as well as with the theoretical study of geomorphologic evolution. According to the SCI/SSCI-indexed articles contributed by China and the international geomorphologic community in the most recent 15 years, China was at its lowest point at the turn of the century, when the total number of articles, total citations and highly cited articles were all far below that of the developed countries, and even below the overall world average. Over the past 5 years, the total number of articles has rapidly increased, reaching the No. 1 ranking in the world; the total citations have reached the 2nd position, while the highly cited articles were also ranked in the 3rd position (Table 17.1).

By comparing the keywords in the geomorphologic articles published in international journals by scholars from China and other countries, one can clearly ascertain the correlation between the development of geomorphology in China and the world (Fig. 17.2). The keyword “China” has been excluded, given that it is the most frequently used word by Chinese authors. On the one hand, “sediments”, “lake”, “river” and “basin” are all among the most frequently used keywords by both Chinese and international authors, showing that sedimentary landform process is the most prominent issue for both Chinese and international geomorphologists. On the other hand, words related to past climate change, such as “late Quaternary”, “climate” and “record”, are also frequently used by Chinese and international authors, indicating that studies on past climate and environmental changes have become more and more important. However, the word “model” is much more frequently used by the international community than by the Chinese authors, reflecting the fact that modeling and simulation are widely utilized in studying geomorphologic-environmental change mechanisms in international geomorphology, but are relatively weak in Chinese geomorphologic studies.

17.3 Roadmap for Further Research

The formation and evolution of landforms result from the long-term development of the earth’s surface elements in achieving a relative balance. Geomorphology in China experienced a comprehensive and rapid development in fundamental theory of landform formation and engineering application; in recent years, this pace slowed or even stagnated in the study of surface processes and related control factors. However, with the maturation of earth surface system science, geomorphology—as the basic discipline of earth surface processes—retains central relevance with respect to the formation, macro- and micro-processes, and evolutionary mechanisms of landforms. Over the past 30 years, geomorphology in China has experienced three stages-initial rapid development, a period of relative stagnation, and a return to increasing relevance. Considering the status of geomorphology in China relative to the international field, the following research foci should be addressed in order to promote geomorphology in China and fully exert its global influence in the science of earth surface systems.

(1) Emphasis on Fundamental Theoretical Research in Geomorphology

Emphasizing process but ignoring theoretical mechanism studies results in scattered research teams and the tendency to slow the pace of development in the discipline. On the one hand, the landscape is a result of long-term evolution and equilibrium of earth surface processes; it is difficult to achieve universal theory based on short-term observation of phenomena and process studies. On the other hand, in China, there are gaps that exist between micro- and macro-scale research, as well as theory and application in geomorphology, which create more difficulties in deriving fundamental principles from phenomena. To promote the development of geomorphology, it is essential to support long-term modern process and monitoring studies, enhance the applications of new technology in related disciplines, and devote more attention to research on the mechanisms of surface processes to enhance the possibility of theoretical refinements in relation to geomorphic evolutionary trajectories.

(2) Promoting the Harmonious Development of Geomorphology and Its Branch Subjects

In China, geomorphology has tended to develop at a sporadic pace characterized by rapid advances and periods of impassivity, but its branches have exhibited upward trends through interconnections with other disciplines. For example, impressive achievements have been made in some branches with related applications (e.g., reservoirs, ports and soil and water conservation) and foci (e.g., Quaternary environmental change records). However, disconnections between theory and practice exist even in these branches, which hinder discussions regarding general scientific questions relevant to addressing practical problems. The lesson to be learned here is that geomorphologists must commit to the overall development of the discipline. They must also strive to express scientific results in clear and understandable forms when applying geomorphologic knowledge to serve practical applications related to economic and social development. This may lead to new knowledge derived from results of practical applications, which may in turn contribute to enhancing the progress of geomorphologic theory.

(3) **Conducting Geomorphologic Research from the Perspective of Earth System Science**

To date, Chinese research in geomorphology, despite its many accomplishments, still lags behind that of the international community. To further raise the level of research, Chinese scientists should conduct their research from the point of view of earth system science. Hence they should not only focus on regional landforms but also consider global-scale landscape evolution and prominent international topics of geomorphology, and apply new methodologies and technologies—in particular modeling—that may help to uncover mechanisms of landform evolution. At the same time, from the perspective of sustainable development, it is also vital to strengthen personnel training and research team building.

17.4 Summary

Geomorphology is essentially concerned with earth surface processes and the shaping of landscapes. Geomorphologic research focused on surface processes in its early period, and then combined with applications and moved toward earth system science, which connects multiple elements of the land surface. In the past 30 years, geomorphic evolutionary history, which takes sediments as the main study foci, fluvial landforms and hazard landforms (with the core foci of water and soil transport and surface erosion), and the geomorphic evolutionary mechanism (studied via model simulations), have become prominent international topics. Geomorphology research in China experienced three stages: rapid development, stagnation and re-emergence. Impressive progress has been made with significant influence in the international arena in research on long-term landscape evolution under tectonic action and deposition control; engineering geomorphology related to reservoirs, ports, and soil and water conservation; and paleo-environmental reconstruction using the sedimentary proxies, landforms with Chinese characteristics (e.g., loess and karst) and simulation modeling. In further research, it is necessary to improve theoretical geomorphology and modern process observation; further promote cross-integration with other disciplines; perform analyses using models; and shift the focus from regional issues with Chinese characteristics to those with global significance. At the same time, more attention should be paid to geomorphologic personnel training and team building as, for example, via the provision of more support in teaching materials, curriculum and geomorphologic projects.

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Ecohydrology

18

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Abstract

Ecohydrology is an interdisciplinary science between hydrology and ecology, which has rapidly developed during the last 30 years. Research theme mainly focuses on evapotranspiration, carbon-water coupling, ecohydrological processes and water balance. Ecohydrology researches in China are well developed in arid and semiarid regions and have distinct practical features in combination with ecological engineering projects. Future researches need to highlight multiple spatiotemporal and multidisciplinary integrated researches and focus on the biotic- and abiotic interaction, surface-groundwater relations, coupling of natural and anthropogenic processes, interactions between geological and biological cycles, and extensions from molecule to global scales.

Keywords

Ecohydrology • Evapotranspiration • Soil water • Vegetation pattern • Soil vegetation atmosphere transfer • Integrated model

A total of 3618 SCI/SSCI-indexed articles are analyzed in the research area of ecohydrology. Articles were identified from 156 international journals from 2000 to 2014. The number of journals that have published more than 15 of the relevant articles is 62 (Appendix O). The search query is as follows: ((“soil moisture” OR “soil water” OR “soil water content” OR “water potential” OR “drought stress” OR “drought” OR “water stress”) AND (“vegetation” OR “plant” OR “ecosystem” OR “forest” OR “grass” OR “shrub”) AND (“water uptake” OR “transpiration” OR “evapotranspiration” OR “water use efficiency” OR “water demand” OR “water consumption” OR “water flux” OR “carbon and water balance”)) OR “ecohydrology” OR “hydroecology” OR “hydrobiology”.

18.1 Overview

18.1.1 Development of Research Questions

Ecohydrology is an interdisciplinary science between ecology and hydrology; it has developed rapidly since 2000. The principles and methodologies of ecohydrology provide novel ideas and approaches to solve a suite of environmental issues including freshwater resource shortages, ecological degradation and sustainable development (Zalewski 2013). Ecohydrology provides a new theoretical framework and interdisciplinary approach for understanding the complex interactions and feedbacks between vegetation and hydrologic flows at diverse scales. Due to the potential impact on the scientific community and subsequent environmental policies, ecohydrology has progressively become a leading field of geosciences.

The term ecohydrology was first proposed by Ingram in peat wetland research in Scotland in 1987 (Ingram 1987). Prior to the formalization of this area of research there was an interest in these topics and researches focused on the aquatic ecosystems such as wetland, swamp and water-land ecotones as early as the 1970s. Additionally, biochemical cycles in aquatic ecosystems and hydraulic engineering measures in watersheds were substantial research fields during this time. Current ecohydrological studies focus on understanding the interconnection between hydrologic flows and ecosystem processes, as well as how these interconnections manifest and

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exert distinct controls across multiple scales (Rodriguez-Iturbe 2000). The primary ideas of ecohydrology concentrate on plant-water relations, soil moisture and evapotranspiration. Additionally, the research themes have expanded from aquatic ecosystems to terrestrial ecosystems (e.g., dryland, forest, rangeland and mountain) since the early 1980s. The topics in this period covered the interactions between soil and atmosphere interfaces, mechanisms of surface runoff generation, flowpaths of overland runoff, ecohydrological and chemical processes. Due to the importance and breadth of this topic, ecohydrology was regarded as one of the core fields of the fifth UNESCO-IHP (V2.3, 2.4, 1996–2001). The topics of ecohydrology have spanned biological and physical processes in the whole watershed and the linkages of riverine systems with the natural-social-economic continuum during this period. Moreover, the journal Ecohydrology, together with several foundational textbooks (e.g., Eagleson 2002; Rodriguez-Iturbe and Porporato 2005; Wood et al. 2007), has undoubtedly propelled the discipline forward through interdisciplinary collaboration and the formation of several ecohydrology-centered graduate research and degree programs worldwide (Asbjornsen et al. 2011). During the seventh phase of IHP (2008–2013), ecohydrology focused on the use of current knowledge gathered utilizing ecohydrology methods to develop novel questions addressing environmental change, ecosystem and anthropologic activities. Currently, the theme of the eighth phase of IHP (2014–2018) is 'Ecohydrology, Engineering Harmony for a Sustainable World'. The focus is on ecohydrology methodologies and problem solving approaches to regulate hydrological and nutrients' cycles in "novel ecosystems" (agricultural and urban) to enhance the carrying capacity of the global ecosystem.

18.1.2 Contributions by Scholars from Different Countries

Using the search terms as described above, this section analyzes the number of academic articles on ecohydrology published in peer-reviewed English journals and their subsequent citations based on the ISI-index (Table 18.1). Statistical analyses of the 3618 SCI/SSCI-indexed articles identified from a global search spanning the period 2000–2014 indicates that scholars in the USA have published around 32.2 % of these articles, while those in China published 11.5 % of these articles, with the remaining articles published primarily by authors in Australia, Spain and Germany.

Despite publishing the second largest number of articles (11.5 %) on ecohydrology, China ranked fourth from 2000 to 2014 in the number of citations. Chinese authored manuscripts accounted for only 5.7 %, trailing the USA, Australia and Germany. The number of highly cited articles from

Table 18.1 Top 20 countries (regions) with the number and citations of SCI/SSCI-indexed articles on "Ecohydrology" during the period 2000–2014

	Number of articles						Cited frequency						Number of highly cited articles					
	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014
Rank	World	104	345	653	1,219	1,746	World	5,584	157	30,344	32,054	11,144	World	22	0	90	87	89
1	USA	40	86	242	422	500	USA	2,912	39	12,902	11,567	3,854	USA	15	0	46	32	36
2	China	3	61	31	109	276	China	86	18	822	2,309	1,065	Spain	0	0	6	4	12
3	Australia	3	15	40	67	121	Spain	80	14	1,619	1,429	864	Australia	0	0	4	4	6
4	Spain	4	22	28	59	112	Australia	51	3	1,872	1,689	790	UK	0	0	4	5	5
5	Germany	6	20	26	51	78	Germany	366	10	2,036	1,425	741	Germany	1	0	4	4	5
6	Italy	3	23	21	51	75	UK	334	13	1,348	1,432	476	France	1	0	3	5	4
7	Canada	2	9	21	65	62	France	323	6	1,101	1,529	413	China	0	0	2	7	3
8	France	6	12	33	41	46	Italy	242	17	775	1,796	396	Canada	0	0	3	6	2
9	UK	8	11	26	46	45	Canada	22	6	894	1,642	346	Italy	1	0	1	5	2
10	Netherlands	2	9	9	27	38	Netherlands	77	3	230	738	192	Portugal	0	0	2	2	2
11	Japan	0	9	21	33	33	Switzerland	233	5	679	498	176	Netherlands	0	0	0	3	1
12	India	2	7	20	24	28	Portugal	71	0	1,317	433	175	Switzerland	1	0	2	1	1
13	Switzerland	3	6	12	12	28	Israel	13	5	300	329	131	Denmark	0	0	2	1	1
14	Brazil	1	5	5	13	24	Japan	0	2	599	624	109	Finland	0	0	1	0	1
15	Belgium	0	5	7	19	18	Denmark	12	0	690	299	108	Israel	0	0	0	1	1
16	Denmark	1	4	9	9	18	Brazil	36	1	199	297	82	Pakistan	0	0	0	1	1
17	Turkey	0	0	1	13	18	Pakistan	0	0	32	289	72	Hungary	0	0	0	1	1
18	Argentina	1	3	12	9	16	India	57	1	454	431	67	Brazil	0	0	1	1	0
19	Israel	1	4	11	11	14	Argentina	27	0	337	242	67	Belgium	0	0	1	1	0
20	Portugal	2	2	8	12	14	Belgium	0	1	269	560	60	Mexico	0	0	0	2	0

Note Countries (regions) ranked by the number of articles, cited frequency and the number of highly cited articles during the period 2010–2014

China accounted for 4.5 % of the total number in the world during the last 15 years, ranking China seventh behind the USA, Australia, Spain, UK, Germany and France.

The data collected shows an increase in ecohydrology-related publications over the past 15 years in China and across the world. For example, the total number of SCI/SSCI-indexed articles addressing ecohydrology topics in China alone increased from 3 in 2000 to 61 in 2014, and the corresponding position in the world jumped from ninth to second. Despite the growth in research and subsequent publications, there is still gap in article citations between China and the USA. With regards to ecohydrology, the total citation counts for USA authors were 3854 from 2010 to 2014, which was over three times that for Chinese authors. Based on total publication and citation data it appears that in terms of the influence of academic work, ecohydrology research in China still lags behind the leading countries.

18.1.3 Key Research Topics

Based on the keywords cluster graph during the period 2000–2014 (Fig. 18.1), we have identified six attractive research themes in ecohydrology. The first topic focuses on climate change and vegetation response, based on keywords of climate change, NDVI, precipitation, and water use. The second topic focuses on ecohydrology and water balance, with keywords focused on ecohydrology, water balance and soil water. The third topic focuses on the estimation of evapotranspiration and carbon cycle. The main keywords in the third theme include evapotranspiration, carbon cycle and eddy variance. The fourth topic focuses on responses of terrestrial ecosystems and carbon-water exchanges to drought and the possible mechanisms in the adaptation of plants to drought. Keywords used in this search include drought, gas exchange, hydrological cycle, and carbon balance and drought tolerance. The fifth topic focuses on the responses of ecosystem water use efficiency and canopy/stomatal conductance to changing environmental conditions. This topic was identified with the keywords of water use efficiency, stomatal conductance and canopy conductance. The sixth topic focuses on the thermal-hydraulic dynamics within the atmosphere-vegetation-soil continuum. The main scientific issues include plant photosynthesis, root water uptake, soil moisture balance and energy transmission. The keywords were soil vegetation,

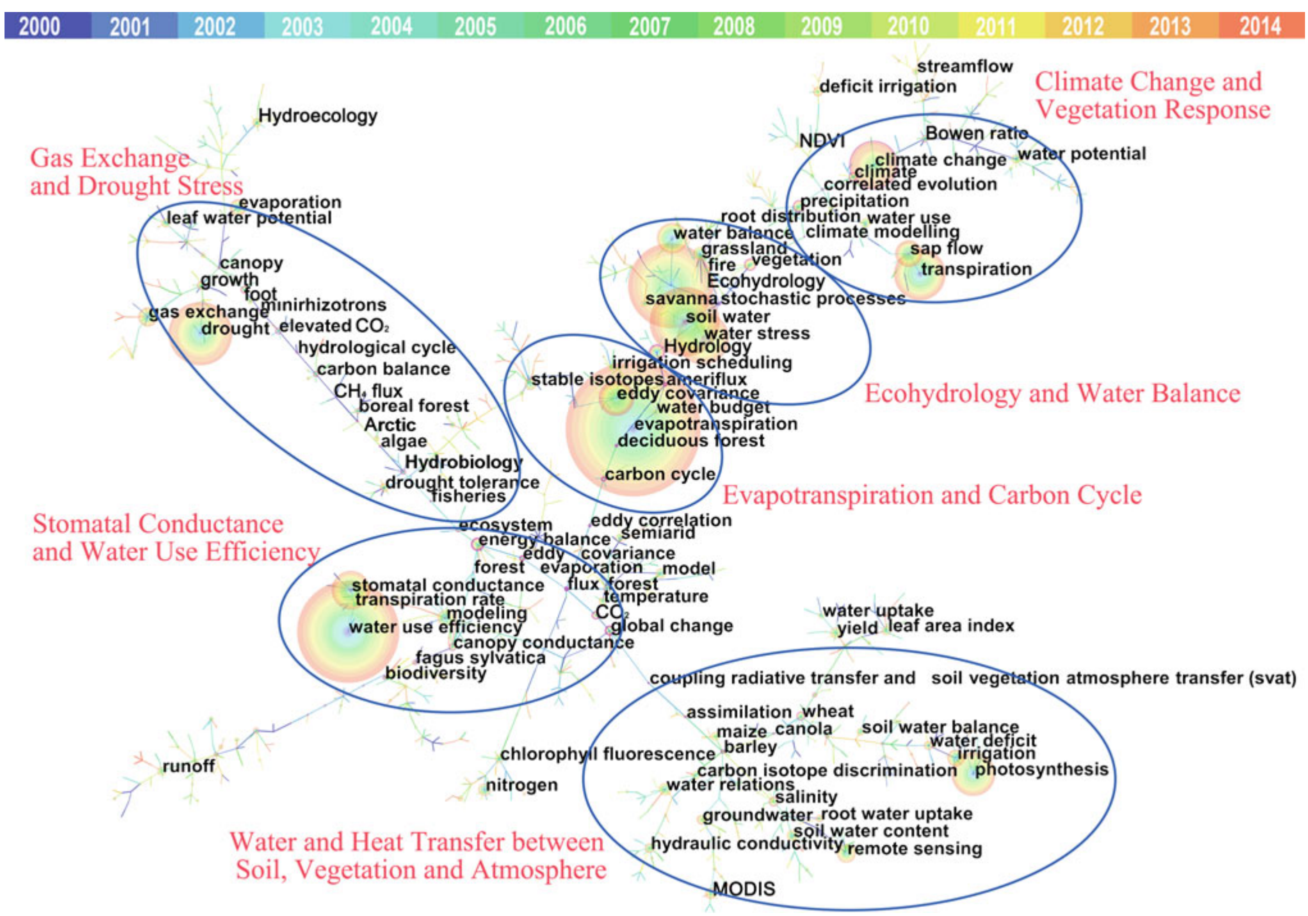

Fig. 18.1 Co-occurrence network of SCI/SSCI-indexed article keywords on "Ecohydrology" during the period 2000–2014

atmosphere transfer, root water uptake, photosynthesis and water deficit.

The temporal changes in the topics of ecohydrology studies during the period 2000–2014 were further examined by analyzing the sequential patterns for keyword appearance in SCI/SSCI journals. All of the keywords were classified into different groups based on the similarity among keywords. Therefore 18 main keywords were identified in descending order of occurrence frequency. Keywords included evapotranspiration, soil moisture, water use efficiency, vegetation pattern, model, water stress, climate change, root water uptake, stomatal conductance, drought tolerance, photosynthesis, gas exchange, sap flow, scale, ecohydrology, hydrological process, eddy covariance, and ecosystem water consumption. These keywords covered the objectives, methods and technical means in ecohydrology studies. Results of the sequential pattern analysis for keywords show an increasing trend in keywords within ecohydrology research themes. The most common included evapotranspiration, soil moisture and water use efficiency (Fig. 18.2). These data suggest that research themes related to evapotranspiration, soil moisture and water use efficiency are still most attractive. It is plausible that these specific research fields of ecohydrology will maintain important areas of studies for years to come. Whereas, occurrence of some other keywords, such as vegetation pattern, model, and water stress, accounted for 8–13 % of the total frequency, suggesting the effects of climate change on vegetation patterns and the model simulations were emerging as another attractive research field worldwide. Additionally, the data show rapid growth in research fields related to sap flow and eddy covariance in recent years. It demonstrates that the application of some new technology, such as heat pulse and eddy covariance, into the measurements of water and energy fluxes has become another new attractive quantitative research field in ecohydrology.

The keywords as described previously in the document were observed approximately 18.3 more times in SCI/SSCI-indexed articles by foreign scholars (1338) than those by Chinese scholars (73) during the period 2000–2004. The latter accounted for approximately 5.2 % of the total frequency of these keywords (Fig. 18.2). In contrast, the

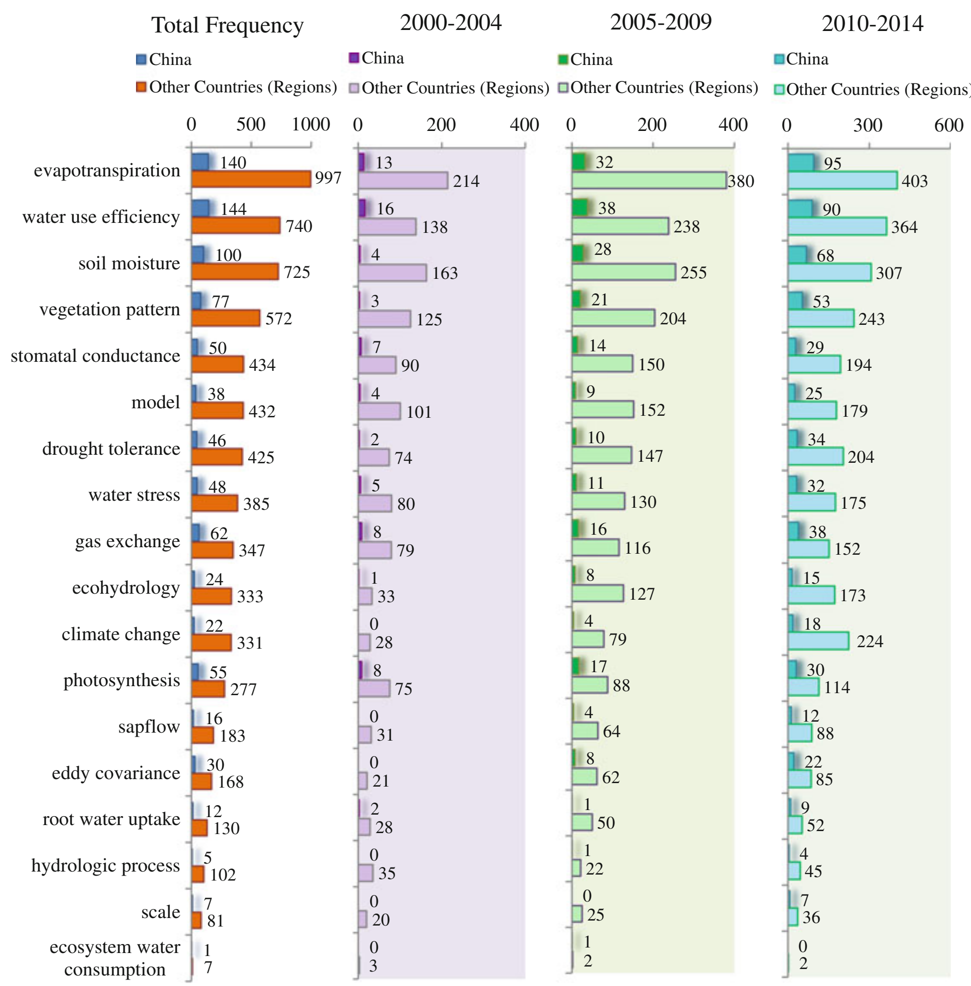

Fig. 18.2 Keyword temporal trajectory graph for SCI/SSCI-indexed articles on "Ecohydrology" during the period 2000–2014

frequency of these keywords in SCI/SSCI-indexed articles by foreign scholars (2291) increased by 70 % during the period 2005–2009. Comparatively, the frequency of these keywords in SCI/SSCI-indexed articles by Chinese scholars (223) increased 3 times during the same period. This increase accounted for 8.9 % of the total frequency of keywords. It showed a dramatic increase in the frequency of those considered keywords in SCI/SSCI-indexed articles by Chinese scholars, although the absolute frequency of those keywords in SCI/SSCI-indexed articles by Chinese scholars was still much less than that by scholars of other countries. During the period 2010–2014, the total frequency of these keywords increased to 3040 in SCI/SSCI-indexed articles by foreign scholars, revealing a much slower rate of increase in the occurrence of those keywords compared to earlier periods. However, the frequency of those keywords increased to 581 in SCI/SSCI-indexed articles by Chinese scholars. This was an increase of 2.6 times in the last five years and accounted for 16 % of the total frequency. This suggests that ecohydrology research is becoming an attractive discipline of study in China and interest has increased in the past five years. Moreover, a marked increase in the international influence was noted. Interestingly, the keyword phrase "ecosystem water consumption" primarily appeared in the SCI/SSCI-indexed articles by Chinese scholars. This preferential keyword usage suggests that ecosystem water consumption study is relatively unique to Chinese research. This unique application of ecohydrology in Chinese research might be a result of China's serious ecological degradation and the limited water supply in the arid regions of China.

18.1.4 The Role of NSFC in Supporting the Research on Ecohydrology

NSFC has played a crucial role in the development of ecohydrology research in China. NSFC financially supported 810 research projects in the field of ecohydrology from 2000 to 2014. This accounted for 7.1 % of the total projects in the geography division. The total funding amounted to 621,060 thousand yuan during the last 15 years (Table 18.2). The number of projects has increased from 4 in 2000 to 126 in 2013. In the last seven years, large research projects funded by NSFC have promoted ecohydrology research in China. These projects include Major Research Plan (1), Major Programme (4), Key Programme (20), Science Fund for Creative Research Groups (1) and National Science Fund for Distinguished Young Scholar (7). A particularly important project is the on-going Major Research Plan entitled "Integrated research on the eco-hydrological process of the Heihe River Basin". This project has the potential to be high impact because it includes 79 research projects with total funding of 177,480 thousand yuan. The groundwork for this ambitious research program was established by building an integrated scientific platform for observations, monitoring, data collection and model simulation of the inland river basin. In addition, NSFC has supported several outstanding ecohydrology research groups, whose studies focus the Loess Plateau, inland river basins, arid desert regions, and alpine mountain regions in China.

From the analysis of articles published by Chinese scholars during the period 2000–2014, 67.8 % of the articles were funded by NSFC (Table 18.2). The number of SCI/SSCI-indexed articles increased simultaneously with the growth of the number of research projects funded by NSFC. The percentage of articles from Chinese authors funded by NSFC increased from 22.6 % during 2000–2004 to 77.9 % during 2010–2014, and the corresponding financial support increased from 31,790 to 496,654 thousand yuan, respectively. Additionally, research institutions and principal investigators also increased over 5 and 8 times, respectively during the last 15 years (Table 18.2). These data indicate that NSFC has played and will continue to play a steering role in the development of ecohydrology research in China.

Based on this usage frequency analysis of ecohydrology keywords coupled with temporal variations among projects funded by NSFC during the period 2000–2014 (Fig. 18.3), several trends in ecohydrology research in China were noted. First, the main research topics included modeling of

Table 18.2 NSFC-funded projects and SCI/SSCI-indexed articles on "Ecohydrology" during the period 2000–2014

SCI/SSCI-indexed articles					NSFC-funded projects			
Periods	Number of articles	% of articles by Chinese authors	% of articles with NSFC funding by Chinese authors	% of articles funded by MOST among those with NSFC funding	Number of projects	Funding (10,000 yuan)	Number of PIs	Number of institutions
2000-2004	653	4.7	22.6	0.0	63	3,179.0	60	27
2005-2009	1,219	8.9	55.0	36.7	193	9,261.6	180	60
2010-2014	1,746	15.8	77.9	48.4	554	49,665.4	514	139
2000-2014	3,618	11.5	67.8	44.7	810	62,106.0	671	162

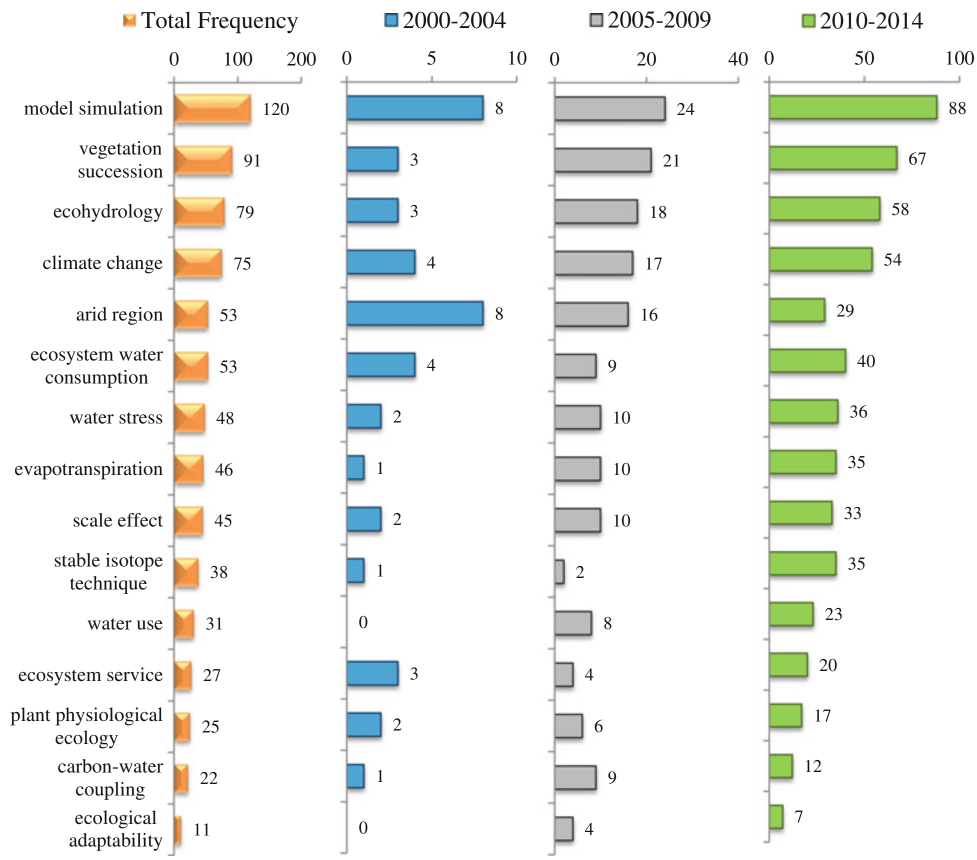

Fig. 18.3 Keyword temporal trajectory graph for NSFC-funded projects on "Ecohydrology" during the period 2000–2014

ecohydrological processes, the effects of vegetation succession and spatial patterns on ecohydrological processes, specifically, the responses of ecological processes to climate change and its effects on water balance, the effects of soil moisture on evapotranspiration and ecological patterns, plant ecophysiology and adaptation mechanisms, and the carbon-water coupling processes at different scales. Second, early studies primarily focused on hydrological cycles and water demands for crops, the dynamic relationships between vegetation penology and soil water, the adaptation mechanisms of vegetation to water stress and the interactions between vegetation dynamics and hydrological processes. During this initial period, most of the studies were conducted at the leaf and plant community levels. As technologies progressed and financial support increased research focus gradually shifted to more complex questions, such as coupling mechanism(s) among multi-scale ecohydrological processes and watershed hydrology in recent years. The third observable trend was that the study regions were mainly concentrated in the arid and semi-arid regions. For example, NSFC supported 52 ecohydrology research projects in the arid and semiarid regions in 2013, accounting for 46 % of total projects funded that year.

18.2 Research Advances and Problems

18.2.1 Bibliometric Analysis of Contemporary Research

There were 3197 peer-reviewed articles on ecohydrology published since 2000 excluding those published by Chinese scholars. A majority of the articles 12 % (435 articles) focused on evaporation. Subsequently, 8 % (294 articles) of these published articles focused on water use efficiency. This analysis indicates that the themes focusing on evaporation and water use efficiency were the most attractive in the field of ecohydrology during the past 15 years, particularly in the period between 2003 and 2010. The other important keywords that appeared in the publications included ecohydrology (282 articles), drought (202 articles), climate change (160 articles), transpiration (157 articles) and water stress (133 articles). It also can be seen in Fig. 18.2, some topics are closely related to responses of vegetation pattern to climate change and simulations of the processes of ecohydrology, including keywords of vegetation pattern, model, soil moisture and climate change. This reflects the dominance of two other critical issues in ecohydrology: vegetation patterns and ecohydrological models.

18.2.2 Contemporary Research

Since being coined in 1987, ecohydrology is a rapidly emerging interdisciplinary research area. It has contributed scientific knowledge through the development of integrated watershed management and policy solutions for pressing environmental challenges facing society today. First, substantial advances in ecohydrology have been made in areas of plant-water relations, especially as they relate to patterns in vegetation water use and mechanisms controlling responses to environmental change. Themes related to the role of plant-water relations include contrasting dynamics of water-limited and water-abundant ecosystems, transferring information about water fluxes across scales, understanding spatiotemporal heterogeneity and complexity, ecohydrological triggers associated with threshold behavior and shifts between alternative stable states and the need for long-term data sets at multiple scales (Asbjornsen et al. 2011). Investigations of ecosystem responses in terms of resistance and resilience to extreme climate events have been increasing in importance worldwide (Allen et al. 2010; Herrero and Zamora 2014). Three key fields for ecohydrology research concerning plant–water relations include: up-scaling water fluxes from the site level to the landscape and the watershed, the effects of plant-soil interactions on soil moisture dynamics, and controls exerted by plant water use patterns and mechanisms on streamflow regime (Asbjornsen et al. 2011). Second, new monitoring techniques and integrated watershed measurements have been developed in recent years, thus improving quantification of ecohydrological processes and integrated studies. For example, stable isotopes have been utilized as a powerful tool in tracing hydrological processes and vegetation water sources (Wang et al. 2010). Additionally, recent developments in spectroscopy have revolutionized the temporal and spatial resolution of isotopic monitoring, providing foundations to use isotope-based techniques to partition ET and characterize large-scale vegetation water use. Furthermore, rapid developments in remote sensing based hydrological monitoring provide unprecedented temporal and spatial coverage in estimates of soil moisture, ET, water level and other important ecohydrological parameters of the system (Wang et al. 2012). In addition, the global flux observation networks (FLUXNET) (Running et al. 1999) and the watershed allied telemetry experimental research with a simultaneous airborne, satellite-borne, and ground-based remote sensing experiment have been used to improve the observability, understanding, and predictability of hydrological and related ecological processes at a catchment scale (Li et al. 2013c). Third, ecohydrological models have been developed not only to improve the understanding of interactions between ecological processes and hydrological processes at different scales, but also to quantitatively evaluate the ecohydrological responses to altered environments (Porporato et al. 2015; Yang et al. 2015). However, the two or three-way coupling models for interactions between ecology, hydrology and society still pose a major challenge. Fourth, the currently available data related to interactions with hydrological process is skewed to plant ecology compared to animal communities in terrestrial ecosystems. For example, the statistical results by Westbrook et al. (2013) from 339 SCI/SSCI-indexed articles showed that 60 % of research articles focus on the effects of the hydrological environment on plant ecology, whereas little data has been reported on the effects of animal communities on hydrological processes. Lastly, presumably, research interests are influenced by a country's need to solve various ecological problems. Specifically, scholars in the USA have focused studies in ecohydrology on riparian ecosystems and shrub encroachment (Wilcox et al. 2003; Wilcox and Newman 2005; Knapp et al. 2008). Canadian scholars focused on elucidating a deeper understanding of the impacts of snow melting on carbon and water exchanges in the boreal forests (Pejam et al. 2006). Scholars in European countries have focused their efforts on the role of vegetation patterns in structuring runoff and the ecohydrological effect of shrub encroachment (e.g., Puigdefábregas 2005; Maestre et al. 2009). Chinese scholars have mainly focused on understanding the responses of hydrological processes to vegetation degradation, specifically, the mechanism of plant drought and salt resistance as well as the effect of soil moisture on vegetation patterns.

18.2.3 Bibliometric Analysis of Contemporary Research in China

In China, ecohydrology studies have grown rapidly since 2000. Chinese scholars have published 421 academic articles on ecohydrology, accounting for 11.6 % of the total number published in this discipline. The themes related to evaporation and water use efficiency are the two most attractive research topics, which contributed 62 and 52, respectively, accounting for 14.7 %, and 12.3 % of the total articles. The other important keywords that appeared in the publications include photosynthesis (28 articles), eddy covariance (22 articles), gas exchange (18 articles), stomatal conductance (18 articles), transpiration (16 articles), Loess Plateau (15 articles), winter wheat (14 articles), climate change (13 articles), water balance (12 articles), sap flow (11 articles), chlorophyll fluorescence (11 articles), drought (11 articles) and water stress (11 articles). These counts indicate that Chinese scholars focus on eco-physiological processes and water flux, consistent with the idea that scholars in particular countries focus on topics of regional importance as discussed in the previous section. Moreover, according to analysis of the highly cited articles, only 9 articles in the Top 20 were authored by Chinese scholars. The focus of these articles varied, 4 articles were related to the influence of vegetation cover changes and land use pattern, and climate change on ecohydrological processes; two articles investigated hydrology and water resources; two examine photosynthesis, stomatal conductance and coupling carbon with water; and one article was related to evapotranspiration estimation. When compared to the increasing level of ecohydrology publications from Chinese scholars, the low citation counts demonstrate that these published articles lack high international academic impact.

18.2.4 Contemporary Research in China

Ecohydrology has been developed dramatically in China since 2000, particularly in the widely distributed arid and semiarid regions. Ecohydrology researchers in China have combined practical features of the discipline with ecological engineering projects (e.g., prevention and controls of desertification, soil and water conservation, grain for green project, three-north shelterbelt construction and natural forest protection). The theoretical ideas and developed methods of ecohydrology have been widely applied in water resource management and ecological restoration projects in water-limited areas. Great progress in ecohydrology research in China has been achieved with respect to reforestation in desert regions, water cycles and water balances in oases, ecological water demands in the inland desert riparian forest, and ecohydrological processes of forest and vegetation degradation in the Loess Plateau. The findings in desert areas revealed the ecohydrological mechanisms of artificial sand-fixation vegetation, which identified the mechanical linkage between biodiversity and water cycles during ecological restoration processes. These results provide a scientific base for ecological restoration by afforestation in desert regions (Li et al. 2013a). Studies in the Loess Plateau have established a soil moisture-vegetation capacity model based on interactions between dry soil-layers and soil moisture (Shao et al. 2010). Forest ecohydrology studies have focused on the impact of forest dynamics on rainfall-runoff production and the processes of soil erosion in arid and semiarid mountain regions. These projects led to systematic studies of the hydrological processes, ecohydrological functions and ecological benefits of typical vegetation types in various climate zones. The concept of the carrying capacity of regional water and vegetation resources was established and provided fundamental scientific support for regional water yield and reasonable afforestation (Yu et al. 2013). The studies in oasis regions revealed water use mechanisms at different scales ranging from individual plants to ecosystems (Zhao et al. 2012, 2013), and determined the amount of water consumption and ecosystem water demands for oasis ecosystems (Zhao and Liu 2010; Zhao et al. 2010). The studies in desert riparian forest demonstrated the relationships between fluctuations in groundwater levels and vegetation growth, and the adaptation of drought stress and ecological water consumption of different plant types (Chen et al. 2003, 2004a, b). Studies in the Inner Mongolia Grassland have analyzed the ecohydrological effects of the Grain for Green Project on evapotranspiration and water balance in grassland ecosystems (Qiu et al. 2011; Feng et al. 2014), and identified the ecohydrological mechanisms of shrub encroachment in response to the intensity of anthropogenic disturbances. These studies also developed an adaptation framework of multi-scale water accumulation for patchy shrub ecosystems (Li et al.2013b).

18.2.5 Contributions by Chinese Scholars and Subsequent Problems

Chinese scholars have pursued similar ecohydrology research topics to scholars worldwide during the last 15 years. Figure 18.4 shows that evaporation and water use efficiency are the most attractive topics not only for scholars in China but also for those in other countries. However, the relative importance of these topics is reversed in the different study periods between China and other countries. The study of evaporation showed an increasing trend from 2000 and 2004 but faded starting in 2004 in foreign countries, while it showed an increasing trend throughout the period 2000–2014 in China. Similar trends exist for the keywords water use efficiency and water balance (Fig. 18.4). The maximum ratio between frequency of keywords and the total number of the articles in Fig. 18.4 for China lags approximately 4–8 years behind the other countries. This data suggests that ecohydrology research in China still follows that in leading countries such as the USA. The other hot topics for ecohydrology study include drought, climate change, transpiration, gas exchange, water balance, water stress, eddy covariance and sapflow. The appearance of the keywords "Loess Plateau" and "winter wheat" (Fig. 18.4) suggests Chinese scholars are attentive to local and regional issues, including ecohydrological studies in the Loess Plateau and focus on crops and processes at the leaf and ecosystem scales. Comparatively, keywords of drought and climate topped the keyword list and remote sensing appears only in foreign authors' works. Taken together these data suggest that scholars in other countries focus their ecohydrology research on large scale issues like climate change and drought using combinations of field observations (e.g., eddy covariance, sap flow), remote sensing and modeling. Therefore, it is proposed that China further promotes large-scale studies.

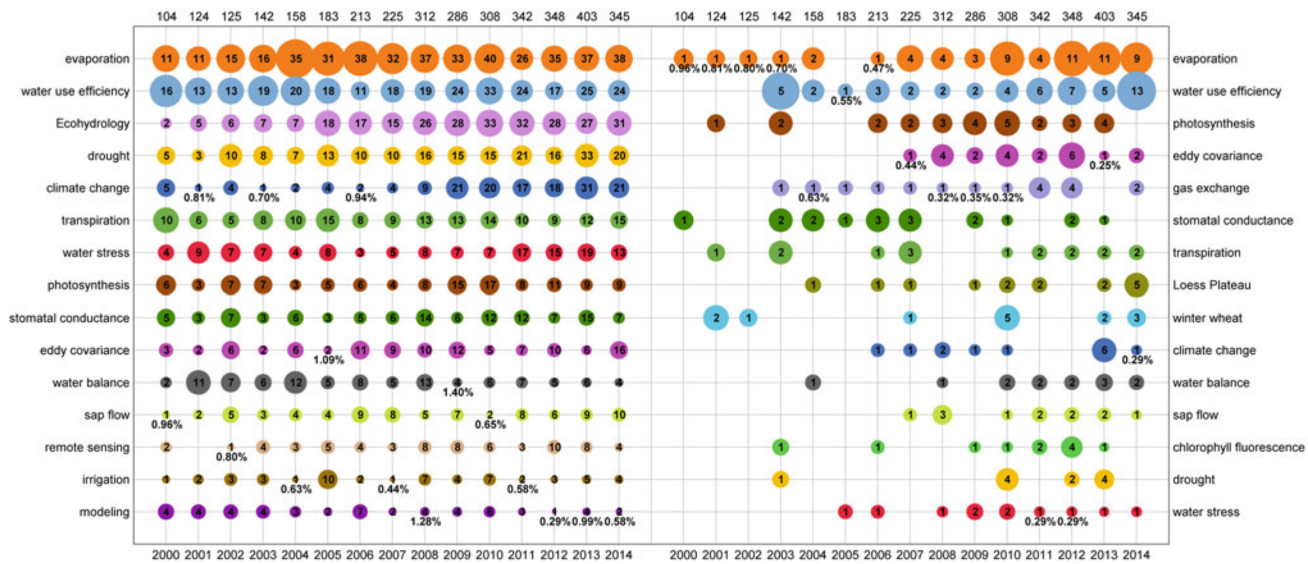

Fig. 18.4 Comparative diagram of prominent keywords on "Ecohydrology" by Chinese authors and others in SCI/SSCI-indexed articles during the period 2000–2014. *Note* Right panel shows keywords used by Chinese authors and left panel shows those used by the authors from other countries (regions). Size of circles denotes the ratio of a certain keyword frequency to the total article number in a specific year. The annual total number of articles is shown at the top of the diagram. The frequency of the keyword is shown inside the circle. The size of circles in the diagram for Chinese authors are magnified for clear display

Such studies could include global issues as well as a holistic observation system of ecohydrological processes to address problems including heterogeneity, scaling, uncertainty, and the water cycle impacted by climate and human activity.

In recent years, China has progressed with watershed ecohydrology research. The current Major Research Plan of integrated research on the eco-hydrological processes of the Heihe River Basin (Heihe Plan) is similar to the program on the Sustainability of Semi-arid Hydrology and Riparian Areas (SAHRA) in the USA. Both of these programs establish a research platform to integrate the observations, data management and model simulations of both physical and socioeconomic processes to foster twenty first century watershed ecohydrology science in China (Li et al. 2013c). The research areas of both SAHRA and the Heihe Plan are located in arid and semi-arid regions; both are concentrated on ecology-hydrology-economic coupling and adopted the observation-experiment-coupling modeling method. However, SAHRA did not focus on a single watershed, but on 4 neighboring sub-basins. As a result of using combined data from 4 sub-basins, the scientific problems considered were broader than those of the Heihe Plan. To date, SAHRA has not established the ecology-hydrology-economic coupling model in this larger watershed; in contrast, Heihe Plan will establish the integrative models of coupling ecology, hydrology and socio-economy in the whole Heihe watershed (approximately 130,000 km^2). Successful completion of this would advance coupled models of large-scale watersheds. Overall, the Heihe Plan is a bold and an innovative attempt to advance watershed science in China. The research approaches, methods and scientific problems described here are on par with worldwide ecohydrology research.

18.3 Roadmap for Further Research

Ecohydrology has been developing rapidly. However, highly influential results are still lacking in China compared to leading countries like the USA, thus suggesting that China needs to improve ecohydrology research quantity and quality moving forward. Due to the unique features of the Chinese landscape, including the wide range of ecosystem types, large areas of arid and semiarid regions, the unique Tibetan and Loess Plateau that suffer from intensive human activities and serious ecological problems, an increase in ecohydrology studies would greatly benefit China as a whole. These future ecohydrology studies in China should focus on the following aspects.

(1) Reinforce Experimental Monitoring of Ecohydrological Processes and Establish Comprehensive Multi-Scale Observation System

Future ecohydrology research needs to conduct integrated multi-scale observations on ecohydrological processes and develop a method to quantify the bi-directional hydrological-ecological interactions and their feedbacks. We also need to investigate how hydrological processes affect the ecological processes at different spatiotemporal scales, and how ecosystem and terrestrial surface processes affect the hydrological processes. The monitoring of ecohydrological processes would involve field observations of water, energy and CO_2 flux in the soil-vegetation-atmosphere continuum at stoma and individual scales, long-term meteorological and hydrological monitoring and remote sensing observations at the watershed or global scales for macroscopic ecohydrology. Future research will bridge and establish the connections between microscale and macroscopic processes to generate new insights into water-ecosystems interactions. Moreover, scale transformation is a challenging problem for future ecohydrology research that will need to be addressed.

(2) **Develop Integrated Model of Ecology-Hydrology-Economy System**

The current ecohydrology models mainly focus on the coupling of ecological and hydrological processes. Few models take into account the coupling of socioeconomic changes and anthropogenic activity effects. Therefore, future model development should connect the ecology, hydrology, and economy and establish integrated analysis and dynamic prediction models based on the coupling of socio-economic systems, water-resource systems and ecosystems.

(3) **Promote Interdisciplinary Study Approach and Sustainable Water Resource Management**

Ecohydrology is an interdisciplinary field between ecology and hydrology; however, further integration with other disciplines would be beneficial. Establishment of a genuine interdisciplinary approach to connect ecohydrology with meteorology to fully investigate interactions between ecosystem and climate changes, with geology to explore groundwater-surface water interactions, with biogeochemistry to understand nutrient availability, with soil science to bridge soil water movement, preferential flow and soil biota activity and with social science to analyze socio-economic impacts is desperately needed. This increased interdisciplinary relationship would provide an understanding of the full cascade of ecohydrological processes and their mechanistic interactions in a holistic way (Wood et al. 2007), which is important for sustainable water resource management.

18.4 Summary

Ecohydrology, an interdisciplinary science between ecology and hydrology, is one of the frontiers in current geoscience. It will be used to solve global shortages of fresh water and provide ecological security. Ecohydrology has developed rapidly during the last 30 years. Additionally, there has been an evolution of research themes from plant-water relations at the small scale of leaf and plant communities to integrated studies with multi-processes and multi-factors at watershed, regional and global scales. Currently, ecohydrology focuses mainly on issues of evapotranspiration, carbon-water coupling, ecohydrological processes and water balances. In China, ecohydrology research is currently well developed in arid and semiarid regions. Additionally, Chinese investigators have developed a distinctive profile in combination with ecological engineering projects. Great progress in ecohydrology in China has been obtained in the fields of revegetation of desert regions, water cycles and water balances in oases, ecological water demand in the inland desert riparian forest, and ecohydrological processes of forest and grassland degradation. Despite this progress, future research need to focus on multi-disciplinary integration that spans multiple spatiotemporal scales, with increased attention paid to the biotic and abiotic interactions, surface-groundwater relations, coupling of natural and anthropogenic processes, interactions between geological and biological cycles and extensions from molecule to global scales.

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Ecosystem Services

19

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Abstract
Ecosystem services, the benefits people obtain from ecosystems, can be comprehended and implemented as integrative indicators in human-environment systems. Researches on ecosystem services have gained an enormous and rising attractiveness for scientists, managers and policy makers since the late 1990s. Chinese scientists caught the international trend on this line of researches and made more and more significant contributions in the last 15 years. This chapter elaborated the development, characteristics, and future potentials of ecosystem service research in China with an international perspective supported by bibliometric analysis, which can be helpful for facilitating the understanding and collaborations for relevant stakeholders.

Keywords
Ecosystem services • Human-environment systems • Ecological indicator • Ecological processes • Landscape pattern

A total of 6902 SCI/SSCI-indexed articles are analyzed in the research area of ecosystem services. Articles were identified from 815 international journals from 2000 to 2014. The number of journals that have published more than 15 of the relevant articles is 97 (Appendix P). The search query is as follows: "ecosystem service" or "ecosystem services".

19.1 Overview

19.1.1 Development of Research Questions

Ecosystem services are the benefits that people obtain from ecosystems. The Millennium Ecosystem Assessment (MEA) grouped ecosystem services into four categories: provisioning services, regulating services, supporting services, and cultural services. The term "ecosystem services" was coined in the early 1980s based on ongoing studies of natural capital, land ethics, ecosystem processes and functions, and environmental services since the late 1940s. However, the term did not receive much attention at the time. It was not until the late 1990s that it began to attract widespread usage (Li 2014). Initially, the anthropomorphic wording "services" was used to describe the functions of an ecosystem and was primarily intended to arouse social concern by emphasizing the important role of natural systems in supporting social (i.e., human) systems. It could therefore hopefully provide a theoretical basis to understand the function and value of ecosystems, promote their conservation, restoration and sustainable utilization, and enable the ecological crisis to be managed by implementing sustainable development strategies. From a methodological point of view, ecosystem services basically represent an environmental evaluation index system. Compared with other index systems, the concept has a more powerful capacity to facilitate communication among scholars, the public, and decision makers, link the social sciences with the natural sciences, and at the same time integrate the structure, functions, and characterization of the social values of ecosystems. Thus the concept establishes a methodological

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foundation for strengthening the depth and scope of interdisciplinary research focusing on the relationship between natural ecosystems and society. From the perspective of epistemology, the formation of the concept of ecosystem services is actually a vivid manifestation of natural value theory, against a background where ecological and environmental problems have become increasingly prominent and sustainable human development is facing serious challenges. Ecosystems are therefore considered to be useful functional entities for human society, and these useful functions can be classified and quantitatively analyzed. Ecosystems can even be linked by unifying economic values; thus they can be used to guide practices adopted for ecosystem management. Ecosystem services research currently occupies an enhanced status due to its active development of "people-land coupling" or "nature-society coupling" systemic frameworks.

19.1.2 Contributions by Scholars from Different Countries

Global ecosystem services research is an expanding field as reflected in the number of articles published in international journals. Ecosystem services research has become a prominent academic field since 2000, and the number of published articles has displayed an exponential growth (Delgado and Marín 2015). During the 15 years from 2000 to 2014, a total of 6902 SCI/SSCI-indexed articles were published around the world in the research field of ecosystem services. The USA is ranked first in terms of the number of published SCI/SSCI-indexed articles, with 2130 published articles, accounting for 30.9 % of the worldwide total. A statistical assessment of the changes in the number of SCI/SSCI-indexed articles on ecosystem services articles published since 2000 in the top 20 countries (regions) shows that the number of published articles in each five-year period is four times that in the previous five years. The number of article citations and the number of frequently cited articles have all increased over the same time period (Table 19.1). Chinese researchers have published 425 SCI/SSCI-indexed, ranking fourth in the world and accounting for 6.2 % of the total number of SCI/SSCI-indexed articles around the world. This is equivalent to 20.0 % of the number of articles on ecosystem services published by the USA researchers. With regard to citation frequency, the total number of citations (4311) of Chinese articles in the past 15 years ranks ninth in the world, accounting for only 3.1 % of the global total, which is significantly lower than the number of published articles expressed as a percentage. The total number of highly cited Chinese articles from 2000 to 2014 was 6, accounting for only 1.1 % of the worldwide total and ranking 12th. During the 15 years from 2000 to 2014, the number of Chinese SCI/SSCI-indexed articles published in the field of ecosystem services increased from 2 to 118, and the impact of the articles has also improved significantly. For example, the average number of total citations of international articles published in 2000–2004, 2005–2009, and 2010–2014 was 85.3, 49.0, and 10.8, respectively, while the average number of citations of China's articles published in the corresponding periods was 20.6, 33.1, and 5.1, respectively, which was 24.1, 67.5, and 46.5 % of the worldwide average, respectively. Ecosystem services research in China has increased rapidly in terms of size (the number of SCI/SSCI-indexed articles) and academic impact (citation frequency) in the past 15 years. However, there is still a large gap between China and the USA, which ranks first in the world, especially in terms of citation frequency. From 2010 to 2014, 1559 SCI/SSCI-indexed articles were published by the USA researchers in the field of ecosystem services, which was nearly 4.5 times of the number published by Chinese researchers, while the number of citations of articles published by the USA researchers was 19,162, which was 11.1 times the corresponding number of citations for Chinese researchers. Overall, the improvement in the international academic impact of ecosystem services research in China lags behind the growing number of relevant SCI/SSCI-indexed articles (Table 19.1).

19.1.3 Key Research Topics

Ecosystem services research has grown rapidly since 2000. The first most prominent scientific issue was the classification and valuation of ecosystem services. The concept of ecosystem services was formed with an anthropocentric perspective that connects ecosystems and human society through a one-way interest flow. Thus ecosystem services research began with the identification of different types of services and their economic valuation (Gómez-Baggethun et al. 2010). The purpose of this research was to develop concern about the significance of healthy ecosystems and human well-being, and provide a scientific basis for wise decision-making and action to promote the utilization, conservation, and sustainable management of ecosystems. The four-category framework of ecosystem services delineated by the MEA has become a macroscopic classification system that has gained more recognition and influence. However, there is still an element of ambiguity in the concept and classification of ecosystem services in practical applications, which includes an inadequate or blurred definition of the term itself and the interpretation of specific ecosystem processes and services (Wallace 2007). This has negative impacts on the understanding and assessment of ecosystems, which typically leads to the problem of double-counting during the quantitative assessment of ecosystem services (Fu et al. 2011). There is also an academic

Table 19.1 Top 20 countries (regions) with the number and citations of SCI/SSCI-indexed articles on "Ecosystem Services" during the period 2000–2014

	Number of articles						Cited frequency						Number of highly cited articles					
	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014
Rank	World	33	1,625	263	1,200	5,439	World	2,195	3,184	22,438	58,854	58,816	World	9	1	71	180	307
1	USA	16	437	120	451	1,559	USA	1,530	772	11,360	24,335	19,162	USA	6	0	34	89	111
2	UK	2	152	29	111	624	UK	49	420	2,991	5,432	8,490	UK	0	0	13	17	51
3	Germany	1	118	7	77	352	Germany	37	248	234	5,471	4,783	Germany	0	0	1	13	29
4	China	2	118	10	72	343	Australia	3	292	610	3,208	2,973	France	0	0	3	4	16
5	Australia	1	84	8	72	298	France	34	126	424	1,271	2,523	Sweden	0	0	5	8	13
6	France	1	72	6	29	214	Spain	102	156	153	763	2,368	Spain	1	0	1	2	13
7	Spain	1	65	2	13	183	Canada	0	45	474	3,356	2,304	Canada	0	0	2	8	12
8	Netherlands	1	58	6	30	171	Netherlands	94	129	338	1,467	1,984	Australia	0	1	2	9	10
9	Canada	0	41	7	37	160	China	88	119	206	2,382	1,723	Netherlands	1	0	1	5	7
10	Sweden	3	39	24	40	128	Sweden	29	101	2,238	2,627	1,499	South Africa	0	0	3	6	6
11	Italy	1	35	1	15	121	South Africa	55	51	699	1,366	1,053	New Zealand	1	0	2	1	6
12	South Africa	1	30	11	38	115	Italy	34	79	34	497	971	China	0	0	0	2	4
13	Switzerland	0	31	2	30	99	Switzerland	0	91	516	1,633	848	Portugal	0	0	0	0	4
14	Brazil	0	37	1	17	98	Portugal	0	16	0	100	826	Argentina	0	0	1	0	3
15	New Zealand	1	21	6	10	73	New Zealand	96	29	496	348	790	Czech Republic	0	0	0	0	3
16	Finland	0	26	1	8	69	Argentina	0	13	670	217	598	Italy	0	0	0	2	2
17	Japan	0	20	1	12	60	Brazil	0	66	51	513	561	Brazil	0	0	0	1	2
18	Belgium	0	18	0	6	56	Finland	0	45	17	170	526	Ireland	0	0	0	1	2
19	Portugal	0	13	0	4	55	Belgium	0	18	0	214	417	Switzerland	0	0	1	5	1
20	India	0	13	5	12	50	Mexico	0	16	274	1,147	251	Mexico	0	0	1	2	0

Note Countries (regions) ranked by the number of articles, cited frequency and the number of highly cited articles during the period 2010–2014

controversy regarding the assessment of the economic value of ecosystem services. Therefore, "valuation" or "economic valuation" is an important topic in the clustering map of keywords related to ecosystem services in international journals from 2000 to 2014 (Fig. 19.1).

Non-linear dynamics, spatial heterogeneity, and uncertainty exist widely throughout ecosystems and their interactions. However, scientific recognition of the mechanisms involved in ecosystem services processes, including their generation, spatial flow, and consumption remains limited (Folke 2006; Morse-Jones et al. 2011). No appropriate methods from either mainstream or ecological economics can be applied in economic assessments of those ecosystem services that have no market value or are intrinsically difficult to measure (Morse-Jones et al. 2011). Furthermore, the economic valuation of ecosystem services also tends to attach monetary value on ecosystems without adequate consideration of the ecological processes and functions that generate those services (Cornell 2010), which is dismissed as "precisely incorrect" (Spangenberg and Settele 2010). Sagoff (2011) even argued that differences in the theoretical paradigms between the natural science-based and economics-based quantification and valuation of ecosystem services have hindered the quantitative determination of the integrated value of ecosystem services. There are two possible objectives for the economic valuation of ecosystem services: one is to improve public policy and the other is to establish new markets (Salles 2011). However, caution must be expressed with respect to the second objective, because the commercialization of ecosystem services may have long-term negative effects on biodiversity conservation and the equitable use of resources (Gómez-Baggethun and Ruiz-Pérez 2011).

In addition to research on the classification and economic valuation of ecosystem services, another major scientific issue is the relationship between biodiversity and ecosystem services. This is actually an extension of a classic scientific issue of ecology—the relationship between biodiversity and ecosystem functions—which is a component of basic studies of the mechanisms of ecosystem services. In this regard, because pollination is closely related to biodiversity, productivity, and other ecosystem services, it has become a prominent topic of current research around the world. For basic scientific research on the underlying mechanisms of ecosystem services, it is very important to perform multidisciplinary network monitoring and experiments in which results are integrated under realistic conditions across spatiotemporal scales (Lü et al. 2012b; Balvanera et al. 2014).

To meet the demands of the quantitative analysis of ecosystem services, the simulation and mapping of ecosystem

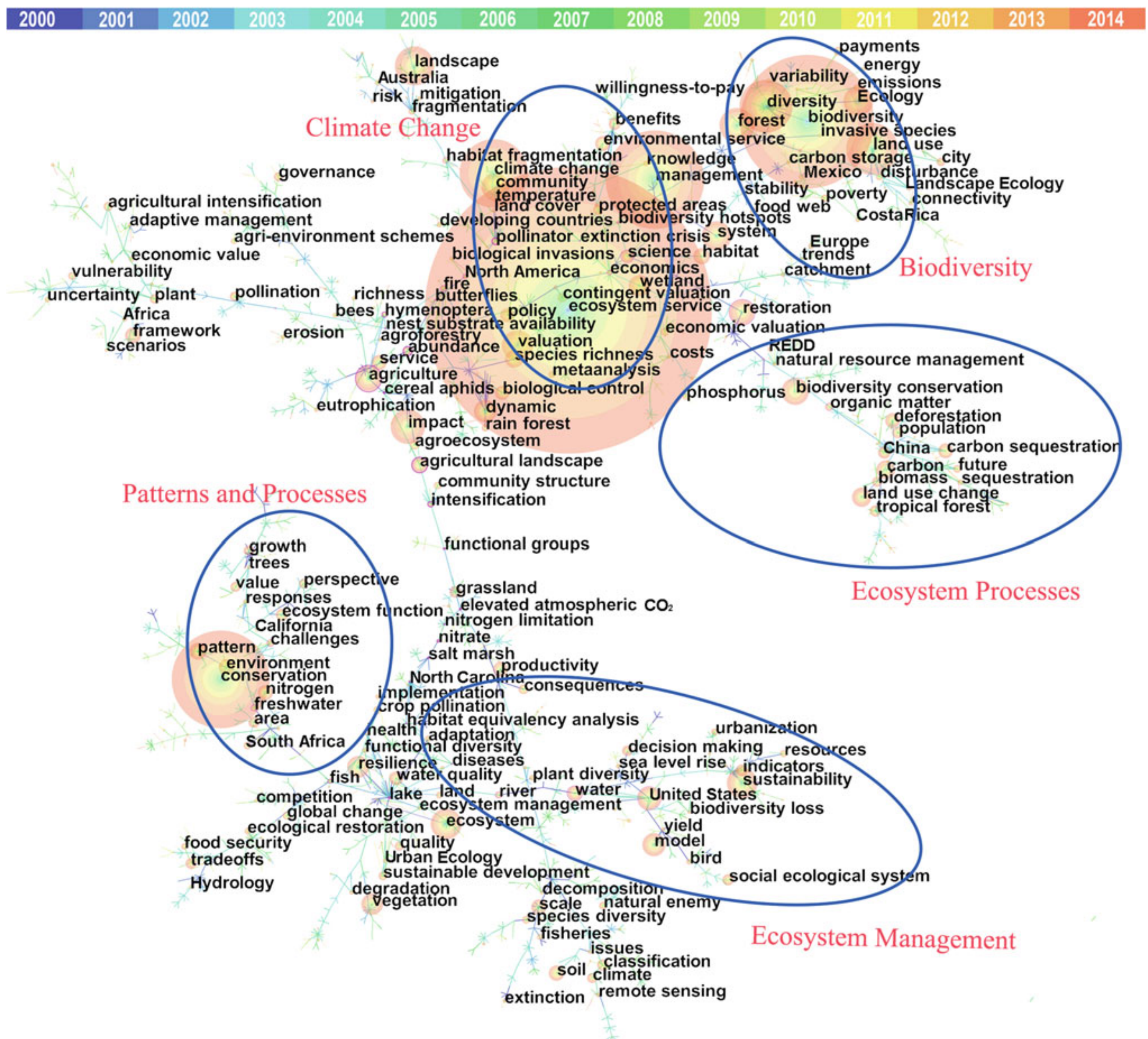

Fig. 19.1 Co-occurrence network of SCI/SSCI-indexed article keywords on "Ecosystem Services" during the period 2000–2014

services have become important complex methodological issues. The initial concern involves which indicators and variables should be used to scientifically characterize ecosystem services. The determination of appropriate indicators should consider their purpose, clarity, reliability, simplicity, and amenability to quantification. Criteria including purpose, type of indicator, linkages to ecosystem services, spatial scale and scalability, applicability of reference or benchmark values, availability of data and standardized protocols, and the applicability of remote sensing can be used to assess the suitability of indicators (Feld et al. 2010). Assessment and simulation models of ecosystem services include both individual and integrated models. The mapping of ecosystem services, which is a method for the spatial visualization of the results of quantitative analyses of ecosystem services, enhances spatial cognition and enables spatially differentiated management (Tallis and Polasky 2009).

Ecosystem services management, which in essence determines how the concept is applied, is also a prominent scientific issue. Current research in this field focuses on the impact of land use/land cover change and climate change on ecosystem services, the effects of ecological conservation and restoration on ecosystem services, trade-offs and synergies between ecosystem services driven by land use change, the spatial congruence between biodiversity and ecosystem services, and the optimization of ecosystem conservation actions (Fuerst et al. 2011). In terms of the ecosystems studied, farmlands, forests, vegetation cover, and water resources have attracted the most attention (Cook and Spray 2012; Schwenk et al. 2012; Cong et al. 2014).

Temporal changes in the research topics directly represented in the core keywords of ecosystem services employed from 2000 to 2014 (Fig. 19.2) show that ecosystem services, biodiversity, conservation, and management feature prominently in each period. The overall distribution of prominent keywords shows that foreign researchers have been most concerned with issues surrounding biodiversity and its conservation; ecosystem management relative to ecosystem services; issues of climate change, land use/land use change and sustainability; the valuation of ecosystem services; and theoretical and applied research on the relationship between ecosystem services and agriculture, ecological restoration, and ecosystem functions. This indicates that the research field of ecosystem services is cross-sectional, with a diverse range of research foci and obvious focal trends developing over time. Prominent keywords in the articles published by Chinese researchers had a similar pattern and displayed similar trends to those mentioned above; but they also had their own features, with ecological conservation and management related to ecosystem services being the most studied subject area, followed by the valuation of ecosystem services based on an analysis of land use and its change. There were fewer studies of sustainability and climate

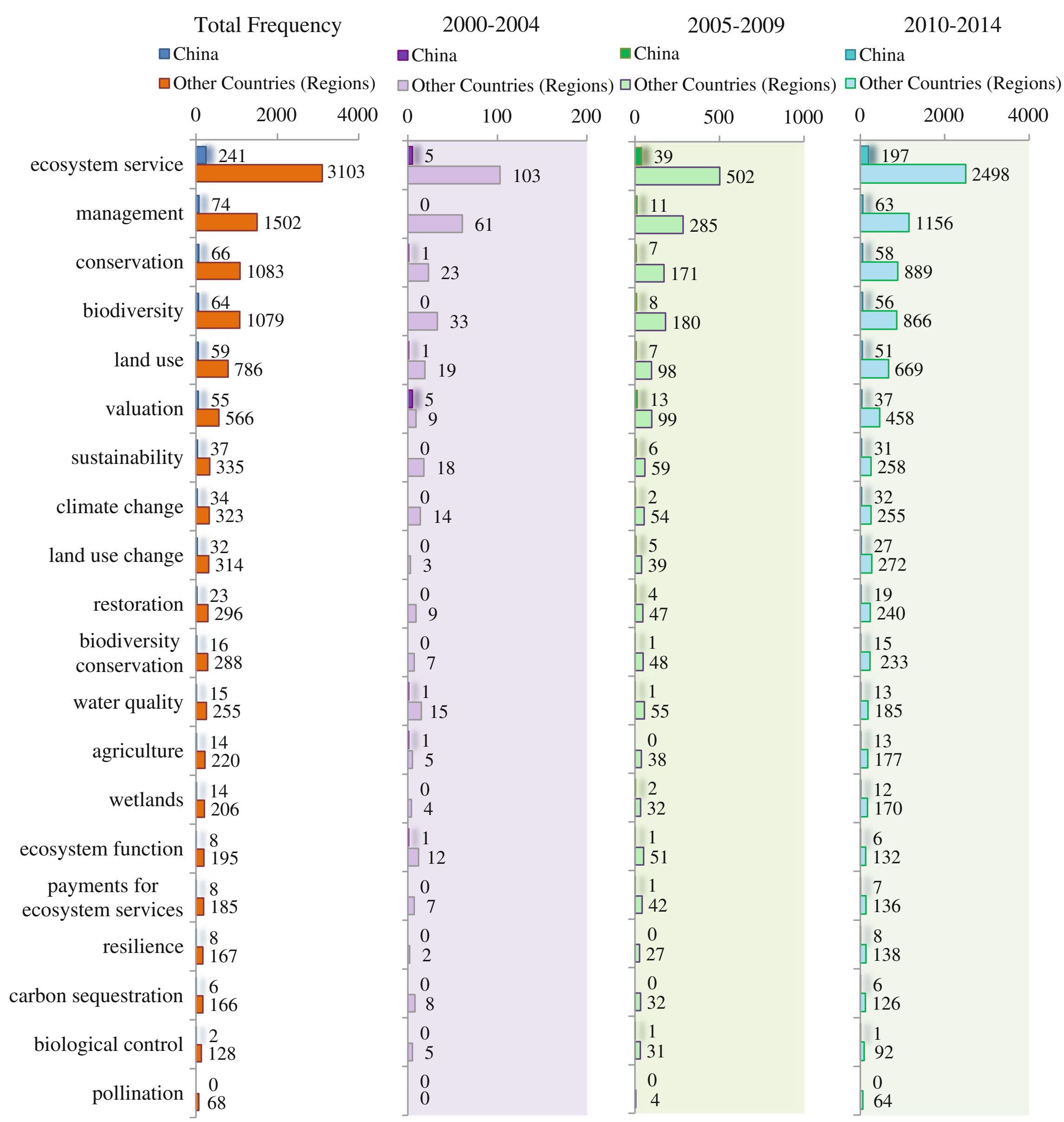

Fig. 19.2 Keyword temporal trajectory graph for SCI/SSCI-indexed articles on "Ecosystem Services" during the period 2000–2014

change, and very few studies were conducted with regard to ecosystem functions. The areas of biological control and pollination have not been well investigated in China compared with the activity of international researchers. Research foci of Chinese investigators have centered on ecosystem management and valuation issues, which have strong policy implications, while research on the theory and methodology of ecosystem structure and functioning, and the relationships between ecosystem services needs to be strengthened.

19.1.4 The Role of NSFC in Supporting the Research on Ecosystem Services

Changes in the number of NSFC-funded projects and SCI/SSCI-indexed publications supported by NSFC show that NSFC's contribution to ecosystem services research has been increasing. NSFC-funded projects focus mainly on "ecosystem services", "climate change", "land use change", "sustainable development", and "ecosystem management" (Fig. 19.2). While "biodiversity" is an important research subject within the SCI/SSCI-indexed literature, it has not been the focus of many NSFC-funded projects. Further analysis revealed that NSFC began funding ecosystem services-related research in 1999 and in recent years the number of NSFC-funded projects related to ecosystem services has increased rapidly, with some fluctuation, reaching 99 in 2010–2014 (Table 19.2). The first NSFC-funded project to clearly focus on ecosystem services was "Research on regional ecosystem services and their economic valuation methods" by **Zhiyun Ouyang** (Research Center Eco-Environmental Sciences of CAS) in 1999. Other early projects on ecosystem services funded by NSFC include "Analysis of regional wetland ecosystem services and the mechanism of their maintenance" by **Xiaoke Wang** in Department of Life Sciences in 2000, and the "Economic valuation of environmental goods: research on contingent valuation and model selection of Ejina ecosystem services" by **Zhiqiang Zhang** (Information Center for Resources and Environment Science of CAS) in Department of Earth Sciences in 2003. The number of SCI/SSCI-indexed articles published by Chinese researchers has increased exponentially since 2000, which is consistent with the international trend. SCI/SSCI-indexed articles with "ecosystem service" as the subject published from 2010 to 2014 have increased by 34.3 times compared to those with the same subject published by Chinese researchers from 2000 to 2004. Moreover, the proportion of these articles funded by NSFC has increased from 10.0 to 72.1 % (Table 19.2). With the growth of the number of NSFC-funded projects, the proportion of NSFC-funded articles published by Chinese scholars has increased rapidly. From 2000 to 2004, the number of NSFC-funded projects was 15, the funding was 7480 thousand yuan, and the proportion of all articles published by Chinese researchers funded by NSFC was only 10.0 %. From 2005 to 2009, the number of NSFC-funded projects increased to 69, with a corresponding increase in funding to 28,842 thousand yuan, and the proportion of all articles (72 articles) published by Chinese researchers that were funded by NSFC increased to 40.3 %. From 2010 to 2014, the number of NFSC-funded projects reached 99, which represented an increase by nearly 1.4 times compared with the number funded from 2005 to 2009, and the funding reached 64,190 thousand yuan, while the proportion of NFSC-funded articles among all articles published by Chinese authors increased to 72.1 % (Table 19.2). Thus NSFC funding has become the core motivating force behind China's scientific development and internationalization in the field of ecosystem services. The proportion of SCI/SSCI-indexed articles published by Chinese researchers and its changing trend show that ecosystem services science in China has basically paralleled the international development trend of the research field in number thanks to the support of NSFC. With the increase in the number of NSFC-funded projects in recent years, the content has also been gradually expanded and enriched. A variety of types of ecosystem services have been included, such as those of grassland and lake ecosystems. Research methods

Table 19.2 NSFC-funded projects and SCI/SSCI-indexed articles on "Ecosystem Services" during the period 2000–2014

SCI/SSCI-indexed articles					NSFC-funded projects			
Periods	Number of articles	% of articles by Chinese authors	% of articles with NSFC funding by Chinese authors	% of articles funded by MOST among those with NSFC funding	Number of projects	Funding (10,000 yuan)	Number of PIs	Number of institutions
2000-2004	263	3.8	10.0	0.0	15	748.0	15	12
2005-2009	1,200	6.0	40.3	20.7	69	2,884.2	69	35
2010-2014	5,439	6.3	72.1	41.1	99	6,419.0	95	54
2000-2014	6,902	6.1	65.2	38.8	183	10,051.2	172	75

have gradually been diversified, model simulations have gradually increased, and research on process mechanisms, relationships, and regional ecosystem services management have gradually been deepened.

Table 19.2 also shows that the number of principle investigators and supporting institutions for NSFC-funded projects have increased rapidly. From 2000 to 2004, the numbers of principle investigators and supporting institutions in the ecosystem services research area were 15 and 12, respectively, while from 2005 to 2009 these numbers increased to 69 and 35, respectively. From 2010 to 2014, the numbers increased further to 95 and 54, respectively. This indicates that ecosystem services research has been in a healthy situation in China since 2000, with both the number of researchers and the number of institutions involved showing a tendency for rapid growth.

19.2 Research Advances and Problems

19.2.1 Bibliometric Analysis of Contemporary Research

A clustering map of keywords related to ecosystem services in international journals from 2000 to 2014 (Fig. 19.1) revealed that ecosystem services research is cross-sectional, focusing on a combination of ecosystem processes, including biodiversity, climate change, and the carbon cycling, following a variety of research directions, including patterns and processes, valuation, and management of relationships between human and ecological systems. However, there are few prominent keywords emerging from this body of research. Valuation focuses more on topics such as "erosion" and "pollination". Climate change is most often represented by keywords such as "temperature" and "land cover". Relationships between ecosystem processes and services are most often described by keywords such as on "tropical forest", "deforestation", "organic matter", "biomass sequestration", and carbon cycling. Biodiversity concerns are depicted mostly via such terms as "invasive species" and "species diversity". Ecosystem management is mainly reflected in keywords such as "social ecological system", "decision making", and "sustainability" (Fig. 19.1).

19.2.2 Contemporary Research

In 1997 the American scientist Gretchen Daily edited and published a book entitled "Nature's Services: Societal Dependence on Natural Capital". In the same year, Costanza et al. (1997) published a paper entitled "The value of the world's ecosystem services and natural capital" in Nature. These two publications attracted great interest and enthusiasm among academia for ecosystem services research, and soon ecosystem services became a prominent area of interdisciplinary research, including both ecology and geography. Another milestone in the development of ecosystem services research was the Millennium Ecosystem Assessment (MEA). The MEA not only promoted the comprehensive interdisciplinary study of ecosystem services globally at different scales, but more importantly, it connected research on ecosystem services with human well-being, and also integrated ecosystem management policy and the needs of decision makers, thereby improving government policy and decision-making processes related to ecosystem services. With the issuance of the MEA, some developed countries began to recognize ecosystem services as an important development direction in scientific research. In December 2010, the 65th UN General Assembly approved the establishment of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). In December 2011, the International Council for Science (ICSU) integrated several global environmental change research programs (DIVERSITAS, IGBP, IHDP, WCRP, and ESSP) and proposed the "Future Earth" project (Wu et al. 2011; Larigauderie et al. 2012; Fu and Liu 2014), which includes ecosystem services as a critical research theme. In this light, scientific research in the field of ecosystem services has emerged as a major area of interdisciplinary research with key contributions from ecology, geography and economics. In the process it has also come to expand the scope of natural resource management and the decision-making realm in public policy.

19.2.3 Contemporary Research in China

Ecosystem services research represents a global frontier and is rapidly developing to be an international agenda. China is currently becoming a full-fledged participant in international research in this field. Ecosystem services research in China has made significant progress in the five major areas of valuation, quantitative assessment, spatial mapping, relationship analysis and integrated management. Such research began in the late 1990s and has been developing rapidly in recent years. By considering the main contents of ecosystem services research and NSFC statistics, a comparative analysis of domestic and overseas research levels and developmental status was conducted. Progress in ecosystem services research was reviewed and summarized in terms of the five areas noted above.

Valuation of Ecosystem Services

Very few of the articles published about ecosystem services were supported by NSFC prior to 2008. During that time, ecosystem services research in China focused on discussing the concept, classification, and monetary valuation methods of ecosystem services (Ouyang and Wang 2000). Influenced by the article regarding evaluation of global ecological assets published in Nature in 1997 by Costanza et al., national and regional scale valuations of different types of ecosystem services were conducted in China. The study included a variety of ecosystems and their integrated valuation, such as forests, grasslands, farmlands, wetlands, and oceans (Zhao and Yang 2007). The method of Costanza et al. (1997) was mostly used to calculate the value of ecosystem types per unit area, while Xie et al. (2006) obtained value equivalency factors for Chinese ecosystem services from questionnaires and developed a valuation method for the calculation of values using existing ecosystem types and spatial distribution data, as well as temporal and spatial dynamics information for ecosystems obtained through remote sensing. Regional scale valuation has covered almost all types of ecosystems in China throughout all provinces, municipalities, and important natural geographic regions, including the Qinghai-Tibet Plateau, Loess Plateau, Inner Mongolia Plateau, and the Karst regions (Li et al. 2011). At the same time, river basins gradually became the characteristic unit of valuation and the scale at which most research occurred, as exemplified by the quantitative assessment and valuation of ecosystems and their services in the Haihe River Basin, Yanhe River Basin and Heihe River Basin (Wang and Zhang 2004; Li et al. 2010; Fang et al. 2011). The valuation of individual ecosystem services also involves water regulation, water and soil conservation, carbon sequestration and oxygen release, air purification, and landscape and recreational attributes. Valuation of such services improves the public's awareness of ecological conservation and provides a theoretical basis for the formulation of ecosystem conservation policies and associated decision making processes (Li et al. 2009).

Monitoring and Biophysical Quantification of Ecosystem Services

Since 2009, promoted by major projects such as the National Key Basic Research Program (973) "Chinese major terrestrial ecosystem services and ecological security" (Fu et al. 2009), the number of NSFC-funded projects and publications has been increasing, and the monitoring and quantification of ecosystem services have become an important focus. The use of keywords such as model simulation, carbon cycle, productivity, and remote sensing monitoring in NSFC projects has increased significantly. Given that ecological processes are the basis of ecosystem services, and thus changes in such processes will drive changes in ecosystem services, process models based on observations and processes can help improve the accuracy of measurement of ecosystem services. NSFC-funded projects that consider processes and mechanisms, and their regulatory pathways in different ecosystems, have been gradually increasing, as exemplified in such studies as "Study on mechanism of carbon and nitrogen cycle and storage function of the typical temperate grassland in Inner Mongolia", "The change process of soil carbon and nitrogen and its regulation in newly reclaimed desert in the middle reach of Heihe River in recent 50 years", and "The effect of subtropical plantations in China on soil organic carbon storage and its mechanism".

At the same time, land use is not only an important driving force for change in ecosystem services, but it also reflects the heterogeneity of the spatial distribution of such services (Fu and Zhang 2014). Therefore, NSFC-funded projects that have studied ecosystem services based on land use change and landscape patterns have accounted for an important share of the funding in the geography sector. Such projects include "The mechanism and evaluation of the effect of land use change in Taihu Lake Basin on water regulation ecosystem services", "Study on temporal and spatial changes of landscape pattern and ecosystem services in Gansu Bailong River Basin", and "The effect of crop distribution pattern changes on farmland ecosystem services". Recent models based on a geographical information system (GIS) and the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model in different land use scenarios, which can evaluate ecosystem services at both global and basin scales, are considered to be efficient tools that have enabled ecosystem services research to be incorporated into management decisions at different scales. These models have also been widely applied in China (Zheng et al. 2013).

Mapping of Ecosystem Services

Mapping of ecosystem services is an important task that enables the results of assessments of such services to be brought into ecological and environmental conservation planning, management decisions and their implementation (Zhang and Fu 2014). Although there has not been a grant awarded to support a specific project to map ecosystem services in China, such mapping has always been an important part of ecosystem services research and cannot be ignored. The valuation of ecosystem services and the measurement of various services need mapping to visually present the research results. "National ecological function zoning" is a typical example of where ecosystem services theory has been applied to function-oriented ecological zoning and has thus provided instructions for the conservation of regional ecosystem services. Since most such services and their valuation are determined using spatial data based on remote sensing and GIS analysis tools, spatial representation is relatively straightforward. However, because of the need to improve management practices, new requirements are constantly placed on ecosystem services mapping. For example, mapping assessment methods need to be able to evaluate the mapping of ecosystem services according to the requirements of management decisions, and descriptions of the spatial distribution of these services need to be quantified at particular spatial and temporal scales, while recognizing that such services can change under the effect of various natural and social factors. Although the fact that spatial mapping is required to determine the patterns of consumption of ecosystem services has now been recognized, how to move beyond the "static map" mode and consider the impact of the dynamic flow of ecosystem services across scales of socio-economic development in different regions remains a challenging task. In light of these and related concerns, ecosystem services mapping has become an important subject in this research field.

Analysis of the Relationships Between Ecosystem Services

Because of the diversity, imbalances in spatial distribution, and the selectivity of human utilization of ecosystem services, win-lose tradeoffs and win-win synergistic relationships between services arise due to the effects of both human activities and natural factors (Li et al. 2013; Wang et al. 2013). Thus studies of the mutual relationships between ecosystem services can form a key component of research about regional integration, and also provide an important basis for the regional management of ecosystem services, which has gradually attracted greater attention. There are currently a number of specialized key projects that focus on analyzing the relationship between ecosystem services.

Management of Ecosystem Services

With regard to the application of the valuation of ecosystem services, given that currency is widely used as the unit of measurement, the development of a regional eco-compensation (or payment for ecosystem services) policy has naturally become one of the most widely used applications (Li et al. 2011). As the drive to value China's ecosystem services has moderately subsided, research priorities have gradually turned to ecological compensation. Temporal changes of keywords from NSFC-sponsored projects related to ecosystem services reveal that ecological compensation appeared only twice from 2005 to 2009, but appeared 9 times from 2010

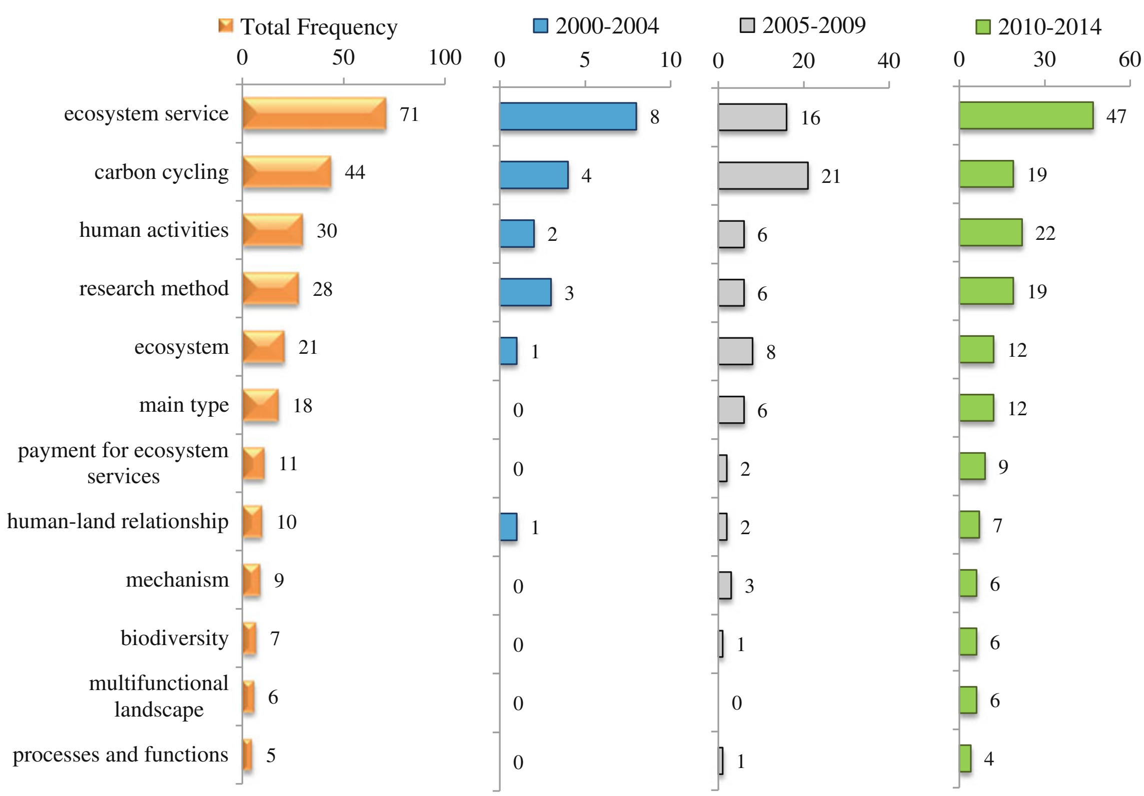

Fig. 19.3 Keyword temporal trajectory graph for NSFC-funded projects for "Ecosystem Services" during the period 2000–2014

to 2014 (Fig. 19.3). Although the existing valuations of ecosystem services have made people aware of the importance of such services in supporting economic and social development, the description of ecosystem services, and the well-being of urban residents and their relations, is still very weak, resulting in the lack of "win-win" regulatory pathways to simultaneously protect ecosystem services and improve the well-being of urban residents.

Comprehensive and Integrated Regional Ecosystem Services

China has vast territories and a diverse range of ecosystems, which has led to a focus on regional ecosystem services in terms of valuation, inter-systemic relationship analysis, and the comprehensive integration of the services provided. To consider practical research aspects such as ecosystem services monitoring, national ecological function zoning, ecosystem valuation, and ecological red line delimitation, a methodological framework that associates ecosystem features with ecosystem services has been established. In some important regions, such as the Loess Plateau, the synergetic and trade-off relationships between ecosystem services have been evaluated via a quantitative assessment of the ecological benefits of the Grain for Green re-vegetation project. In addition, changes in major ecosystem services using the combined techniques of remote sensing, model simulation, multivariate statistical analysis, and analysis of the social and economic effects of changes in ecosystem services, were further investigated. It has been proposed that adaptive management, considering the linkage of human-nature systems via a dynamic feedback relationship, plays a key role in the sustainability of regional ecological restoration efforts (Lü et al. 2012a). A preliminary integrated system model has been developed based on self-reliance (Hu et al. 2015), which has strengthened scenario creation, trade-off analysis, and spatially explicit ecosystem services optimization relative to existing integrated models (e.g., InVEST), and will likely define the future direction of the development of integrated models.

Construction of Theoretical Framework of Ecosystem Services Research

In contrast to the European conceptual framework of Ecosystem Service Cascades, Chinese researchers have proposed a holistic conceptual framework connecting ecosystem structure, process and services, which reflects the dependencies of human social and economic systems on natural ecosystems, and identifies the differences and connections among ecosystem processes and ecosystem services, as well as the relationship between internal components, structure, and function of individual ecosystems (Fu et al. 2013). With regard to ecosystem management, according to the principle of scale matching, Chinese researchers have distinguished each applicable scale of market, government, and culture in economic systems, social systems, and the complex systems of nature, and proposed a theoretical mode of ecosystem services management that combines all three systems (Wang et al. 2013).

19.2.4 Contributions by Chinese Scholars and Subsequent Problems

From an objective perspective, Chinese research in this field still lags behind the advanced level achieved internationally. From an academic standpoint, most Chinese studies are replications, while only a few are original research. Most research has been conducted on the valuation of ecosystem services. For example, from 2000 to 2014, 20 of the 400 highly cited articles published in English with a title containing the term "ecosystem service" were published by Chinese scholars (Fig. 19.4). Of these, 60 % focused on monetary valuation. In contrast, very little research has been conducted on the production, delivery, spatial flow and consumption mechanisms of ecosystem services. Most have been static studies, while only a few were dynamic simulations. In addition, most focused on natural ecosystem features, while only a few addressed their coupling with socio-economic systems (Li et al. 2011). Compared to the international forefront, the number of articles about ecosystem services published by Chinese researchers is acceptable, but the impact of the research is relatively small. A number of research gaps have been identified.

First, the fundamental gap is with respect to the process and mechanisms of ecosystem services generation. In the past, most Chinese studies of ecosystem services focused on economic valuation. In recent years, the feedback relationship of the ecosystem structure-process-service chain has been considered, but very little research on the mechanism of ecological processes and services has been conducted. This has led to a gap in research compared to the international development of this subject area. There is a need to study the components and structure of ecosystems, important ecological processes, and the relationship between ecosystem functions and services based on long-term observations and experiments together with model simulations to: (1) clarify how changes in ecosystem structure and processes affect the generation, transmission, and implementation of ecosystem functions and services; (2) identify the coupling mechanisms of ecosystem structure, processes, patterns and services; and (3) develop principles and methods of ecosystem services assessments.

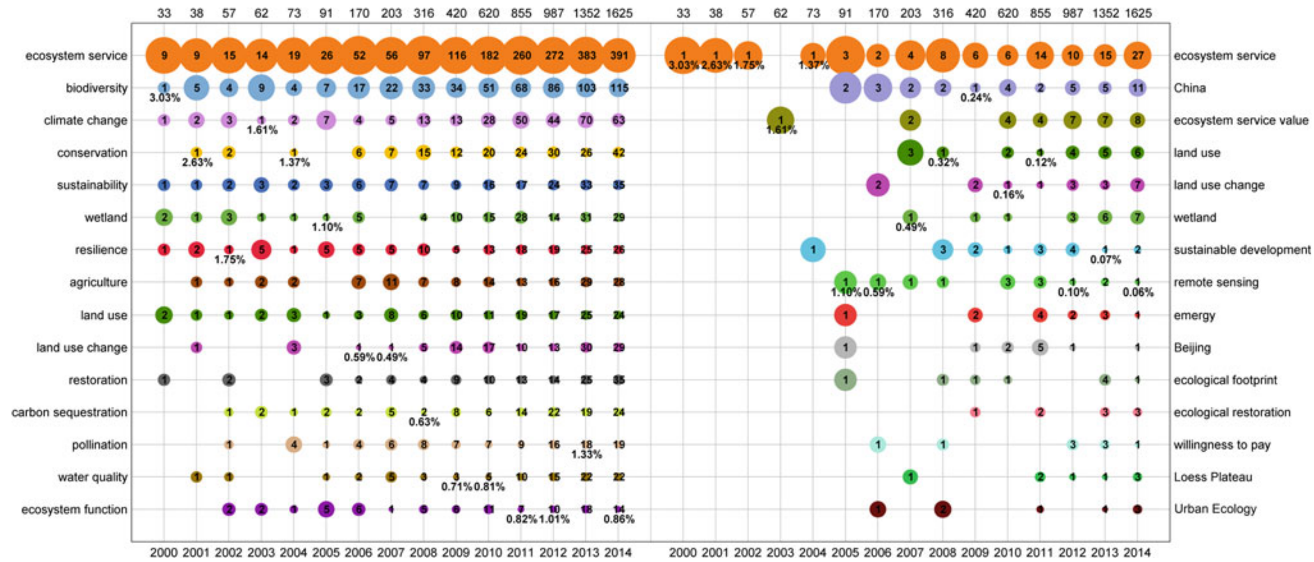

Fig. 19.4 Comparative diagram of prominent keywords on "Ecosystem Services" by Chinese authors and others in SCI/SSCI-indexed articles during the period 2000–2014. *Note* Right panel shows keywords used by Chinese authors and left panel shows those used by the authors from other countries (regions). Size of circles denotes the ratio of a certain keyword frequency to the total article number in a specific year. The annual total number of articles is shown at the top of the diagram. The frequency of the keyword is shown inside the circle. The size of circles in the diagram for Chinese authors are magnified for clear display

Second, the development of modeling approaches to the integration of regional ecosystem services remains quite weak. Ecosystem services at different scales have different levels of importance for respective stakeholders. Effective ecosystem services management requires a regional scale and multidimensional integration that depends on a thorough understanding of ecosystem structure, processes, and patterns at various spatial and temporal scales. For this reason, spatiotemporal and organizational scaling and regional multidimensional integration have become important and complex scientific issues in ecosystem services research. There is a need to study the scale characteristics and scaling method for the particular types of ecosystem services, and regional integration approaches are required for different types of ecosystems and the important services they provide. Such approaches would also identify the characteristics, interactions and temporal and spatial patterns of the variations in landscapes and regional-scale ecosystem services. Based on the above efforts, integrative models and methods for regional ecosystem service quantification, assessment, and simulation can be established and advanced.

Third, integrated ecosystem services management is waiting for concrete research advancement towards societal policy support demands. Through an integrated process, ecosystem services move from perception, quantitative assessment, and demonstrations to real-world management practices. Thus strengthening ecosystem services management and achieving sustainable development requires a deepening of related systematic studies in many ways, including the design of policies to provide compensation mechanisms to enable payment for ecosystem services (PES), the incorporation of ecosystem services into environmental assessment programs, and the planning and assessment of ecological conservation and restoration actions. Research and practical programs to include ecosystem services in ecological and environmental assessments have been conducted in many countries outside China. This also requires strengthening knowledge of the coupling mechanism for ecosystem services and regional human well-being, which in particular will require studies of the intrinsic connections between the different behaviors of stakeholders and ecosystem services at multiple scales. Finally, there is a key need to further explore the basic pathways through which the results of ecosystem services research are ultimately translated into management decisions, which in turn will serve to promote the efficiency and sustainability of ecosystems and regional ecological management practices.

19.3 Roadmap for Further Research

As ecological and environmental protection, restoration, and management have become stronger in China and strategic tasks to promote the development of ecological civilization have been proposed in recent years, unprecedented opportunities have been opened up for the development of ecosystem services research. Given the current status of ecosystem services research in China, there is a need to orient research to the significant demands of national environmental and ecosystem management. Ecosystem services research should be condensed into priority directions in the future by learning from the main trends in the international research field, thus providing a reference for academic exploration and practical application of research on ecosystem services.

(1) **National Demands**

In 2012, the 18th National Congress of the Communist Party of China proposed the strategic vision of "promoting the development of an ecological civilization", and defined the strategic task of optimizing a spatial development pattern for land, promoting resource conservation, intensifying efforts to protect natural ecosystems and the environment, and strengthening the institutional system needed for an ecological civilization. In 2013, the "Communique of Third Plenary Session of the 18th Communist Party of China Central Committee" declared that a sound system of natural resource assets and their use and control should be established. A red line should be drawn for ecological protection and used to demark a clear spatial range of strict protection. The ecological space should be determined; important mechanisms to maintain the pattern of national ecological security should be established; a system for the paid use of resources and ecological compensation should be implemented; and existing systems of ecological and environmental protection and management should be reformed. The "National Ecological Conservation and Restoration Plan" released in 2014 proposed specific goals, main indicators, nine regional layouts, and seven priorities for national ecological conservation and restoration by 2020. It also defined 12 key tasks, including the conservation of different types of ecosystems (such as forests, grasslands, deserts, farmlands, cities and oceans), water resources and biodiversity conservation, soil erosion control and regional priorities for integrated environmental governance. To achieve steady progress toward a national ecological civilization strategy and the effective implementation of an ecological conservation and restoration plan, existing systems must be systematically strengthened and in-depth studies and practices at institution, policy, science and technology levels must be undertaken, which will ensure that ecosystem services become a major practical component of national resource management and environmental science.

At present, ecological degradation and environmental pollution seriously hinder the process of national ecological civilization. They are severe challenges and difficult tasks that must be faced and solved in the development of an ecological civilization. These problems rarely arise and develop by way of a single factor or process. Interactions between social, economic, and natural factors, interrelations at local and regional scales, as well as the impact of economic globalization all combine to make ecological and environmental issues intricate and complex. Long-term ecological conservation and environmental pollution control practices also suggest that it is difficult to achieve the desired effect focusing on a single factor and process, or a single technology and end-of pipe control, which can result in half the results for double the effort. This is also one of the important reasons why the effects achieved have not been ideal despite China's great efforts in environmental protection and governance in recent years. Another important reason is that a panoramic understanding of various ecosystem services and the requirements for a healthy environment has not fully developed, including their effective integration with research and decision-making processes, leading to a one-sided emphasis on resource exploitation and utilization and economic interests. Remedying this requires explicit recognition of the overall strategic direction of ecological civilization development and the significant demands it places on environmental protection, restoration, and governance. This in turn defines the need to undertake comprehensive studies of ecosystem services, develop multi-disciplinary and integrative ecosystem services science, and promote the effective implementation of ecological and environmental protection, restoration, and governance, which together may foster a harmonious and sustainable development of the relationship between humans and their natural environment.

(2) **Priorities for Future Research**

To meet the major goals mentioned above, ecosystem services research must be conducted at both basic and applied levels, and the strategic significance of its connection between economy, society, and nature must be highlighted. From the perspective of the inter-disciplinary domain of geography and ecology, and in light of China's unique national conditions and the progress and trends of international ecosystem services science, the priority research directions for the future may be summarized as follows.

Theoretical Paradigm in Ecosystem Services Science

Although the Millennium Ecosystem Assessment has had a great impact on the concept and classification of ecosystem services, there is still no real consensus among academics regarding the precise delineation of the concept. A fundamental reason for this is that the scientific knowledge and research base for ecosystem services is not sufficient. Some researchers even believe that because the ecosystem services concept has been popularized successfully, a “take it for granted” atmosphere has become increasingly common. Robust scientific support to combat the strong uncertainty and controversy related to the concept is still required. In this light, the future development of ecosystem services should give full consideration to the dynamic processes, scientific mechanisms, and sustainable management implications of ecosystem services from their generation to practical utilization in order to deepen the scientific underpinning of ecosystem services as a theoretical paradigm. Structure, processes, and functions of ecosystems are the basis for the generation of these services. The implementation of an ecosystem services framework is affected by a combination of factors including the level of scientific knowledge, value judgments, markets, and temporal and spatial scales. Thus ecosystem services management requires an effective combination of comprehensive measures that take account of the respective roles of government, markets, and culture. In summary, a comprehensive theoretical paradigm of ecosystem services still needs to be developed, one in which such services are derived from ecosystem structure, processes and functions, and are manifest in spatial associations and grounded in temporal dynamics wherein feedback mechanisms operate to support their sustainable management. The furthering and refinement of research on classification, indicator systems, evaluation methods and models of ecosystem services under this paradigm should be encouraged and pursued.

Methodologies for Assessment, Simulation, and Regional Integration of Ecosystem Services

Long-term ecological research is flourishing around the world and is currently in an important transition period. Protocols for remote sensing ground-truthing are growing rapidly, and significant strides are being made in three-dimensional measurement, large scale network observations, and comprehensive regional studies. New technologies have been applied more widely in geography and ecology, with geographical and ecological informatics having become thriving research fields. Within these trends, geography should play to its subject strengths in assuming a leading role in ecosystem services research. Geographers need to conduct comprehensive, integrated research on the spatial manifestations of the dynamic relationship through which ecosystem structures and processes serve to create ecosystem services. This will require developing an indicator system for the monitoring and assessment of ecosystem services at multiple scales; analyzing the large-scale spatial and temporal variation of such services and their driving mechanisms; and constructing methodologies for understanding the geography of ecosystem services as it relates to their sustainable management at local and regional scales.

In addressing the above challenges, there is a need to develop comprehensive simulation models that can adapt to various spatial and temporal scales and consider multiple natural, social, and economic factors, multiple links in the supply-flow-consumption chain, and trade-offs and synergies between ecosystem services and policy formulation. Such integrated simulation models will play an important role in enhancing scientific support for sustainable management of regional ecosystem services. Via the use of such comprehensive models, the development of diversified approaches for specific management needs should also be encouraged. For example, in situations with insufficient data, developing more targeted, simple, and practical methods of assessment and mapping to solve specific issues (e.g., the determination, development, and conservation of priority areas for governance) would be a useful supplement to the models and better serve the practical needs of management decisions. Spatial mapping of ecosystem services is the visual expression of simulation and assessment results, and the development of large-scale, high-resolution spatial mapping for ecosystem services is an urgent task.

Applied Research in Ecosystem Services

On the basis of the demand for sustainable management of landscapes and from the perspective of forests, grasslands, deserts, wetlands, farmlands and cities, as well as complex surface landscapes composed of various landscape types, there is a need to conduct in-depth studies of the quantitative relationship between landscape patterns and their changes in association with ecosystem services. There is also a need to develop ecosystem services-oriented landscape geography and further conduct theoretical and practical explorations of landscape ecological assessments and planning. Research subjects that need to be urgently investigated include: sustainability assessments; the planning and management of cities and urbanization based on ecosystem services; the diversity of ecosystem services as part of the sustainability of agricultural landscapes; ecosystem services valuation for nature conservation and the effectiveness of landscape conservation; and regional integrated ecosystem management for ecosystem services and landscape function optimization. To improve large-scale ecological and environmental protection, restoration, and management and actively promote the development of ecosystem services, it is critical to strengthen research in the following areas: the production potential for ecosystem services; the carrying capacity and regional division of ecosystem services; assessing impacts of ecological and environmental degradation on ecosystem services and gross ecological production; identification of priority areas for ecological conservation and restoration; planning and evaluation of the effectiveness of conservation and ecological restoration; ecological compensation and its temporal and spatial configurations; and a protocol for performance assessment of regional ecological and environmental management based on the dynamic monitoring and assessment of ecosystem services.

19.4 Summary

Scientific research on ecosystem services is an emerging interdisciplinary field that has flourished in the 21st century. Disciplines such as geography, ecology, and ecological economics have played an important role in its development. The main contribution of geography is to emphasize the high degree of spatial heterogeneity that exists in the generation, flow, and consumption of ecosystem services, and the perception and realization of their economic value. In so doing, the quantitative assessment and valuation of ecosystem services must be based on a dynamic social-ecological approach, which is also the end-result from a geographic perspective. At the same time, the spatial mobility of ecosystem services during their generation and consumption determines their scale and cross-regional characteristics, which is also an important area where geography plays a key role. From a global perspective, the most prominent topics in the field of ecosystem services research since the year 2000 can be summarized into four major areas: classification and valuation of ecosystem services; mechanisms of biodiversity-ecosystem services interactions; temporal and spatial simulation and the mapping of ecosystem services; and ecosystem services management. In China, research on ecosystem services has gradually evolved from initially tracking international prominent topics to now working in parallel with international trends. NSFC funding and guidance have played a key role in this development and have nurtured some possible potential directions for further Chinese contributions to the international research landscape. A comprehensive theoretical framework and regional integration approaches toward ecosystem services have been adopted. In the future, there is a need to actively promote research in three key areas: refining the theoretical paradigm of ecosystem services science; quantitative assessment, simulation, and integration of ecosystem services; and applied research in ecosystem services. It is also essential to continue strengthening the capacity building of China's ecosystem services science to better serve the needs of a national ecological civilization and further enhance the theory and assessment methods of the geography of ecosystem services.

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The Urbanization Process and Mechanism 20

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Abstract

Based on the analysis of 1676 papers published in the 131 SCI/SSCI English journals from 2000 to 2014, and 1689 Chinese papers published in the 14 domestic journals from 1980 to 2014, we have found urban and regional development under globalization, population and economic growth and the function of market and policy, urban and regional sustainable development and planning, are the 3 major topics of the global urbanization research in the new millennium. Some important phenomena with urbanization including global change, land use, energy, ecological landscape and environmental pollution have also attracted many studies in the world. China's urbanization research has risen with the rapid urbanization process since the end of the 1970s. Compared to its international counterparts, China's urbanization research mainly focuses on how to lead and settle population into the cities, pays more attention on the urbanization's process, dynamics, temporal and spatial variation, problems, influence and policy, etc. It has been clearly characterized by the close combination of theoretical research, policy implications and planning practice. Urban land use, ecological landscape and environmental pollution are the recent key topics connecting to urbanization. China needs to strive in the global perspective, theoretical innovation, and integrated study in its future urbanization research.

Keywords

Urbanization • Dynamics • Mechanism • Literature quantitative analysis • China

A total of 1676 SCI/SSCI-indexed articles are analyzed in the research area of the urbanization process and mechanism. Articles were identified from 131 international journals from 2000 to 2014. The number of journals that have published more than 15 of the relevant articles is 26 (Appendix Q). The search query is as follows: "urbanization".

20.1 Overview

20.1.1 Development of Research Questions

The word urbanization was firstly used by **A. Serda** in 1876 to describe rural-urban transformation. Many disciplines have joined in urbanization research from their own specialties during the past one and half centuries. Demography treats urbanization as a migration process from the countryside to cities (Hertzler 1963); economics focuses on the economic change from the primary to the secondary and tertiary industries (Hauser and Schnore 1965); sociology pays more attention on the change from rural to urban ways of life (Wirth 1938); geography studies the extension of urban landscapes into rural areas. A more common understanding of urbanization is that it is a multi-dimensional process, involving demographic, social, cultural, spatial, lifestyle, values and landscape issues (for example, Friedmann 1966).

Some scholars think that urbanization began around 5500 years ago (Woolley 1981), while most researchers agree that modern urbanization started with the industrial revolution in the 18th century. The urbanization ratio of the developed countries reached 55 % in 1950, 70 % in 1980, and 78 % by the end of 2014; most developing countries

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started their rapid urbanization after the end of the Second World War; the urbanization ratio grew from 17.6 % in 1950 to about 30 % in 1980, and then to 48 % in 2014; with the rapid development of developing countries, the world's urbanization ratio also increased from less than 30 % in 1950 to 54 % in 2014. Every country has shown its own special features of process and mechanism although all countries ostensibly had the similar urbanization growth trends in the past decades.

Urbanization has given rise to more and more research which developed through 3 main phrases: the infancy stage from the mid-18th century to 1900, the rapid development stage from 1901 to 1980, and the diversification stage since the 1980s. In the first stage, scholars from the Western Countries advanced the definition of urbanization, studied urban origins, urbanization characteristics, and the economic driving forces, etc. In the second stage, urbanization dynamics, laws, urban systems, urban structures, and the developing countries' urbanization were studied. Economic locational theories, "push-pull" migration model, "S Curve" and other urbanization process models were established. In the recent third stage, influenced by the development of globalization, economic, social and spatial restructuring, and the theoretical turns in human geography in the Western Countries (Johnston 1979), urbanization research has shown new tendencies, such as being more critical and interdisciplinary, more closely combined with globalization and urban reality, and diversification of theory and methodology. The main research topics include planetary urbanization (Harvey 2012; Brenner 2013), glocalization (Amin and Thrift 2002; Brenner 2004; Robertson 2012), comparative urbanism (Robinson 2002; Nijman 2007), production of space (Soja 1989; Ye 2012), world city/global city (Fridemann 1986; Sassen 1991; Castells 1996; Taylor 1997; Hill and Kim 2000; Taylor 2004; Sassen 2006), metropolitan area, urban renewal and regeneration (DETR 1999; Carmona 2001; DETR 2000), gentrification (Ley 1986; Lees 2000; Smith 2002; Rofe 2004), counter urbanization and post suburbanization (Fishman 1987; Lang 2003), edge city (Garreau 1991), development zone, and creative city (Clarke and Gaile 1998; Hall 1998; Landry 2000; Florida 2005). Topics closely related to urbanization but focusing on feminism (Bush 1992), crime, ethnicity, and ecological cities have also attracted a lot of attention.

Although urbanization research in developing countries began at the turn of the 19th and 20th centuries, it did not enter a rapid development period until the 1950s when Western scholars started research on it. The early research focused upon urban origins, urban growth dynamics, urbanization path, migration, etc. It has turned to problems in the process of urbanization, such as slums (Mangin 1967; Turner 1968; Perlman 1976), housing, social movement, informal sectors, etc., since the 1970s. The concepts and statements of over-urbanization, urbanization without industrialization, and urban bias were put forward (Lipton 1977). After the 1990s, urbanization research in the developing world diversified as had developed country research. Globalization, post colonialism, post Fordism, and neoliberalism become the new dominant context; urban social segregation (Crot 2006; Rodgers 2009), policy and space (Schuurman 1989; Server 1996), poverty, crime, aging, illness and health (Gilbert 1994; Harpham et al. 1988; Aguirre 1994; Hardoy et al. 1995; Smith 1998; Pacione 2005; Muggah 2012), became the main topics; new models like desakota were proposed (McGee 1991). Among developing counties, Brazil (Hauser 1961; Cornelius and Trueblood 1974; Smith 1974; Perlman 1976; Ward and Sanders 1980; Fernandes and Valenca 2001), Russia (Ofer 1977; Rowland 1992; Becker et al. 2012), India (Wheeler 1966; Bose 1976; Murphey 1977; Alam and Alikhan 1987; Zachariah 1966), China and South Africa (Bloom 1964; Welsh 1971; Davies 1981; Hindson 1987; Lemanski 2004; Oldfield 2004) have contributed to more notable research results.

20.1.2 Contributions by Scholars from Different Countries

Statistical analyses of the 1676 articles mentioned at the beginning of this chapter indicate a doubling in the number of papers every 5 years during the past one and half decades (Table 20.1), which certify that urbanization has become a more and more important worldwide research topic.

The articles come from 67 countries, of which the USA, China, and the UK are the top 3 countries, accounting 25.2, 15.0 and 7.9 % of all the articles since 2010; 63 countries' articles were cited, of which the USA, China, and the UK were the top 3 countries, occupying 30.1, 19.8 and 9.4 % of all the citations since 2010; 103 articles, from 16 countries, were among the highly cited, of which the USA, China, and the UK were again the top 3 countries, occupying 27.7, 27.7 and 10.6 of all the highly cited articles since 2010.

In the top 10 countries of respectively paper publication, citation, and highly cited articles, there are only 2 (China and Brazil), 1 (China) and 3 (China, Malaysia and South Africa) developing countries, reflecting that the developed countries still dominate this research field. Although China ranked the second in terms of the numbers of articles, citations, and highly cited articles, it still has a long way to go to catch with the first, the USA.

20.1.3 Key Research Topics

Based on the graph of keyword clusters (Fig. 20.1), the six most important themes connected with urbanization research

Table 20.1 Top 20 countries (regions) with the number and citations of SCI/SSCI-indexed articles on “The Urbanization Process and Mechanism” during the period 2000–2014

	Number of articles						Cited frequency						Number of highly cited articles					
	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014
Rank	World	44	240	252	477	947	World	1,122	89	6,270	8,743	3,536	World	6	0	26	30	47
1	USA	18	58	101	168	239	USA	423	37	2,720	3,169	1,064	USA	2	0	13	15	13
2	China	3	42	23	38	142	China	32	17	795	886	700	China	0	0	5	2	13
3	UK	5	15	21	51	75	UK	172	4	795	1,402	333	UK	2	0	4	4	5
4	Netherlands	0	10	5	6	37	Netherlands	0	7	69	168	136	Australia	1	0	1	1	3
5	Germany	0	11	3	6	35	Italy	0	0	14	27	125	Netherlands	0	0	0	1	2
6	Australia	3	8	7	8	33	Australia	119	1	190	156	119	Germany	0	0	0	0	2
7	Canada	5	7	18	33	29	Germany	0	4	32	153	118	Italy	0	0	0	0	2
8	Spain	0	12	5	17	29	Japan	0	0	24	477	91	Japan	0	0	0	4	1
9	Italy	0	8	2	2	25	Canada	249	0	565	465	79	Belgium	0	0	1	1	1
10	Brazil	1	3	3	10	19	Sweden	0	3	19	195	78	France	0	0	0	0	1
11	Sweden	0	3	3	8	17	Singapore	22	0	57	40	74	Malaysia	0	0	0	0	1
12	France	0	7	1	6	17	France	0	1	34	98	69	South Africa	0	0	0	0	1
13	Japan	0	1	1	16	15	Belgium	0	1	307	351	57	Greece	0	0	0	0	1
14	Belgium	0	5	2	5	15	Spain	0	2	137	107	44	Singapore	0	0	0	0	1
15	Turkey	0	2	3	6	14	Mexico	3	0	30	123	37	Canada	1	0	2	1	0
16	Mexico	1	0	3	6	14	South Africa	0	2	36	34	29	Sweden	0	0	0	1	0
17	Singapore	1	2	3	5	12	Brazil	17	1	37	73	15	Spain	0	0	0	0	0
18	Argentina	1	2	3	4	11	Israel	0	1	0	72	13	India	0	0	0	0	0
19	Chile	2	1	3	4	10	Estonia	13	0	86	22	12	Brazil	0	0	0	0	0
20	South Africa	0	3	4	2	10	Taiwan, China	0	1	88	59	10	South Korea	0	0	0	0	0

Note Countries (regions) ranked by the number of articles, cited frequency and the number of highly cited articles during the period 2010–2014

from 2000 to 2014 were identified. The first focused on urban and regional development under globalization, including the keywords economic growth, urban form, housing, management, governance, etc. The second focused on urban and regional sustainable development and planning, including the keywords community, land cover, conservation, impact, network, planning, etc. The third focused on population and economic growth and the function of market and policy. China, developing countries and Europe are the most typical countries and regions for this research. These three are the major themes of urbanization research at the world level in the first 15 years of new millennium. The following three themes are the most important phenomena in the course of urbanization. The fourth focused on the ecological landscape system and spatial pattern, including the keywords growth, system, landscape, cover, bird, urban ecology, etc. The fifth focused on land use and urban expansion, including the keywords state, metropolitan area, urban expansion, sprawl, scale, politics, etc. The USA is the most typical country for this research. Remote sensing is the mostly used method. The sixth focused on ecology, environment, migration, poverty and other problems in developing countries, including the keywords economy, sustainability, reform, rural, urban growth, etc. Africa and India are the most typical regions and countries for this research. In addition to the above mentioned 6 themes, land, habitat, innovation, productivity, development, transformation, agglomeration and model are also important research topics.

In order to find the commonality and difference between urbanization research in China and the rest of the world, the above mentioned 1676 English articles were divided into two groups: the first group includes 1473 articles written by authors from countries and regions other than China; the second includes the other 203 articles by authors from China.

There were 727 keywords in the first group besides urbanization itself, of which 88 appeared no less than 100 times. We classified the top 60 keywords (used more than 155 times) into 19 groups based on their similarity (Fig. 20.2), to reveal the following characteristics of urbanization research outside of China. **First**, the USA and China are the mostly studied two countries, suggesting that China’s urbanization has been a subject of interest for scholars all over the world along with USA. **Second**, “city” is the main studied spatial unit, some spatial terms such as “region”, “area” and “urban community” are also important studied units. Basin and rural area are the other two major spatial types. **Third**, there are 4 main research themes: (1) dynamics, model and impact of urbanization; (2) the

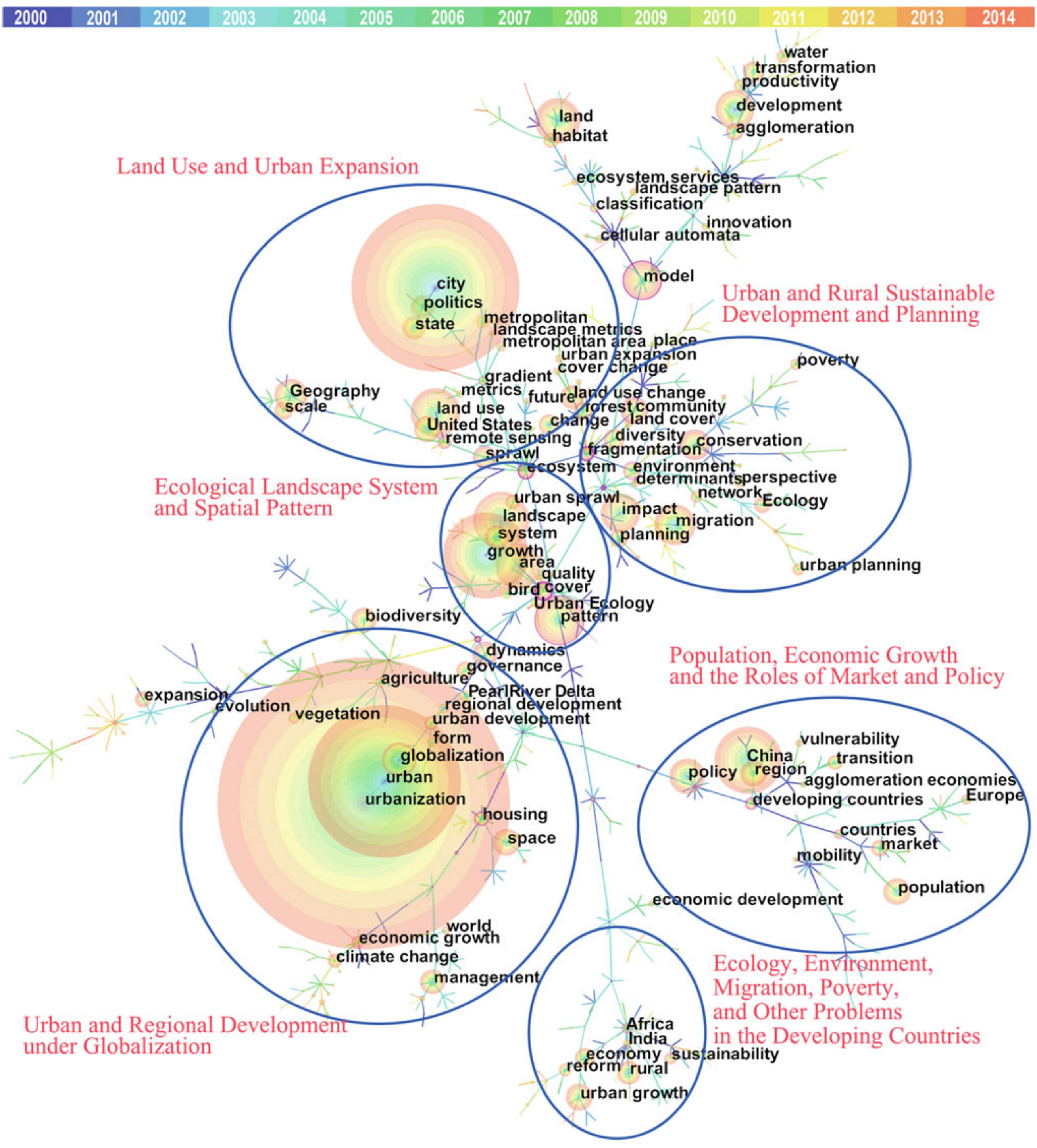

Fig. 20.1 Co-occurrence network of SCI/SSCI-indexed article keywords on "The Urbanization Process and Mechanism" during the period 2000–2014

main changes with urbanization including the keywords growth, trends, change and development; (3) the most important aspects for human being in the course of urbanization including the keywords population, habitat, health and migration; (4) urbanization and management including the keywords management, conservation and policy. **Fourth**, environment and land use are the mostly studied themes connected with the background of urbanization. The environment here includes the keywords climate change, ecosystem, environmental pollution, water, vegetation, soil

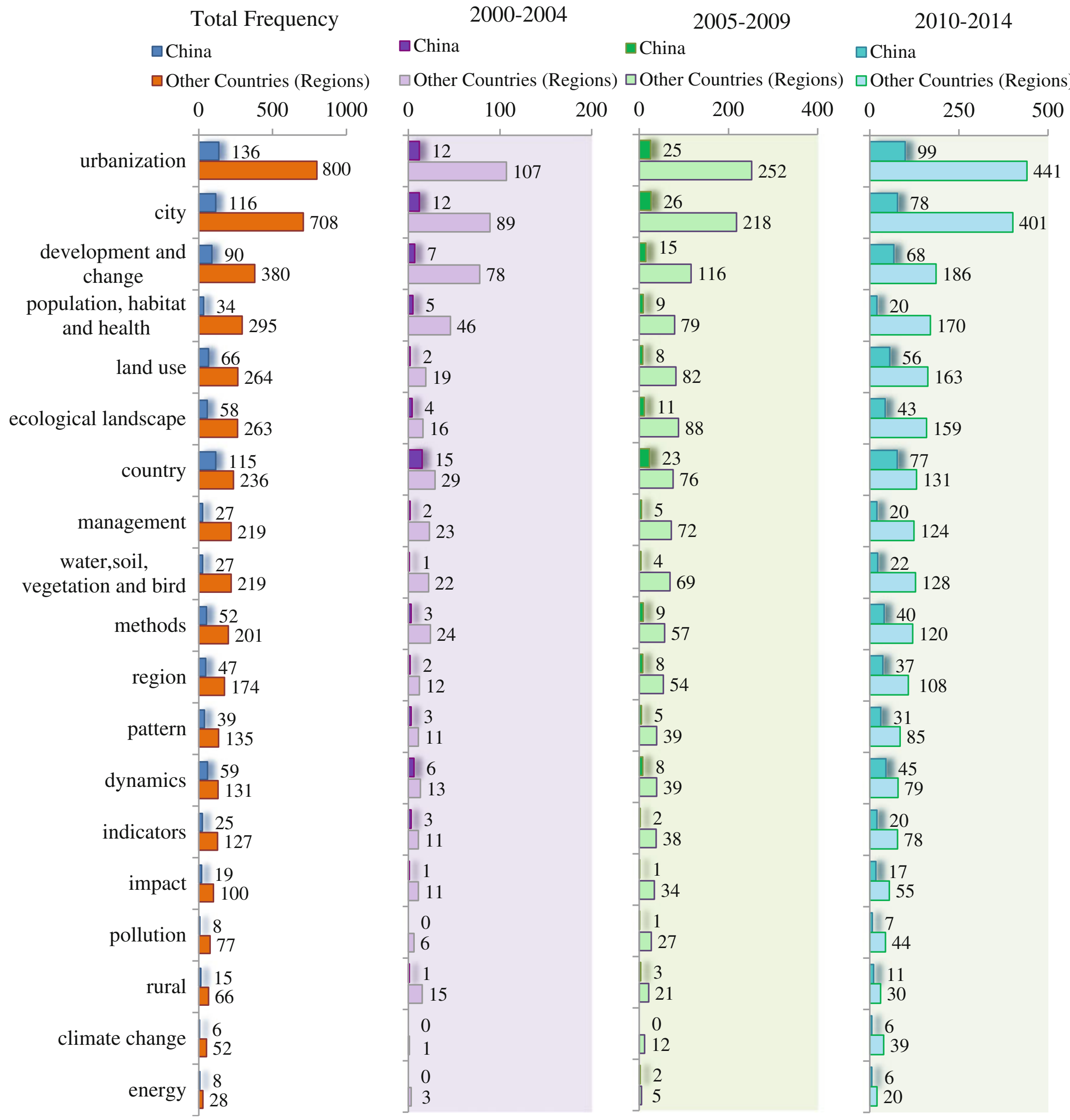

Fig. 20.2 Keyword temporal trajectory graph for SCI/SSCI-indexed articles on "The Urbanization Process and Mechanism" during the period 2000–2014

and bird, etc. **Fifth**, remote sensing, model, system and scale are the major methods used in urbanization research.

There were 566 keywords in the second group besides urbanization itself, of which 12 appeared no less than 100 times. We classified the top 60 keywords (occurring more than 35 times) into 19 groups based on their similarity (Fig. 20.2), which reveal the following characteristics of urban research within China. **First**, China and the USA are the mostly studied 2 countries, suggesting that the USA was the main comparative country in China's urbanization research. The Pearl River Delta, Hong Kong, Shanghai, and South China are the most important regions and cities within China. **Second**, "city" is the main studied spatial unit, but the spatial units "region" and "area" are also important studied spaces, rural area is the other major spatial type. **Third**, rapid urbanization is one of the most remarkable characteristics of China's urbanization. **Fourth**, there are 3 main research themes in China's urbanization: (1) impact, model, pattern and dynamics of urbanization; (2) the main changes caused by urbanization including the keywords of growth, trends, change, development and expansion; (3) urbanization and management including the two keywords of management and policy. **Fifth**, environment and land use are the mostly studied themes connecting with the context of urbanization. The environment includes the keywords climate change, ecosystem, environmental pollution, urban heat island, water, vegetation, soil, metal, energy and carbon, etc. **Sixth**, remote sensing, model, system and scale are the major methods used in urbanization research.

Based on the above information, there are 5 main common aspects of urbanization research outside of and within China. **First**, the USA and China are the mostly studied two countries. **Second**, "city" is the main studied spatial unit. **Third**, impact, dynamics, pattern and trends are the most important themes of urbanization research. **Fourth**, environment and land use are the mostly studied themes connecting with the background of urbanization. **Fifth**, remote sensing, model, system and scale are the major methods used in urbanization research.

There are also 4 main differences between the research outside of and within China. **First**, rapid urbanization is the most remarkable characteristics of China's urbanization compared with other countries. **Second**, China's urbanization research focuses on how to lead and settle more population in cities, while the Western Countries pay more attention to human being's habitat, health and migration. **Third**, the research surrounding "environment" in China is more connected to environmental pollution, while the Western Countries pay more attention to a variety of environmental changes. **Fourth,** China's research concentrates more on the country level, while research outside of China concentrates more on the macro global and micro urban community levels. These differences reflect China's development stage and special national realities.

Further analysis of the temporal changes of the 19 keyword groups in 5-year intervals helps to yield more findings (Fig. 20.2). **First**, climate change, ecological landscape, region, land use, pattern and pollution are the 6 most rapidly growing topics outside of China, while pollution, climate change, energy, land use, region and impact are the most rapidly growing within China. **Second**, ecological landscape and spatial pattern have attracted more and more research interest outside of China, while energy and impact are the most rapidly growing topics within China. **Third**, all the other 5 most rapidly growing topics except ecological landscape are not the most important topics (the most frequently used keywords), suggesting that they will emerge as new hot topics in urbanization research.

20.1.4 The Role of NSFC in Supporting the Research on the Urbanization Process and Mechanism

Urbanization has been an important research field funded by NSFC since the 1990s. NSFC financially supported 167 urbanization research topics from 2000 to 2014, with a total funding of more than 73 million yuan (Table 20.2). The number of projects increased from 22 in 2000–2004 to 105 in 2010–2014, and the funding increased from 7200 thousand yuan to about 49,925 thousand yuan at the same time. The numbers of projects and the amount of funding have almost doubled every five years.

NSFC supported 151 project managers in 82 research institutions from 2000 to 2014 (Table 20.2). The average project number for each principal investigator decreased from 1.1 in 2000–2004 to 1 in 2010–2014. The average number of principal investigators in each institution decreased from 1.8 to 1.5 at the same time period. The numbers of principal investigators and research institutions have also doubled every five years, while the degree of concentration of projects by managers and institutions have decreased. This demonstrates that NSFC has successfully attracted more scholars and institutions in the field of urbanization research in China during the past one and half decades.

Further statistics has shown that 32.0 % of SCI/SSCI-indexed articles published by Chinese scholars during 2000–2014 were funded by NSFC (Table 20.2), with the percentage increasing from 13.0 % in 2000–2004 to 37.3 % in 2010–2014. The main reason for the low percentage of NSFC supported articles is that the articles published by scholars from Hong Kong accounted for more than one-half of all Chinese articles, while Hong Kong scholars secured comparatively fewer projects from NSFC than their Mainland colleagues.

Table 20.2 NSFC-funded projects and SCI/SSCI-indexed articles on "The Urbanization Process and Mechanism" during the period 2000–2014

SCI/SSCI-indexed articles					NSFC-funded projects			
Periods	Number of articles	% of articles by Chinese authors	% of articles with NSFC funding by Chinese authors	% of articles funded by MOST among those with NSFC funding	Number of projects	Funding (10,000 yuan)	Number of PIs	Number of institutions
2000-2004	252	9.1	13.0	0.0	22	720.0	20	11
2005-2009	477	8.0	23.7	11.1	40	1,675.0	39	25
2010-2014	947	15.0	37.3	22.6	105	4,992.5	102	67
2000-2014	1,676	12.1	32.0	20.0	167	7,387.5	151	82

Fig. 20.3 Keyword temporal trajectory graph for NSFC-funded projects on "The Urbanization Process and Mechanism" during the period 2000–2014

There were 494 keywords in the 167 NSFC-funded projects from 2000 to 2014, of which 44 appeared more than 3 times (including 3). These 44 keywords were classified into 15 groups based on their similarity (Fig. 20.3), revealing the following characteristics of urbanization research funded by NSFC. **First**, types of urbanization connecting with the recent state policy constitute one of the keywords together with urbanization, China's urbanization and regional urbanization since 2010. **Second**, China, Beijing and the Pearl River Delta are the main study areas. **Third**, human-land relationships, sustainable development and urban-rural relationships are the main theoretical perspectives and basis of urbanization research. **Fourth**, model simulation, remote sensing, evaluation, and process observation are the main research methods. **Fifth**, dynamics, mechanism, and temporal and spatial patterns are the major research themes of urbanization itself. **Sixth**, water environment, soil, ecology, landscape, land use and environmental effects are the main research themes closely connecting to the background of urbanization.

These projects have demonstrated similar research trends with the formerly mentioned English articles. NSFC has strongly supported China's urbanization research during the last 2 decades, and needs to lead the research about health, energy and management, and particularly encourage research at the micro scale within cities.

20.2 Research Advances and Problems

20.2.1 Chinese Publications on Urbanization Research

Urbanization research in Mainland China started around the end of the 1970s (Wu 1979). China witnessed its rapid urbanization process and parallel growth in research since then. There are more Chinese articles published than English SCI/SSCI-indexed articles on China's urbanization research. These publications in Chinese are more closely connected with China's urbanization reality. Focusing on the research

Table 20.3 Articles on "The Urbanization Process and Mechanism" published in selected Chinese journals in 1980–2014

Periods	1980-1984	1985-1989	1990-1994	1995-1999	2000-2004	2005-2009	2010-2014	Sum
Sum	17	39	70	141	319	426	677	1,689
Annual average	3.4	9.8	14	28.2	63.8	85.2	135.4	67.6

themes of urbanization, while excluding the themes connecting to the background of urbanization, we try to sketch and summarize the progress of urbanization research during the past three and half decades based on selected Chinese articles and books published during this time.

Most Chinese articles on urbanization are published in the journals of geography, urban planning and urban studies. We chose 9 geography journals including *Acta Geographica Sinica, Scientia Geographica Sinica, Geographical Research, Progress in Geography, Economic Geography, Human Geography, World Regional Studies, Journal of Geographical Sciences(English), Chinese Geographic Science(English)*; three urban planning journals including *City Planning Review, Urban Planning Review, Urban Planning International,* and 2 urban studies journals including *Urban Problems, Modern Urban Research. There were* 1689 articles published in these 14 journals from 1980 to 2014 identified by using "urbanization" as the keyword.

20.2.2 Stages of China's Urbanization Research

Through the statistics of published articles, we divided the 35 years since 1980 into three periods. The 1980s was the starting stage of China's urbanization research, with on average less than 10 articles published per year (Table 20.3). The 1990s, especially the first 5 years, was the rapid development stage, with the number of publications doubling every 5 years. The 10 years since 2005 were both a rapidly growing and an improving stage, with a significant progress in both the quantity and quality of publications.

20.2.3 Main Progress of China's Urbanization Research

An analysis of these articles and some books suggests that most progress was made in the following research themes.

Dynamics of Urbanization

Only several urbanization driving forces were paid close attention to in the first stage. They mainly concentrated on industrial, agricultural and economic development, which revealed the roles of industrial restructuring in rural area (Zeng and Yu 1989) foreign investment (Xue and Yang 1995), export-oriented economy (Zheng and Wang 1985), infrastructure and public facilities development (Shi 1991), on urbanization in some regions. The ideas of urbanization from below and top-down urbanization were advanced (Lin 1984; Zheng and Wang 1985).

Research on urbanization dynamics was tremendously extended and deepened in the second stage. **First**, more urbanization driving forces were revealed such as regional institutional environment (Zhang 1998), management system (Wang 2002; Zhang et al. 2002), ecological and environmental resource (Li et al. 2005), tourist industry (Meng et al. 2002), etc. **Second**, a systematic analysis of the various aspects of urban dynamics started. System Models were advanced, such as "Endogenous-Exogenous dynamics system" (Ning 2000), "Basic-Special dynamics system" (Cai 1997), "Government-Enterprise-Individual multi dynamics system" (Ning 1998), "History-Resource-Industry-Project-Institution integrated system" (Liu et al. 2002). **Third**, the model of "Urbanization from below" (Cui and Ma 1999), the interaction of industrial restructuring and urbanization (Li et al. 2004b), the role of the New International Division of Labor under globalization in shaping China's urbanization (Wu and Gu 2005) were more deeply studied.

Research on urbanization dynamics was further developed during the third stage. **First**, it turned from the universal dynamic mechanism to the specific dynamics in the given regions. Different models for special regions were advanced, such as the dynamic models of China's Eastern, Middle and Western areas (Zhao and Ning 2009), the dynamic mechanism of semi-urbanization (Zhang et al. 2008), the dynamics of Rural in Situ Urbanization (Weng and Yan 2011), etc. **Second**, the restriction of urbanization mainly from the perspectives of resource consumption and environmental pollution started to be examined (Wu et al. 2011; Zhang et al. 2012b). **Third**, the informal dynamics of urbanization was studied including informal employment, informal sectors and informal housing (Yin et al. 2009; Liu et al. 2010).

Problems and Impact of Urbanization

Two main types of problems were studied including the problems restricting urbanization development and the problems caused by urbanization.

Research on the first type of problems started in the early 1980s, when a lack of economic capacity was the main concern (Luo 1981). Restrictions on urbanization associated with the household registration (Hukou) system and administrative system were explored since the 1990s (Tao 1996; Zhang and Chen 2003; Wei et al. 2009; Liu 2010).

Research on the second type of problems started in the mid-1990s. The main problems included the low quality and low efficiency of land use and development caused by rural urbanization (Sun and Lin 2000; An et al. 2002); environmental problems of acid rain, water pollution, damage of regional river systems caused by rapid urbanization (Liu 1998; Gao et al. 2003; Yang et al. 2004; Fang 2008; Yao et al. 2010); social problems of social norms, labor force market (Zhang and Yao 1997), urban village renewal (Yan et al. 2004), conflicts in the course of rural land requisition (Shi 2002), land ownership transfer (Liu 2010), semi-urbanization and hollowed-out villages (Liu et al. 2013; Lv et al. 2013), and the forced urbanization of some peasants (Zhang and Gu 2006). Problems in some specific areas of Middle and Western China and the old manufacturing area of North Eastern China were also examined during the last two decades (Guan and Yao 2002).

Models of Urbanization

China witnessed the development of small towns, and advanced the model of rural urbanization before the mid-1990s. The related rural population transformation and migration models based on different regions were put forward, such as "Both Workers and Peasants" (Yao and Wu 1982), and top-down urbanization in the Southern Jiangsu Province, Bottom-up urbanization in Wenzhou, Zhejiang Province, rural urbanization driven by comprehensive forces in the Northern Jiangsu Province and Beijing suburban areas (Sun and Lin 1988), double track urbanization influenced by the registration system (Meng 1992), etc. Special urbanization models of Southern Jiangsu Province, and Zhejiang Village in Beijing were studied in the 1990s (Zhang 1996; Hu 1997). A quasi-urbanization model was explored and systematically studied based on research in some coastal developed areas in the new millennium (Zheng et al. 2003; Liu et al. 2004, 2005; He and Huang 2012). Some other models were also suggested, including urbanization driven by the tourist industry (Zhu and Jia 2006; Ge et al. 2009), and urbanization on the spot in some developed rural areas (Zhu 2006), based on empirical research.

Urbanization Policy and Strategy

The research on urbanization policies in China has been changing with the major problems in the course of urbanization, and has also notably influenced the policies in different periods.

This research mainly focused on the discussion of City Size in the 1980s. The core question was which size(s) of city China should develop in its urbanization, and different opinions advocate respectively small town, mid-size city, large city, or multi-level city development (Li 1983). Most human geographers supported developing large cities or multi-level cities. The former thought that large cities could take the advantage of scale economies (Hu 1984), while the latter argued there was not a best city size choice, therefore, China should pay attention to developing the regional urban system with multi-level cities (Zhou and Yu 1988).

There were two foci of urbanization policy research in the second stage. The first was the sustainable urbanization strategy against the backgrounds of resource consumption and environmental pollution at the state level (Meng and An 1996). A similar strategy was integrating industrial restructuring, informational development and environmental regulation (Zhang 2004). The second was the diverse policies more closely connected to the special characteristics of different regions (Ning 1997; Zhang et al. 2004).

Extended research followed the second stage since the mid-2000s. More comprehensive, healthy and high quality urbanization integrating "population-resource-environment-society" was put forward (Lv and Chen 2006; Sun et al. 2012), in which human oriented ideas were highly valued (Chen and Ye 2011).

Measurement and Evaluation of Urbanization

Scientific measurement and evaluation of urbanization are the basis for formulating planning rationales and policy. Single indicator and multi indicators evaluations of urbanization have been conducted in China since the 1980s. The urbanization ratio (the proportion of urban population in the total population) was the only indicator used to measure the urbanization levels of the whole country and a given region from early 1980s to mid-1990s. A lot of research focused upon how to calculate precisely the national and regional urbanization rate through establishing and applying statistical models in the last two decades of the 20th century (Li 1986; Cai 1992). Later some scholars tried to revise the census data and statistical models in order to get a more accurate estimate of the urbanization degree (Shen 2005; Zhao et al. 2005). Since the late 1990s, some research attempted to measure the urbanization level of a given region with multiple population-economic-social-environmental indicators (Chen et al. 1999; Ge et al. 2003; Han and Liu 2009; Fang and Wang 2011; Zhang et al. 2012a). Some scholars started comparative research on the urbanization development trajectories of China and the Western Countries in the last 10 years (Chen and Luo 2006; Chen et al. 2011; Chen 2012b).

Process and Spatial Pattern of Urbanization

Research on urbanization processes has been done at both national and regional levels (Dai and Liu 1998; Tang and Yao 1999; Li et al. 2004a; Yeh et al. 2006). Suburbanization and de-urbanization have also been studied (Wang and Li 1995; Feng et al. 2004). Research on the spatial pattern of urbanization mainly focused on national and regional city systems (Xu 1986), development of urban-rural integrated areas (Wei 1997; Chen and Li 2004), metropolitan areas (Hou 1999), megalopolis, urban clusters, the inner city spatial structure, and land use pattern (Wang and Zhao 2004; Zhang and Zhang 2004; He et al. 2005; Huang and Zhu 2005; Shen 2006; Lu 2007; Liu et al. 2008a, b).

Theories of Urbanization

Chinese researchers started to introduce urbanization theory from Western Countries since the early 1980s; they were at the same time also gradually committed to construct China's own urbanization theory based on empirical research in China. The main theoretical work includes setting up the standard and definition of China's cities and urban population (Zhou 1984; Ma 1992), establishing the special urbanization models of rural urbanization, urban-rural integration, urbanization from below, semi-urbanization (Xue et al. 1998; Xue and Zheng 2001; Liu et al. 2004; Chen 2012a), and the special migration models of "Both Workers and Peasants", "Leaving the land but not the countryside", "farmer-peasant worker-urban inhabitant" in the course of China's urbanization (Yao and Wu 1982; Shen 1999; Li et al. 2011), which differ from the experience of Western Countries. A systematic research framework for the study of urbanization from a geographical perspective has been advanced recently (Lu 2013).

20.2.4 International Comparisons and the Main Problems in China's Research

China has achieved great progress in its urbanization research in the past three and half decades, although this research started much later than in developed countries. The major differences between Chinese and Western Countries' research are as follows:

Different Urbanization Development Stages

China's urbanization ratio is about 50–55 %, so China is still in a phase of rapid urbanization, while the urbanization ratio of most Western Countries has reached more than 75 %, and they are at a highly developed stage in which in the eyes of some scholars urbanization has largely been completed (Andersen et al. 2011).

Different Research Foci

Chinese articles published since the 1980s indicate that urbanization research in China is mainly focused on the process, dynamics, mechanisms, spatial patterns, models, policy, etc. The final aim is to promote urbanization, and is greatly influenced by China's urbanization stage and reality. The projects funded by NSFC and SCI/SSCI-indexed articles written by Chinese authors since the 2000s also show that land use and environmental pollution have become the two main research themes closely connecting to the context of urbanization; research on ecological landscapes, water, soil and vegetation have been growing rapidly. In the Western Countries, the quality of urban life, health, newly emerging socio-economic development, and spatial change have attracted more research interest. Changes accompanying rapid urbanization, including land use, environment, landscape, ecosystem and energy, have become important topics with even more publications than urbanization itself.

Different Research Perspectives

Researchers in Mainland China have mostly chosen urbanization in China as their research topic, but seldom discussed China's urbanization from a global perspective. Most oversea Chinese scholars have studied China's urbanization in the light of Western theories, but still lack global perspectives. Conversely many Western scholars have got used to studying urbanization at the global level.

Different Research Scales

Most research on China's urbanization was at the more macro scales of state, trans-province, province and municipality, and coincide with administrative levels. Choosing these scales helps provide policy suggestions for governments at different levels. Research in Western Countries tends to choose the two extremes of the global scale and the micro community scale within a city. Some western scholars

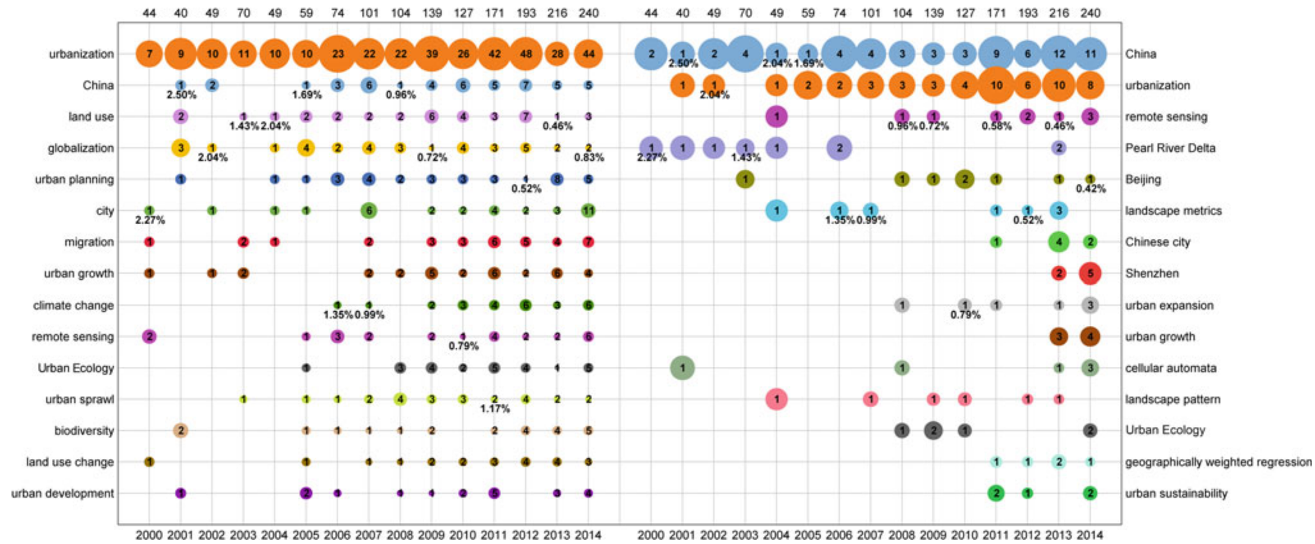

Fig. 20.4 Comparative diagram of prominent keywords on "The Urbanization Process and Mechanism" by Chinese authors and others in SCI/SSCI-indexed articles during the period 2000–2014. *Note* Right panel shows keywords used by Chinese authors and left panel shows those used by the authors from other countries (regions). Size of circles denotes the ratio of a certain keyword frequency to the total article number in a specific year. The annual total number of articles is shown at the top of the diagram. The frequency of the keyword is shown inside the circle. The size of circles in the diagram for Chinese authors are magnified for clear display

think that today's urban study has transcended the traditional paradigm of urbanization. It is dominated by urban community research (Harvey 1997), and pays more attention to the problems in people's everyday lives.

Different Roles of Governments

Because of the special political and institutional system in China, the central government plays an essential role in decision making relating to state investment, which due to its scale greatly influences urbanization. Local governments also play important roles in urban planning and construction. Urban development policy, urbanization strategy, urban and regional planning are all among the important topics of urbanization research in China. Compared to China, there is much less research on governmental functions in the urbanization research of Western Countries.

Different Orientations of Theoretical Innovation and Practical Application

Influenced by the idea that knowledge must serve society and the state, the emphases of urbanization research in China are on the solution of practical problems, and serving national needs. Although problem orientation is also emphasized in Western Countries, academic research pays more attention to find the scientific patterns and establishing theories.

Because of different development stages and backgrounds, urbanization research at home and aboard has shown some commonalities and differences. Based on the most frequently used keywords (Fig. 20.4), we find that urbanization research outside of China not only focuses on urbanization itself which mainly covers city, urban planning, urban growth, urban sprawl, urban development, and migration, but also incorporates much wider fields such as land use, climate change, urban ecology, and biodiversity set against the background of globalization. Research on China's urbanization mainly focuses on issues directly related to urbanization and includes urban expansion, urban growth, and urban sustainability in those most developed cities and regions including Beijing, Shenzhen and the Pearl River Delta. Urban ecology and landscape patterns closely connected to urbanization are also studied. In addition to remote sensing, more specific methods have been used in China's research, including cellular automata, geographically weighted regression, landscape metrics, etc.

A comparison of Chinese and Western urbanization research points to the following problems:

Lack of a Global Vision

China's urbanization has not been studied at the global level. Chinese geographers have seldom studied urbanization outside of China, hindering a more comprehensive understanding of China's urbanization.

Lack of Theoretical Innovation

Theoretical innovation is one of the weak points in China's urbanization research. Compared to Western Countries, China has a very different history of urban development, standards of urban area and population, national political and institutional systems, and cultural background. China's urbanization is not a replica of Western urbanization. Establishing China's own urbanization theory based on solid empirical studies will be helpful for understanding and guiding China's urbanization. The world will also benefit from China's urbanization experience and theory in the future.

Lack of Comprehensively Integrated Research

Urbanization is a comprehensive process affected by many natural and human factors. It also involves processes taking place at different scales, from the global to the local. Up until now a number of different disciplines have individually examined urbanization issues (crossover study). In order to better understand urbanization in all its complexity, integrated multi-disciplinary research is needed in the future, bringing together geography, ecology, biology, environmental science, economy, sociology, anthropology, planning, architecture, engineering, psychology, culture, etc.

Lack of Nuanced Research at the Micro Level

Nuanced studies are necessary for revealing the deep reasons and mechanisms causing urbanization phenomena, and yet empirical research at the micro level within cities is still not often found in China. It should be strengthened in the future in order to improve theoretical innovation and solve practical problems.

20.3 Roadmap for Further Research

China's urbanization is characterized by its high speed, large population size, powerful government, diversified social and cultural backgrounds, and complicated environmental problems. To adapt to these features and problems and learn from international experiences, Chinese urbanization research should in future pay more attention to the following points:

(1) **Adjust Research Directions and Contents, and Serve New National Needs**

China has entered the "New Normal" stage with lower economic growth and less resource consumption. Urbanization will correspondingly change from the former mode of only emphasizing fast growth to stressing higher quality. In the face to the new situation and the New National Urbanization strategy, the following issues should receive more attention in future research: **First**, research should change from "how to attract and settle more population in the city" to "how to improve the quality of China's urbanization"; **second**, research should change from providing conditions for urban growth to better urban life and health; **third**, research on resource and environmental limitations, energy and ecological security, should be increased; **fourth**, research at the scale of the urban community and neighborhood should be strengthened, in order to provide scientific support for more careful and efficient urban management.

(2) **Expand Global Vision, Strengthen Theoretical Innovation, and Contribute Global Urbanization Research and Practice**

Some Western scholars have realized the limitations of urban theories derived solely in the light of the reality of Western cities, so they recently initiated wider and deeper research into cities in the Global South, in order to achieve new theoretical innovation (Ong and Roy 2011; Sheppard et al. 2013; Scott and Storper 2015). We should study China's urbanization with a global vision, to explore new theories based on existing mainstream theories. At the same time, Chinese geographers should more widely participate in urbanization research outside of China by engaging in international cooperation and comparative study, in order to better understanding the urbanization in China and the whole world, and make a greater contribution to global (particularly to other developing countries') urbanization research and practice.

(3) **Attract More Disciplines to Join Integrated Research**

Many disciplines have so far studied urbanization from their own perspectives. More and more scientists have realized the necessity of multi-disciplinary research for a full understanding of urbanization. Geographers have recently started to cooperate with economists in research on the economic dynamics of urbanization, with sociologists in research on social problems, with planners in research on urban planning and management, with ecologists and environmental scientists in research on ecological and environmental problems. But existing inter-disciplinary studies limited to several disciplines will not fulfill the requirements of a future demands of complicated research. We should take advantage of geography's synthetic ability, and promote multi-disciplinary, multi-factor, and multi-scale integrated research, so as to explore new theories, methods and models in future urbanization research.

20.4 Summary

Urbanization is one of the most notable economic, social and spatial processes in human history. Many disciplines have studied urbanization from their own perspectives, of which geography mainly deals with its spatial characteristics and processes.

Western Countries started their modern urbanization at the time of the industrial revolution. People movement from the countryside to the city was largely completed (but at different times in different countries) by the end of the post-war ‘golden age’ of full employment and relatively fast growth. Instead of continuing to increase rapidly in size of urbanization, urban restructuring and improvements in the quality of urban life assumed more importance as many social, economic and political problems emerged in western cities after the mid-1970s economic crisis. Urbanization research of Western Countries started earlier in the late 18th century. Based on their urbanization and urban experiences, a series of definitions, theories and models of urbanization, migration, urban development and urban spatial structure, were established. These Western theories have dominated mainstream urbanization research all over the world in the past century. In the new millennium three major themes emerged in global urbanization research including urban and regional development under globalization, population & economic growth and the function of markets and policy, and urban and regional sustainable development and planning. Some important phenomena closely connected with urbanization, such as global change, land use, energy, ecological landscape and environmental pollution, have also become intensively studied topics in the world as a whole.

The rapid urbanization in China started in the late 1970s. In 2012 after 3 decades more than one-half of the Chinese population lived in urban areas. So China’s urbanization has entered a stage of pursuing both rapid speed and high quality. Compared to Western Countries, urbanization research in China started later at the end of the 1970s. So far Chinese scholars have made great progress in the introduction of Western urbanization theories, and also produced many empirical studies dealing with the measurement and evaluation of urbanization, dynamics and models, problems and impact, policy and strategy, process and patterns, etc. Based on China’s special urbanization reality, Chinese scholars have advanced some special urbanization models such as rural urbanization, urban-rural integration, urbanization from below, semi-urbanization, and migration models such as “Both Workers and Peasants”, “Leaving the land but not countryside”, “farmer-peasant worker-urban inhabitant”, etc. China’s urbanization research is clearly characterized by the close combination of basic research, policy implications and planning practice.

Urbanization has become a hot topic of global research in the new millennium. China has reached the second place in the number of papers publication and citations in the field of urbanization research during the past five years. China’s urbanization has focused on how to lead more population into cities, and taken the whole nation and large regions as the main spatial scale. Phenomena closely connected with urbanization including land use, ecological landscape and environmental pollution, have also been studied recently. Considering the new national needs and international academic progress, Chinese scholars should in the future adjust the research directions, contents and scales, expand their global vision, strengthen theoretical innovation and promote integrated studies.

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21 Medical and Health Geography

Linsheng Yang, Hairong Li, Yang Cheng, and Binggan Wei

Abstract

Since the 1990s, medical & health geography is developing rapidly in China and over the world. The number of SCI/SSCI papers by Chinese authors and their citation times have highly increased. In developed counties, scientists give substantial attention to health care accessibility, health equity and their relationships with space, neighborhood, landscape, area, economic, culture, aging and other social determinants, as well as the health impacts of global environment change and large scale environment degradation. In China and other developing countries, scientists pay more attention to the health risks of local environment pollution (either heavy metals or POPs in air, soil or water) and the prevalence of local diseases. Research in China has continued for nearly half a century and has made great contributions to the control of endemic diseases and the prevention of environmentally-induced health problems.

Keywords

Medical and health geography • Environmental health • Health care • Global health • Health risk assessment

A total of 20,891 SCI/SSCI-indexed articles are analyzed in the research area of medical and health geography. Articles were identified from 598 international journals from 2000 to 2014. The number of journals that have published more than 15 of the relevant articles is 218 (Appendix R). The search query is as follows: ((“disease” OR “health” OR “exposure” OR “cancer”) AND (“selenium” OR “fluoride” OR “iodine” OR “arsenic” OR “lead” OR “mercury” OR “cadmium” OR “heavy metals” OR “rare earth” OR “trace elements” OR “POPs” OR “PAHs” OR “PBDEs” OR “atmospheric particulate matter” OR “$PM_{2.5}$” OR “polycyclic aromatic hydrocarbons” OR “antibiotics” OR “endocrine disruptors” OR “pesticides” OR “PFCs” OR “nano-particles”) AND (“environment” OR “geography” OR “spatial” OR “distribution” OR “endemic”)) OR ((“environment” OR “pollution” OR “climate change”) AND (“health” OR “disease” OR “exposure” OR “cancer”) AND (“geography” OR “spatial” OR “distribution”)) OR ((“health” OR “disease” OR “medical” OR “death” OR “longevity” OR “infectious” OR “cancer” OR “SARS” OR “malaria” OR “schistosomiasis”) AND (“geograph*” OR “spatial distribution” OR “GIS” OR “remote sensing”)).

21.1 Overview

21.1.1 Development of Research Questions

Medical and health geography is concerned with geographical distribution patterns of diseases and population health and its relationship with the living environment, as well as the location and allocation of health care services and facilities. Based on the theories and methodologies of geography, major research interests are to analyze the temporal-spatial distribution patterns of diseases and population health and its influencing factors; the interaction and

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management of environment, development and population health; assessment of regional health risks; and the location and allocation of health care services and facilities. Medical and health geography is a frontier discipline melding geography with the human and life sciences. Within geography, it is an interdisciplinary field of physical geography and human geography (Kearns and Moon 2002; Gatrell 2002; Tan 2008; Yang et al. 2010a, b).

Medical geography has become a modern science since its origin in the late 18th century and early 19th century. The German physician **L.L. Finke** used the term "medical geography" when producing a world map of diseases in 1792. He discussed the meaning of this concept in the book "Medical Application of Geography". The term has come to be clearly defined as the medical description of the features in all regions in the world inhabited by humans (Tan 1994). Two branches have been developed in modern medical geography, namely ecological medical geography and health care geography. The former focuses on the spatial ecology of diseases and the geographical features of human health, while the latter centers on the geographical arrangements of health care resources (Tan 1994; Qi et al. 2013).

Before the middle 20th century, research in medical geography focused on the geographical prevalence and diffusion of infectious diseases, disease ecology and disease cartography. Since then the occurrence, prevalence and structure of diseases have clearly changed with the mercurial pace of global socio-economic development and the rapid progress of medical technology. The control of infectious diseases with biological origins has achieved great success, especially in the developed countries. Apart from the spatial distribution and control of established infectious diseases and endemic diseases research, medical geography gradually turned its attention to the relationship between the environment and common chronic diseases such as cancer, cardiovascular diseases, and diabetes, as well to special groups such as the elderly, new born with birth defects, and people with blood abnormalities along with the spatial distribution of their physiological characteristics (Tan 2004; Feinberg 2007; Novembre et al. 2008; Patterson et al. 2009; Yang et al. 2010a, b; Li et al. 2011; Qi et al. 2013). In addition, with the development of public service and social welfare systems in western countries since the middle 20th century, healthcare geography became a distinct focus of research, centering mainly on the rational geographical allocation of health care services and facilities and the degree of congruence between the spatial distributions of health care services and population demand for such services. Location-allocation models have been applied to analyze the differences in the spatial accessibility of health care services and the optimization of health care facility locations (Smyth 2008; Yang et al. 2010a, b; Rosenberg 2014).

Since the 1970s, as environmental pollution has worsened in many global localities, research on environmental health has dramatically increased. The methodology and protocols for the assessment of health risks caused by pollutants have greatly improved. The methods in traditional ecological medical geography have been applied to the study of the spatial distribution and relationships of pollutants and their health effects and/or health risks. Meanwhile, newly developed spatial analysis techniques and other refinements in geographical analysis have also been employed to assess the integrated effects of exposure to pollutants in the atmosphere, water, and soil (particularly in relation to crops) and their relationship to human daily activities, all in relation to physical environment where people live. The new methodologies have also been applied to study the environmental contributions to diseases and health at various scales (Liao et al. 2004). Since the 1980s, as concerns about global climate change have increased, its potential impacts on health and health adaptation have attracted more and more attention and been included in related research projects (Lafferty 2009). Topics addressed include the impacts of extreme weather events such as heat waves, floods and droughts, on human health; climate change and infectious diseases; climate change and urban heat islands; effects of air pollution and ozone depletion on human health; and the impact of climate change and land use/cover change on food production, human nutritional structure and health. Medical geographers have played important, at times even crucial, roles in the process of developing research topics and projects in these areas (Yang 2010a, b).

Since the arrival of the 21st century, along with the cultural turn in human geography and the emphasis on the concept of "place", medical geographers have focused more on how the socio-cultural environment of place affects human health (including mental health) and the spatial distribution of health care facilities. Researchers proposed to summarize these topics as a new emerging field of the "Geography of Health". Topics of major concern include health care utilization and accessibility by vulnerable populations, living environment and health, health status and environmental justice, and others (Chakrabarti and Fombonne 2001; Victora et al. 2003; Newell et al. 2004; Rosenberg 2014).

Modern medical and health geography in China began in the 1960s. Research in earlier times focused on the fields of endemic and infectious diseases and their environment. The publications "Atlas of endemic diseases and their relationship with environments in the People's Republic of China" (Tan 1990) and "Atlas of plague and its relationship with environment in the People's Republic of China" (Tan and Liu 2000) were outputs of this research. After the 1990s, Chinese medical and health geography has developed in many areas, especially those concerned with health risks of environmental pollution (Yang et al. 2010a, b).

21.1.2 Contributions by Scholars from Different Countries

Table 21.1 shows the progression of the research field of medical and health geography for researchers from China and foreign countries (regions) from 2000 to 2014. It can first be seen that environmental health geography has developed rapidly in the last 15 years. The overall number of articles and the number of highly cited articles published by researchers around the world have significantly increased. The number of articles, cited frequency and highly cited articles were highest from the USA. However, from the periods of 2000–2004 to 2010–2014, those proportions dropped from 34.9, 40.8 % and 39.9 to 25.5, 30.0 and 33.6 %, respectively. Although the total articles from the UK dropped from the second to the third in the world, cited frequency and highly cited articles still ranked second, higher than China. However, the proportions of those three measures from the UK dropped from 11.9, 14.5 % and 15.0 to 7.2 %, 10.8 and 11.6 %, respectively. At the same time, compared to developed countries, the status of the medical and health geography in China was continuing to ascend. From the periods of 2000–2004 to 2010–2014, the total number of articles published by Chinese researchers increased by a factor of 15, from 95 to 1403. The proportion of total articles at the international level increased from 3.2 to 12.2 % and the ranking improved from the eighth to the second. The total article citations increased from 3152 to 6825, with a ranking improved from the eighth to the third. The proportions of cited articles increased from 2.3 to 9.5 %. "Highly cited articles" (SCI/SSCI citations >50 times) increased from 8 in 2000–2004 to 34 in 2005–2009 and to 58 in 2010–2014, while the proportion of highly cited articles increased from 2.0 to 9.7 % and the ranking improved from the seventh to the third. Based on the above data, with the increase of science and technology inputs in China, the research achievements of medical and health geography in the country improved rapidly and their influence was greatly enhanced. However, the relatively low number of "highly cited articles" from Chinese researchers suggests that the international academic influence of Chinese medical and health geography can still be further improved.

21.1.3 Key Research Topics

In order to analyze the prominent research in medical and health geography in the last 15 years, the 20 most commonly used words in SCI/SSCI-indexed articles for each year from 2000 to 2014 were employed in a cluster analysis. The result is depicted in Fig. 21.1. More clustered areas of the circle reflect the more frequent use of the words. The warmer colors

Table 21.1 Top 20 countries (regions) with the number and citations of SCI/SSCI-indexed articles on "Medical and Health Geography" during the period 2000–2014

	Number of articles						Cited frequency						Number of highly cited articles					
	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014
Rank	World	472	2,365	3,002	6,369	11,520	World	23,676	934	138,139	176,425	71,730	World	77	1	393	513	601
1	USA	172	552	1,049	1,918	2,973	USA	10,482	303	56,385	58,724	21,482	USA	33	0	157	191	202
2	China	8	368	95	418	1,403	UK	3,577	64	19,963	18,079	7,773	UK	14	0	59	63	70
3	UK	66	140	358	588	831	China	176	110	3,152	10,081	6,825	China	0	0	8	34	58
4	Canada	49	121	238	473	708	Canada	1,824	54	8,832	12,764	4,036	Canada	6	0	28	41	28
5	Australia	19	84	102	225	479	Australia	951	30	5,184	8,062	3,162	Australia	4	0	19	24	25
6	France	16	82	73	192	392	France	430	34	2,571	4,627	2,602	Spain	1	0	7	9	22
7	Spain	7	94	57	184	391	Spain	469	40	1,982	4,228	2,335	France	2	0	8	11	18
8	Italy	11	74	81	171	336	Italy	389	23	2,596	5,169	2,158	Germany	3	0	15	22	16
9	Germany	10	60	112	185	318	Germany	777	14	5,513	6,057	2,038	Italy	1	0	10	20	16
10	India	4	48	50	115	265	Switzerland	734	17	2,936	5,882	1,555	Switzerland	1	0	6	7	16
11	Taiwan, China	1	43	29	130	203	India	418	11	1,787	2,370	1,209	Netherlands	3	0	10	11	13
12	Brazil	5	46	39	92	194	Netherlands	459	18	2,651	3,055	1,184	Belgium	0	0	3	3	8
13	Sweden	12	34	71	124	184	Sweden	566	13	4,562	3,655	1,085	Norway	1	0	2	3	8
14	Japan	11	20	68	125	183	Belgium	0	11	1,295	3,475	1,053	South Korea	0	0	0	3	8
15	South Korea	0	45	9	44	171	Japan	351	9	3,375	2,605	918	Japan	2	0	9	5	7
16	Netherlands	7	30	48	115	160	Taiwan, China	0	7	1,273	2,608	851	Sweden	2	0	19	11	6
17	Portugal	1	44	18	65	154	Brazil	96	6	1,177	1,529	749	India	1	0	4	7	6
18	Switzerland	11	26	56	106	152	Denmark	271	11	1,756	1,674	660	Taiwan, China	0	0	4	7	5
19	Belgium	0	30	37	88	139	Norway	269	3	777	1,390	599	New Zealand	0	1	2	7	5
20	Denmark	6	22	37	63	84	New Zealand	84	29	900	2,238	468	Denmark	0	0	3	5	5

Note Countries (regions) ranked by the number of articles, cited frequency and the number of highly cited articles during the period 2010–2014

indicate that the words emerged in later years. The figure reveals that research on medical and health geography has focused mainly on two fields in the last 15 years. One is the geography of health research, which has centered primarily on population health. Foci of attention include geographical distribution, accessibility and social impact factors of health and medical care resources—for instance, the relationships among space, neighborhood, community and socioeconomic status to health and health care—and relationships between the status of women and equitable health distribution. The other important focus has been the geography of environmental health. This can be divided into two subfields. One is the environmental behavior and toxicology of heavy metal and organic contaminants, and the other is the health effects of environmental contamination and environmental changes, including exposure, change in health status, mortality and risk assessment of air, soil and water contamination. In addition, GIS and remote sensing are widely applied in monitoring and simulation of diseases and health.

Research foci in medical and health geography has differed among countries in light of the variety of health problems encountered in each. For the USA and Canada, geography of health research has been the main focus, emphasizing relationships between chronic disease and lifestyle; medicine treatment and health service (e.g., medical services, health foods, physical training, and so on) of vulnerable populations impacted by their socio-economic characteristics; and cultural customs and spatial distance (including factors of geography, social, economy and culture) (Block et al. 2004; Lopez et al. 2006); as well as health effects of global change and global pollutants (Tong et al. 2000; Tchounwou et al. 2003; Fewtrell et al. 2004; Lafferty 2009; Selin 2009; Pan et al. 2010). Research in Africa and South America has focused primarily on the spatial distributions and influence factors of tropical disease and regional infectious diseases (Gryseels et al. 2006; Hotez et al. 2008; Hotez and Kamath 2009). China and other rapidly developing countries have generally focused on the toxicology, exposure and health risks caused by environmental contamination (Ikeda et al. 2000; Flynn et al. 2003; Wang et al. 2003; Luo et al. 2011), while India and Bangladesh have devoted much attention to endemic arsenic poisoning caused by exposure to high arsenic concentrations in drinking water (Haque et al. 2003; Hossain 2006).

In order to explore the changing pattern of prominent research in the last 15 years, more than 300 keywords of articles in the database were divided into 25 categories based on the research fields, and word frequency was analyzed for successive 5-year periods. The result is depicted in Fig. 21.2. This shows that the word frequency of those 25 categories in articles written by foreign researchers increased by a factor of 3–5. Growth was uniform by a factor of 2 for each 5-year period. This suggests that the foci of the research field in international medical and health geography have become increasingly experienced in the early 21st century. The word frequency in articles from Chinese researchers increased by 5–10 times, with some words increased at an even higher rate. Several research fields emerged in China for the first time. This is consistent with the results depicted in Table 21.1, suggesting that China has been catching up with the developed countries over the past 15 years. With respect to the identity of research fields, those in China were similar to the international pattern. However, research in China placed more emphasis on investigating environmental contamination, accumulation of contaminants in water, soil and plants, toxicology of exposure levels, and health risk. The international research community focused somewhat more on health outcomes, e.g., diseases and mortality.

21.1.4 The Role of NSFC in Supporting the Research on Medical and Health Geography

In order to analyze the contribution from National Natural Science Foundation of China (NSFC) to the research and development of medical and health geography in China, we identified 271 medical and health related programs from all geographical programs funded by the Department of Earth Sciences of NSFC in the last 15 years. The identified Programs included 1 Major Research Plan (MRP), 3 Major Programmes (MP), 1 National Science Fund for Distinguished Young Scholars (DYS Fund), 9 Key Programme (KP), 116 General Programme (GP), 113 Young Scientists Fund (YSF), 22 Funds for Less Developed Regions (LDR Fund) and 4 International Joint Research Programme. NSFC-funded programs, the proportion of articles by Chinese authors, and the proportion of the SCI/SSCI-indexed indexed articles with NSFC fund to that from Chinese authors, were calculated for each 5-year period from 2000 to 2014 (Table 21.2).

The results show that the number of the programs related to medical and health geography funded by NSFC increased substantially (by more than a factor of 10) from 18 during 2000–2004 to 198 during 2010–2014. At the same time, the amount of funds rose from 6200 thousand yuan to 125,720 thousand yuan, a 24-fold increase. The number of researchers who received funding from NSFC increased from 17 to 190 and the number of the funded institutions increased from 11 to 118. This indicates that although the amounts, intensity and the number of authors were increasing, few research groups were steadily funded for the long term. That is to say, few researchers focused on investigating the field of medical and health geography for extended periods. The number and proportion of articles in SCI/SSCI journals published by Chinese were continually increasing from 96 (3.2 %) in 2000–2004 to 1405 (12.2 %) in 2010–2014. Similarly, the number and proportion of articles

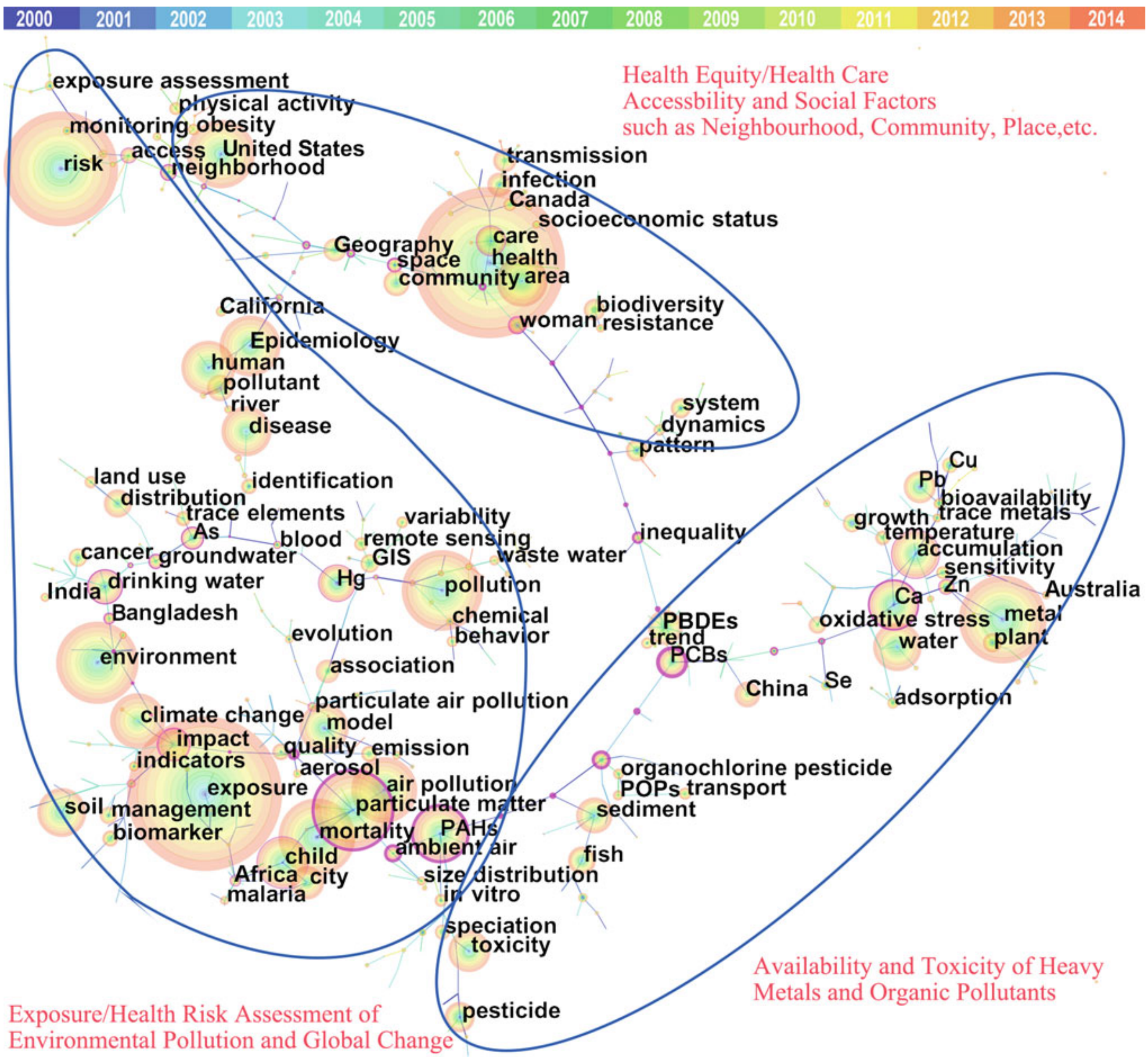

Fig. 21.1 Co-occurrence network of SCI/SSCI-indexed article keywords on "Medical and Health Geography" during the period 2000–2014

funded by NSFC to the total articles published by Chinese authors were increasing from 12 (12.6 %) to 899 (64.1 %). Although 32.6 % of these were co-funded by the Ministry of Science and Technology, it is reasonable to assert that NSFC has become the most important sponsor for medical and health geography research in China.

Because research on impacts of the geographical environment on human health involves multidisciplinary fields, the articles funded by NSFC mentioned above were supported not only by the Geographical Department, but also by other departments of NSFC. In order to analyze the related studies funded by the foundation's Geographical Department, 730 topic words from the titles, abstracts and keywords of the 271 NSFC Geographical Department funded projects were identified and classified into 19 groups, after which they were analyzed for each 5-year period. The results are depicted in Fig. 21.3. Comparing Fig. 21.2 with Fig. 21.3, it can be seen that some topic words from NSFC Geographical Department funded articles—including health and health risks, diseases, environment and environmental pollution, exposure, physical geography and climate change, human environment and habitat, and GIS and models—were also topic words for the international articles, showing that the research fields of NSFC Geographical Department funded projects were in accordance with those of articles published by foreign and

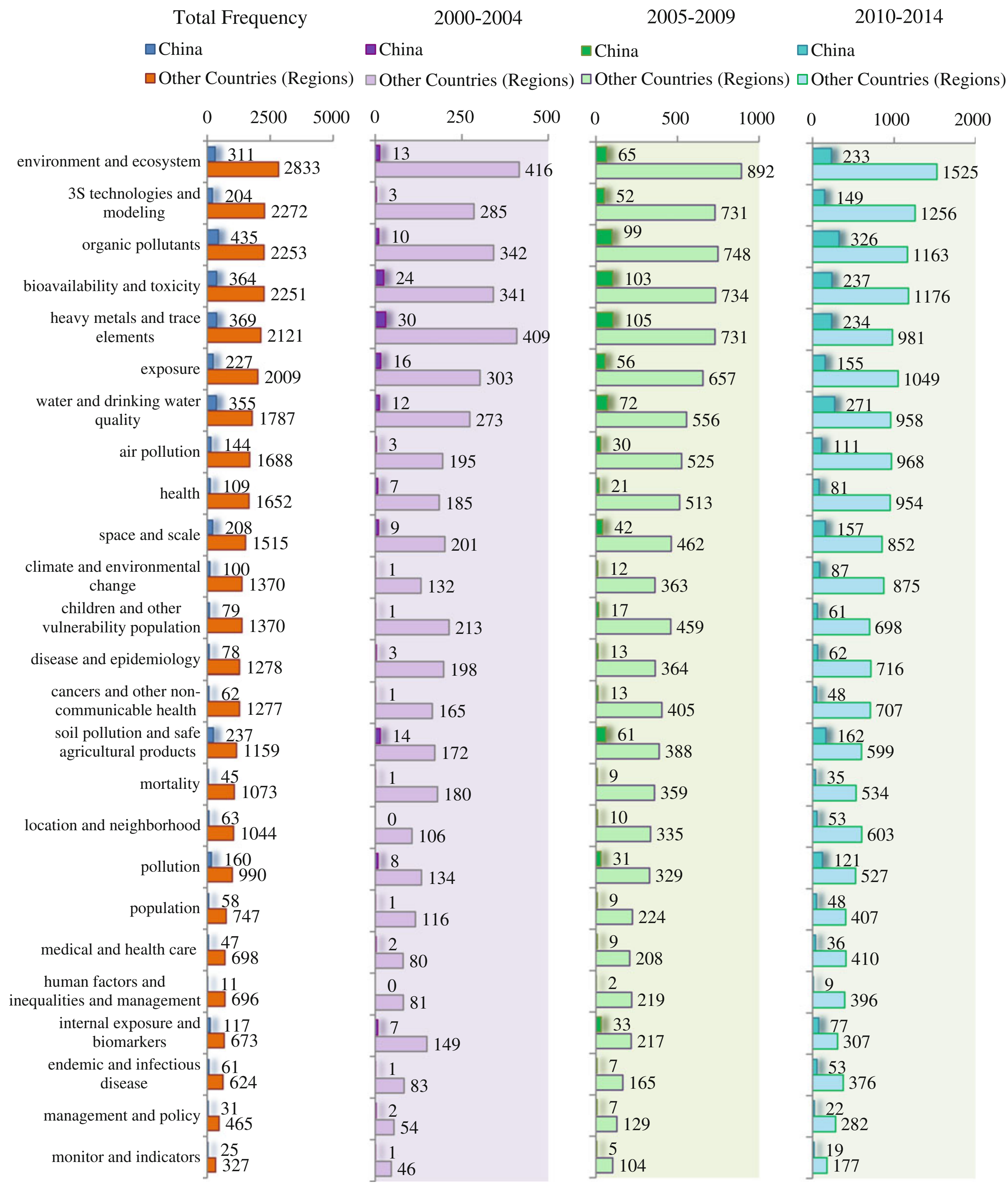

Fig. 21.2 Keyword temporal trajectory graph for SCI/SSCI-indexed articles on "Medical and Health Geography" during the period 2000–2014

Chinese authors. Moreover, they were also consistent with the developmental pattern of international medical and health geography in this century.

From a temporal perspective, prior to 2004 the projects funded by NSFC focused mainly on the research areas of endemic and infectious diseases, behavior and toxicology of

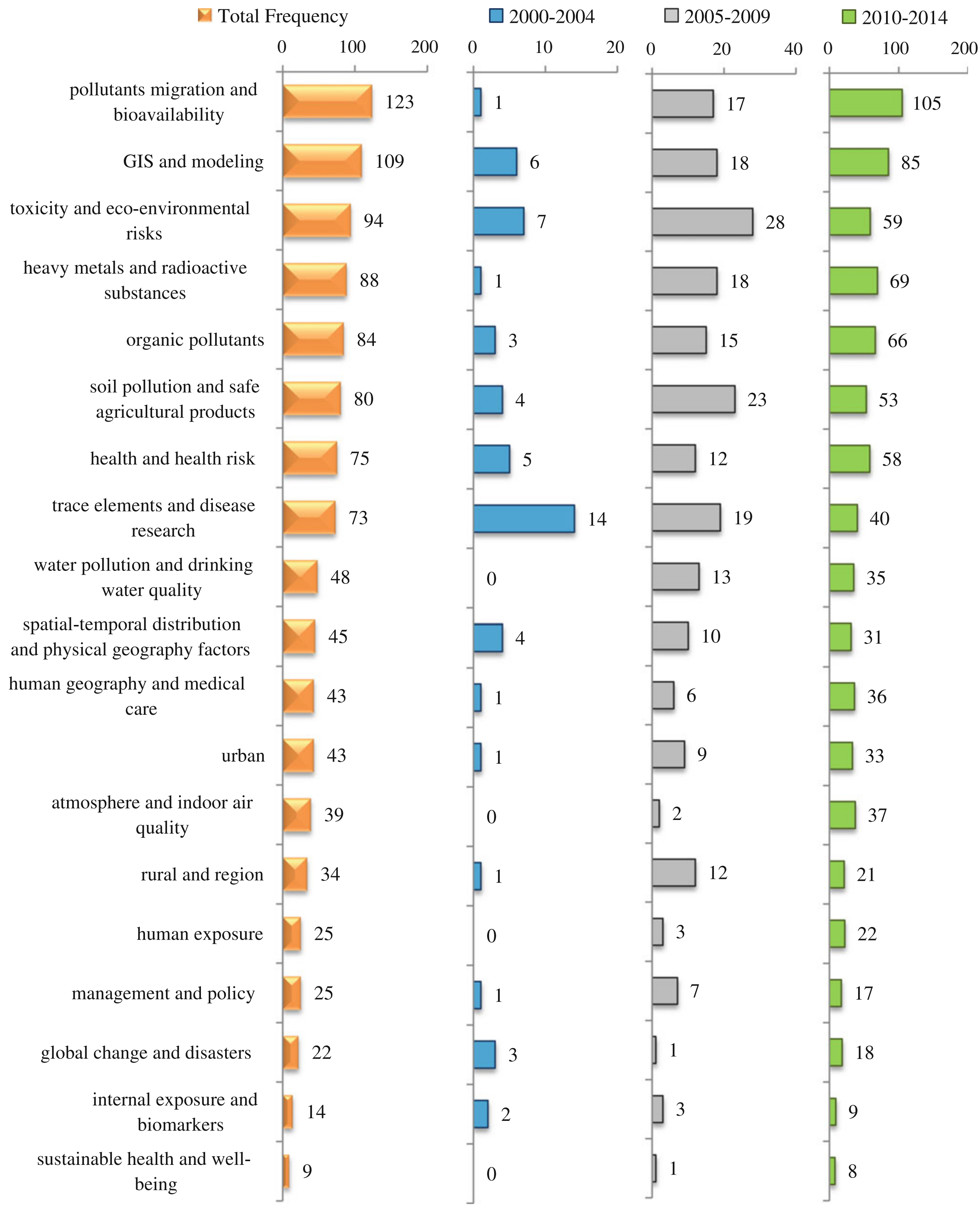

Fig. 21.3 Keyword temporal trajectory graph for NSFC-funded projects on “Medical and Health Geography” during the period 2000–2014

Table 21.2 NSFC-funded projects and SCI/SSCI-indexed articles on "Medical and Health Geography" during the period 2000-2014

SCI/SSCI-indexed articles					NSFC-funded projects			
Periods	Number of articles	% of articles by Chinese authors	% of articles with NSFC funding by Chinese authors	% of articles funded by MOST among those with NSFC funding	Number of projects	Funding (10,000 yuan)	Number of PIs	Number of institutions
2000-2004	3,002	3.2	12.6	0.0	18	620.0	17	11
2005-2009	6,369	6.6	29.6	31.5	55	2,098.0	54	34
2010-2014	11,520	12.2	64.1	33.2	198	12,572.0	190	118
2000-2014	20,891	9.2	54.0	32.6	271	15,290.0	239	130

environmental pollutants, and medical geo-information technology. During 2005–2009, funding increased dramatically for all the related fields, especially those focusing on the biological availability and toxicity of organic pollutants and heavy metals in soil and water. Since 2010, research foci including exposure to pollutants, health effects of air pollution, human factors and health care, the health risks of global change, sustainable health, human well-being, and health risk management, have received an increasing amount of funding from NSFC.

21.2 Research Advances and Problems

21.2.1 Bibliometric Analysis of Contemporary Research

From 2000 to 2014, a total of 20,891 articles were published around the world, 18,975 of which were published by foreign authors. Among the latter, 6673 articles contained 33 most-used keywords, accounting for 35.2 % of all articles published by foreign authors. Each of those keywords was found in more than 100 articles. Foreign scholars focused mainly on keywords such as air pollution, GIS, As, Cd, Hg, Pb, climate change, pesticide, remote sensing, PAHs, exposure, soil, and biomarkers. The research field of environmental pollution and health was very strongly represented according to the frequency analysis of these 33 keywords. There were 367, 297, 283, 256 and 189 articles for the keywords As, Cd, Hg, Pb and metal, respectively, accounting for 7.3 % of the international articles and 6.7 % of the total articles. For the keywords of pesticide, PAHs, PBDE and PCBs, there were 275, 242, 175 and 164 articles, respectively, accounting for 4.5 % of the international articles and 4.1 % of the total articles. With respect to environmental factors, foreign scholars attached great importance to air pollution. There were 404 articles using air pollution as a keyword, ranking first among all articles. For soil, water and groundwater, the number of the articles were 209, 126 and 124, respectively. With regard to the health consequences, foreign researchers focused on exposure (217 articles), biomarkers (199 articles), health (172 articles), mortality (46 articles) and toxicity (119 articles), as well as epidemiology (189 articles) and impacts on children/child (161 articles). GIS (374 articles, ranking second among all articles), remote sensing (253 articles) and spatial analysis were among the methods given the most attention. In addition, the number of articles with the keyword "climate change" soared to 277, ranking sixth among all articles. The number of the articles focusing on "neighborhood" in health geography and "malaria" in disease geography were 113 and 104, respectively.

21.2.2 Contemporary Research

Through analysis of the international literature, it was found that air pollution and health were very important, since the former was closely associated with asthma and other respiratory diseases, based on simulations and analysis of the spatial and temporal relationship between air pollution and hospital emergency and clinic visits and mortality. Increasingly clear evidence also implicated air pollution as an important factor inducing high morbidity rates of lung cancer in urban areas. Meanwhile, air pollution was recognized as an allergen which caused circulatory system disorders, reproductive system disorders and other diseases. It can also lead to excess morbidity and mortality and other serious health damages among vulnerable populations such as the elderly and the sick (Nyberg et al. 2000; Monn 2001; Jerrett et al. 2005; Kampa and Castanas 2008). Environmental health has always focused on investigating heavy metals due to their wide presence and multi-source exposure to humans in the environment.

Foreign researchers have given substantial attention to inhalation exposure to road dust and cumulative toxicity of heavy metals in water and sediment (de Mora et al. 2004; Birmili et al. 2006), as well as the relationships between different elements (Falnoga et al. 2000; Tully et al. 2000). However, China and other developing countries have paid more attention to the multi-pathway exposure routes of heavy metals, particularly regarding the transport of heavy metals in the soil-crops system and related agricultural food safety hazards, due to pollution caused by nonferrous metal mining, smelting and electronic demolition (Tong et al. 2000; Wang et al. 2003; Yang et al. 2004; Zahir et al. 2005; Feng et al. 2007; Jarup and Akesson 2009; Luo et al. 2011). Endemic arsenicosis caused by high arsenic in drinking water has been widely found in India, Bangladesh, China, and several other countries since 1990. These countries have provided research sites for investigating the relationships between arsenic pollution and health. Numerous studies have clearly illustrated the speciation, toxicity and metabolic characteristics of arsenic, the internal and external exposure routes of arsenic, and its association with various cancers, systemic multi-system diseases and specific clinical skin damages (Yang et al. 2002a; Yang et al. 2002b; Haque et al. 2003; Chen and Ahsan 2004; Sun 2004; Ahsan et al. 2006; Hossain 2006; Argos et al. 2010; Wu et al. 2014). These results have greatly reduced the uncertainty regarding health effects caused by arsenic exposure.

Persistent organic pollutants, represented by POPs, have engendered worldwide concern owing to their global migration. In recent years, research has focused primarily on cumulative effects of some new pollutants—such as polychlorinated biphenyls (PCBs), polybrominated biphenyls (PBDEs) and fluorinated compounds—in aquatic food chains, as well as their exposure risk, and concentrations in blood (serum), urine and human milk (Voorspoels et al. 2004; Toms et al. 2007; Wu et al. 2007; Polder et al. 2008). In addition, acute and chronic toxicity, biological accumulation in milks and fruits, population exposure and biomarkers for dioxin, brominated dioxin and furans have also been widely investigated (Hahn 2002; Leung et al. 2007). Moreover, the content, exposure and health effects of pharmaceuticals, personal protective chemicals and natural hormones in solid waste, waste water, sludge and surface water have also been attracting increasing attention from researchers (Golet et al. 2002; Kolpin et al. 2002; Focazio et al. 2008).

Global environmental change, with climate change as its core, has directly and indirectly affected human health in many ways (Kovats et al. 2003; Ford et al. 2010). In the last 15 years, studies have mainly concentrated on excess deaths resulting from extreme heat and cold arising from temperature changes. In particular, excess deaths caused by a heat wave across Europe in 2003 attracted much attention from scholars in European countries (Webber et al. 2008; Fischer and Schar 2010). Mainstream research fields in climate change have also focused on the global diffusion of malaria, dengue fever and other infectious diseases related to changing climate; the relationships between globalization and climate change to the area expansion of local natural focus diseases; as well as new emerging infectious diseases (Mayer 2000; Hales et al. 2002; Hay et al. 2002; Snow et al. 2005; Ferguson et al. 2005; Ostfeld et al. 2006; Viboud et al. 2006; Ochiai et al. 2008; Ogden et al. 2008); and the diseases and death risks related to ozonosphere destruction in high latitude areas caused by large-scale greenhouse gas emissions and climate change (Fuhrer 2003; Levy et al. 2005).

In the field of health geography, the investigation of community had been enhanced. The general focus has been on spatial differences in the living environments of human communities, the health condition of residents, and their correlations, and the influence of living environment on health promotion (de Vries et al. 2003; Tanser et al. 2006; Kwan 2012; Rosenberg 2014). In developed countries, health geography has been particularly concerned with disease burdens imposed by the environment and the relationship between lifestyle and chronic diseases (Wolf-Maier et al. 2003; Fewtrell et al. 2004). Almost all diseases and health issues have a certain spatial scale (Richardson et al. 2013). The rapid development of 3S technology has provided an effective tool for data acquisition and spatial analysis by health geography researchers. The technology has been widely used to undertake spatial-temporal qualitative analysis and modeling of disease transmission, as well as to investigate spatial accessibility and optimal layout of healthcare facilities, urban planning, and community living conditions and their health effects (Rosero-Bixby 2004; Tanser et al. 2006; Leslie et al. 2007). The 3S technology has also been used to simulate and analyze the health impacts of climate change in combination with climate change models (Aspinall and Pearson 2000; Emberson et al. 2000; Jerrett et al. 2001; Manel et al. 2001; Cromley and McLafferty 2002; Hochadel et al. 2006).

21.2.3 Bibliometric Analysis of Contemporary Research in China

From 2000 to 2014, Chinese scholars published 1916 articles in the aforementioned SCI/SSCI journals, accounting for 9.2 % of the total publications. There were 950 articles containing the first 35 most used keywords, accounting for 49.6 % of all articles. Every keyword was utilized in more than 13 articles. The main keywords employed by Chinese scholars were: PAHs, Cd, soil, PBDE, distribution, health risk, As, Hg, GIS, antibiotic, Pb, PCBs, and trace elements. For contaminants, there were 69, 30, 30, 22 and 19 articles containing the keywords Cd, As, Hg, Pb and metal, respectively, accounting for 7.9 % of the articles from Chinese authors and 0.7 % of the total articles. There were 82, 51, 24, 22 and 14 articles that utilized the keywords PAHs, PBDE, antibiotic, PCBs and organ chlorine pesticide, respectively, accounting for 9.7 % of the articles by Chinese authors and 0.9 % of the total articles. In terms of environmental media, Chinese scholars tended to pay more attention to soil pollution, drinking water and groundwater, with 57, 126 and 124 articles for these media, respectively. With regard to the health consequences, Chinese authors emphasized health risk (38 articles), exposure (18 articles), oxidative stress (17 articles) and biomarkers (14 articles). Regarding research methods, there were 28, 19 and 13 articles containing the keywords GIS, remote sensing and spatial analysis, respectively. Chinese scholars also devoted substantial attention to distribution patterns (48 articles), trace elements (22 articles) and selenium (21 articles).

21.2.4 Contemporary Research in China

Analyzing the keywords and highly cited SCI/SSCI-indexed articles published by Chinese researchers together with some publications in Chinese, we found that health risk assessment of heavy metals and organic pollutants was the major focus of research in China due to the severity of pollution in recent years (Tang et al. 2005; Qu et al. 2007; Deng et al. 2007; Tao et al. 2008; Hu et al. 2010). With respect to exposure pathways, health risk assessment of pollutants in the soil-food system was also a major focus of research. Specific topics to which attention was devoted included integrated exposure patterns of different crops (food), transport and transformation of pollutants in soil-plant systems, as well as associated health risks (Li et al. 2008; Luo et al. 2011). Research on the relationships between trace elements (e.g., selenium, iodine, fluorine, arsenic, etc.) and endemic diseases in the geographical environment in Western China continued to increase (Zhang et al. 2011; Shen et al. 2011; Wang et al. 2013). In addition, with the improvement and disclosure of monitoring data on diseases and the environment, the 3S technology has been increasingly applied to investigate spatial epidemic patterns of diseases, their pathogenesis and relationships with environmental factors, disease transmission and diffusion models, and disease surveillance and early warning protocols (Zhang et al. 2007; Cao et al. 2008; Liu et al. 2008; Zhou et al. 2008; Yang et al. 2010a; Li et al. 2012; Qian et al. 2014).

21.2.5 Contributions by Chinese Scholars and Subsequent Problems

Figure 21.4 shows the changes in keyword usage in articles published by foreign and Chinese researchers in SCI/SSCI journals from 2000–2014. It is evident that the interests of Chinese researchers were generally in accordance with those of foreign researchers. However, several differences were also observed. (1) Environmental pollution and health was

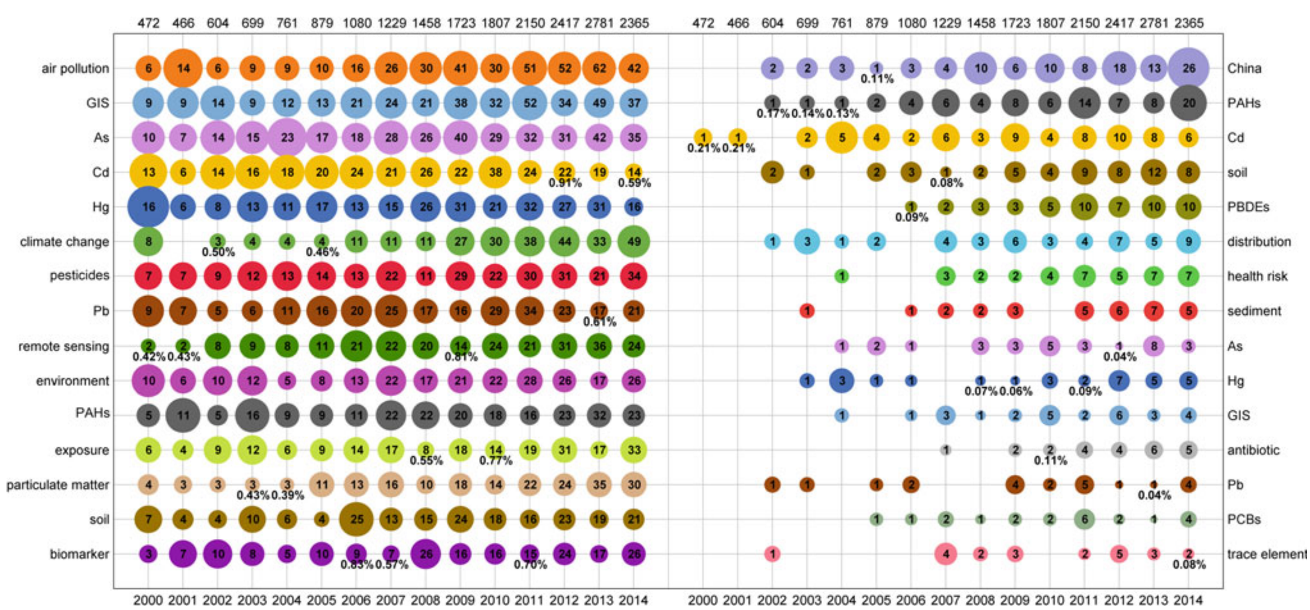

Fig. 21.4 Comparative diagram of prominent keywords on "Medical and Health Geography" by Chinese authors and others in SCI/SSCI-indexed articles during the period 2000–2014. *Note* Right panel shows keywords used by Chinese authors and left panel shows those used by the authors from other countries (regions). Size of circles denotes the ratio of a certain keyword frequency to the total article number in a specific year. The annual total number of articles is shown at the top of the diagram. The frequency of the keyword is shown inside the circle. The size of circles in the diagram for Chinese authors are magnified for clear display

the main research field of both foreign and Chinese scholars. However, Chinese scholars paid more attention to this field. (2) Both foreign and Chinese scholars focused on investigating contamination caused by heavy metals and organic pollutants, but Chinese scholars tended to devote more attention to the latter. Meanwhile, the studies from Chinese scholars were relatively concentrated on typical substances and typical regions, while the studies of health impacted by long time series and spatial-temporal analysis were insufficient due to the lack of large-scale and long-term monitoring data. (3) Among environmental media, foreign scholars placed substantial emphasis on air pollution, while Chinese scholars paid more attention to investigating soil and water pollution. (4) For health consequences, foreign scholars focused on exposure and health effects, while Chinese scholars were mainly concerned with health risk assessment. (5) Chinese scholars clearly lagged behind in studying the social and human factors related to diseases or health. Studies of community, neighborhood and social justice dimensions of environmental health issues were also lacking. (6) The sharing and disclosure mechanisms for Chinese researchers were unsatisfactory due to the diversity of data sources and management ownership issues, which ultimately restricted the application of geographic information technologies in the fields of medical and health geography. (7) Chinese scholars focused more on the relationships between disease and climate. Occasional studies considered potential responses to health results and how to cope with the health risks caused by climate change with a global vision.

21.3 Roadmap for Further Research

Population health has been given more attention by foreign geographers than Chinese geographers. Since the turn of the century, an increasing amount of scientific research has been concentrated on health threats posed by the global environment and globalization to local populations in Western developed countries, while in developing countries, with the exception of traditional geographical environment and health issues, local environmental health risks arising from industry and development have garnered more attention. With the attempt to understand and solve the ongoing environment and health problems occurring in connection with the social and economic transformation in China, research on medical and health geography has been developing rapidly and merging into the broader body of research of global medical and health geography studies. In the fields of endemic diseases, along with the impact of environmental pollution on health, Chinese scholars have been keeping pace with international research, but have not as yet given enough attention to human health in geographical research in general. In the future, Chinese medical and health geography should concentrate on the relationship among health, environment and development with the support of ongoing advances in modern geographic theory and techniques. In so doing it will even more effectively contribute to meeting challenges posed by national and international environmental change and development, in the process promoting both global health and a healthy China. Major research areas are listed as follows.

(1) Geographical Pattern of Health Hazards from Environmental Change and Environmental Pollution

Human beings, especially populations living in environmentally vulnerable areas, are facing threats of health damage, diseases and, for some, even ultimate survival caused by global climate change, environmental pollution and existing ecological imbalances. China is vulnerable and sensitive to environmental change, as well as to wide-ranging and long-term environmental pollution. The health-response has been an uncomfortable blend of hysteresis, chronicity and complexity. Medical and health geography should strengthen its research base by doing the following: (1) study the spatial relations between health/diseases and air, water, and soil pollution (and associated agricultural land use) in China and in the process identify areas sensitive to environmental health problems; (2) set up the parameters and models of long-term exposure and health effects through dynamic monitoring of local environment and disease patterns in various geo-ecosystems and geographic regions to ascertain health risks from exposure to pollutants potentially arising from multiple sources; (3) study the potential diffusion and spread of new diseases, identified at a global scale as potentially catastrophic to local populations, in geographic areas in China that are sensitive and vulnerable to environmental change; (4) study the health issues in urban areas impacted by both air pollution and climate change, and investigate ways to ensure drinking water safety and agricultural food safety in these times of great social and environmental changes in rural areas; (5) establish measures to improve the ability of the field of public health to address environmental change and environmental pollution; and (6) assess the health benefits from mitigating and effectively adapting to climate change and environmental pollution.

(2) Population Health Response to Socio-Economic Changes

With development of social economy and urbanization, humans have higher expectations for health and health care. However, the effects on human health and diseases impacted by aging, changing population structures, lifestyles and food nutrition have become more and more obvious. The transmission of emerging and reemerging infectious diseases from local to global populations will be more rapid and complex, and health threats from trans-boundary diffusion of unknown pathogens, pollutants and chemicals will tend to be more uncertain. Health care gaps between the rich and poor (people, regions, countries) are hard to remedy within a short time frame and the demands for social, environmental and health justice from the people living in poverty-stricken areas and environmentally vulnerable regions are more urgent. In the coming years in China, with the promotion of new urbanization, adjustments in economic structures, industry transfers, ecological civilization construction, implementation of new environmental protection measures, reform of the household registration system, implementation of a new medical insurance system, and countless other economic and administrative events, great changes will take place in population structure, migration patterns, life styles, and work and residential environments. Medical and health geography should strengthen research related to humans in geographic settings by undertaking the following: (1) studies on the differences and changes in disease patterns and health demands between urban and rural areas, and among different regions; (2) research on individual and population health behaviors at different scales, e.g. urban or rural settings, communities, building areas, families, etc.; (3) research on health and healthcare accessibility, equality and efficiency in different populations; (4) research on disease transmission and health issues triggered by population migration, trade, and tourism; (5) research on health effects of trans-boundary diffusion of chemicals and pollutants, as well as trade barriers to medicine and hygiene products; and (6) research on health issues for the elderly, elder care, environmental exposure of vulnerable elderly populations, and the nutrition and health security of children in poverty and environmentally fragile areas.

(3) **Balance and Regulation of Regional Health, Environment and Development**

In China, population health displays obvious geographic differences due to regional imbalances in socio-economic development and regional variations of the natural environment. Medical and health geography should focus on the spatial distribution of regional differences in major health indices and morbidity/mortality of diseases from national to local scales. This will require research on: (1) the relationship of the above foci to environmental health and regional development activities; (2) comprehensive health effects of physical geography, ecological landforms, pollutant emissions, regional environmental quality, social and economic development, cultural diet habits and adequacy of health care systems; (3) geographical regionalization of human health in China, and allocation of health or environmental protection resources in different health zones; (4) control of diseases and health promotion and risk reduction in areas with abnormal health conditions through ameliorating environmental threats and developing regional economies; and (5) regional human longevity, exposure to harmful materials emanating from the natural environment, and the geographical prevalence and control of endemic new or recurring infectious diseases.

21.4 Summary

In Western Countries, medical and health geography is an important branch of the geographic sciences. Its rapid development over the past 15 years reflects a broadening of the focus of traditional medical geography to encompass the spatial distribution, including environmental influences, of the health status and provision capabilities of human populations. On the one hand, new concepts and theories in human geography, such as space, place, landscapes, and scales, and new qualitative methods including interviews, focus groups, participant observation and photo voice, have been applied to the study of health care utilization behavior and accessibility of vulnerable groups including the elderly, children, the disabled, minorities, immigrants, and people with certain diseases, as well as those who live in remote and/or rural areas, and urban slums. In addition, *concepts* in epidemiology such as exposure, disease burden, disability adjustment life years (DALY), the *theories and methods* such as risks, vulnerability, and adaptation in climate change and disasters, and *new technologies* such as geographical information and remote sensing technology, modeling simulation, gene technology, and risk assessment technology, have been applied in research on the geography of health to study the impact of environmental pollution and environmental and socio-economic changes on population health and disease prevalence at global, national and regional scales, as well as global disease prevention and health promotion in the context of globalization and global environmental management.

Research in medical and health geography in China has continued for nearly half a century and has made great contributions to the control of endemic diseases and the prevention of environmentally-induced health problems. Since the turn of the century, the theories and technologies in medical and health geography have played an increasingly significant role in disease surveillance and environmental health risk assessment in China. However, Chinese research on environmental health issues at global, national and regional scales has been limited, especially from the perspectives of human geography. In addition, existing studies have been quite scattered and dispersed in various research fields, while being funded by several administrative departments, as well as different divisions of NSFC. There is a lack of stable support and teaching/research teams. Therefore, we strongly recommend that NSFC and other related administrative departments continuously recognize and enhance research in medical and health geography. We also advocate that universities and institutions with geography teaching and research units devote more efforts to strengthening medical and health geography and improving the teaching and training of professionals in this field, in order to meet the health demands of the nation's citizens and the strategy of Health China. In this way, we can also further enhance the research status of Chinese medical and health geography in the world.

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International Rivers and Transboundary Environment and Resources

22

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Abstract

Since new century, transboundary issues on resource, environment, and ecosystem in international rivers have become the hot topics of interdisciplinary researches in Geography, Ecology, Geopolitics, etc. Relative studies focus on not only the frontier scientific problems but also on practical sensitive issues, which need extensive and in-depth international and domestic cooperative studies. Although the developed countries overall takes the leading role, China has made substantial progresses in some fields, funded by NSFC and other national research programs. Relevant studies have supported rational development and management of international rivers in China.

Keywords

International river • Transboundary water resources • Transboundary ecosystem • Transboundary eco-security • Geo-cooperation and globalization

A total of 3474 SCI/SSCI-indexed articles are analyzed in the research area of international rivers and transboundary environment and resources. Articles were identified from 127 international journals from 2000 to 2014. The number of journals that have published more than 15 of the relevant articles is 62 (Appendix S). The search query is as follows: "international river*" OR "trans*boundary river*" OR "shared river*" OR "trans*boundary water" OR "trans*boundary basin*" OR "trans*boundary resource*" OR "trans*boundary eco*" OR "cross*border river*" OR "cross*border water" OR "cross*border eco*" OR "Awash River" OR "Congo River" OR "Zaire River" OR "Cuvelai River" OR "Etosha River" OR "Juba River" OR "Shibeli River" OR "Kunene River" OR "Lake Chad" OR "Lake Turkana" OR "Limpopo River" OR "Niger River" OR "Nile River" OR "Ogooue River" OR "Okavango River" OR "Orange River" OR "Ruvuma River" OR "Sabi River" OR "Senegal River" OR "Volta River" OR "Zambezi River" OR "Amur River" OR "Aral Sea" OR "Amu Darya" OR "Syr Darya" OR "Xijiang River" OR "Hsi River" OR "Ganges River" OR "Brahmaputra River" OR "Yarlung Tsangpo River" OR "Meghna River" OR "Har Us Nur" OR "Helmand River" OR "Ili River" OR "Indus River" OR "Irrawaddy River" OR "Jenisej River" OR "Yenisey River" OR "Kura River" OR "Araks River" OR "Mekong River" OR "Lancang River" OR "Ob River" OR "Irtysh River" OR "Oral River" OR "Ural River" OR "Red River" OR "Song Hong" OR "Salween River" OR "Nujiang River" OR "Nu River" OR "Tarim River" OR "Tigris River" OR "Euphrates River" OR "Shatt al Arab" OR "Danube River" OR "Dnieper River" OR "Don River" OR "Elbe River" OR "Odra River" OR "Rhine River" OR "Rhone River" OR "Vistula River" OR "Wista River" OR "Volga River" OR "Colorado River" OR "Columbia River" OR "Fraser River" OR "Grijalva River" OR "Nelson River" OR "Saskatchewan River" OR "Rio Grande River" OR "St. Lawrence River" OR "Saint Lawrence River" OR "Yukon River" OR "Amazon River" OR "Essequibo River" OR "La Plata River" OR "Lake Titicaca" OR "Orinoco River".

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22.1 Overview

22.1.1 Development of Research Questions

Rivers that cross or form national boundaries are collectively called international rivers. Some international rivers flowing through two or more states are called transnational or multinational rivers, while some international rivers (lakes) separating two or more states are called boundary rivers (lakes). Earlier, international society normally paid attention to visible surface rivers and water resources of the international rivers, largely ignoring underground aquifers and groundwater resources. At the end of the 20th century, with more attention upon river ecosystem integrity and groundwater resources, the concept of international watercourse systems emerged. The international watercourse system concept refers to watercourse with components in different countries, including surface rivers (lakes) crossing or forming national boundaries, glaciers, as well as underground rivers and aquifers (UN 1997), and its connotation is broader than traditional international rivers.

With the changes in political boundaries and connotation of international rivers, its number significantly changed, increasing from 214 in 1978 to 263 in 2002 (Varis et al. 2008), among which 52 are multi-national rivers. International river basins cover about 45.3 % of the land surface of the Earth (excluding Antarctica), with transboundary water resources accounting for 60 % of global freshwater (Wolf et al. 1999; UN-Water 2008). Based on the data released by the United Nations at World Water Day in 2013 (UN-Water 2013), there are 276 international rivers and 200 transboundary underground aquifers (identified), involving 148 countries and 40 % of the world's population.

International rivers flow across political boundaries, which closely link the co-riparian country's resource development, geo-cooperation, environmental change and influence, transboundary ecological and geopolitical security, and make transboundary issues more complicated, sensitive and extremely hard to study at a basin-wide level.

The transboundary issues are mainly driven by climate change, land use and land cover change, building of cascade hydropower dams, and construction of road systems, international navigation, sloping land cultivation, and mineral exploration. Research on these issues requires interdisciplinary and international cooperation from the fields of hydrology, geography, ecology, meteorology, hydraulic engineering, risk management, politics, policy, and law. Since 2000, transboundary resource development and water disputes, environmental changes and ecological security have become key issues in numerous regional conflicts. In recent years, the ongoing regional conflicts in water-short regions, such as the Middle East, North Africa, Central Asia, and South Asia, show that transboundary water security has become a fundamental and strategic issue for regional sustainability. The *2015 World Economic Forum* indicated that the biggest challenge in the next decade will be the water crisis, and the second will be water disputes and related intensified geo-competition between neighbors. Therefore, the rational utilization, cooperative protection and management of international rivers is required to ensure regional food, water and ecological security.

The study of international rivers and transboundary environment and resources mainly involves six major scientific issues (Wolf 2009; Hennig et al. 2013; Wouters and Chen 2013; He et al. 2014b): (1) background resources and environments; (2) hydro-ecological processes; (3) effect and influence of water environment change; (4) water rights and water allocation; (5) river health, ecological compensation, and coordinative management; and (6) geo-cooperation and geo-security.

22.1.2 Contributions by Scholars from Different Countries

This section analyzes the number of articles on international rivers published in English journals and their citations. A total of 3474 SCI/SSCI-indexed articles were published from 2000 to 2014 in the world. In the past 15 years, the total number of research articles on international rivers has significantly increased, rising by 69 % from 643 during the period 2000–2004 to 1094 during the period 2005–2009, and the number of articles (1737) published during the period 2010–2014 was nearly equal to the number of articles published during the former two periods (Table 22.1).

According to the number of published articles by country during the period 2000–2014, the top 20 countries have published about 80 % of the articles. The USA, China, Canada, Germany and the UK have published around 60 % of the articles. The USA ranks first with 1107 published articles, accounting for about a third of the total number of publications. China ranks second with 360 published articles (10.36 %), followed by Canada, Germany and the UK. Table 22.1 also shows that the number of articles on international rivers published by Chinese scholars increased rapidly, and the rank jumped from eleventh in 2000 to second in 2014.

However, during the periods 2000–2004, 2005–2009 and 2010–2014, the average number of citations of articles published by other scholars is respectively 28, 18.6, and 4.9, while, for the articles published by Chinese scholars during the same period, the average number of citations is only 20.5, 10.6, and 3.5, respectively. In terms of the total number of citations, China ranked third in the world from 2000 to 2014, accounting for 5.54 % of the total citations. The total number of citations of the articles published by the US

Table 22.1 Top 20 countries (regions) with the number and citations of SCI/SSCI-indexed articles on "International Rivers and Transboundary Environment and Resources" during the period 2000–2014

	Number of articles						Cited frequency						Number of highly cited articles					
	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014
Rank	World	112	324	643	1,094	1,737	World	3,838	105	18,008	20,300	8,459	World	16	0	58	64	95
1	USA	42	88	255	352	500	USA	1,635	32	9,340	8,068	3,101	USA	7	0	35	29	41
2	China	2	37	25	120	215	Canada	328	13	1,466	1,417	900	Canada	0	0	2	4	8
3	Canada	16	28	67	96	154	China	9	7	515	1,303	775	China	0	0	1	2	8
4	Germany	5	15	30	49	89	Netherlands	194	2	562	562	444	Netherlands	1	0	3	2	6
5	UK	9	17	20	52	64	Germany	286	5	1,032	989	381	UK	2	0	2	6	5
6	France	6	11	35	42	62	UK	289	7	512	1,396	324	Germany	2	0	5	4	4
7	Netherlands	2	8	12	31	54	France	214	3	885	742	268	France	1	0	2	2	3
8	Russia	1	8	4	29	42	Australia	16	2	74	1,172	193	Brazil	0	0	0	2	3
9	Japan	4	8	13	35	34	Brazil	0	0	243	444	171	Italy	1	0	1	1	2
10	Poland	3	7	25	24	33	South Africa	0	2	61	144	157	Sweden	0	0	0	0	2
11	Australia	1	7	7	25	33	Japan	46	2	133	235	149	Spain	0	0	1	2	1
12	Brazil	0	1	8	11	28	Switzerland	347	2	606	362	130	Australia	0	0	0	3	1
13	India	3	6	11	9	27	Italy	70	4	85	213	113	Denmark	0	0	1	0	1
14	Switzerland	2	5	8	17	26	Finland	0	2	93	82	113	Singapore	0	0	0	1	1
15	Romania	0	7	4	4	21	Denmark	0	0	205	70	92	Japan	0	0	0	0	1
16	Spain	1	5	5	15	18	India	40	0	157	163	62	South Korea	0	0	0	0	1
17	Finland	0	4	6	5	17	Spain	16	5	143	390	52	Taiwan, China	0	0	0	0	1
18	Austria	3	7	6	9	16	Austria	67	1	134	186	42	Belgium	0	0	0	0	1
19	South Africa	0	5	5	10	16	Poland	60	0	324	271	41	Switzerland	1	0	2	1	0
20	Sweden	1	4	3	9	13	Norway	81	0	85	182	36	Norway	1	0	1	2	0

Note Countries (regions) ranked by the number of articles, cited frequency and the number of highly cited articles during the period 2010–2014

scholars (20,509) is nearly eight times that by Chinese scholars (2593). Viewing the number of highly cited articles during the last 15 years, only 11 highly cited articles were published by Chinese scholars, compared to 105 and 14, respectively by American and Canadian scholars. These numbers demonstrate that, in terms of academic influence, "International Rivers and Transboundary Resources and Environment" research in China still obviously lags behind the leading countries, especially the USA.

22.1.3 Key Research Topics

The keywords of the 3474 articles that were retrieved have been analyzed in order to describe main themes and development tendencies of the field of International Rivers and Transboundary Environment and Resources in the recent 15 years.

Based on the keyword clustering (Fig. 22.1) of the 3474 articles, six research topics were identified. The first topic focuses on the impacts of climate change on water resources of international river basins; the keywords include climate change, water resource, climate variability, impact, etc. The second topic deals with hydrological and meteorological factors; the keywords include precipitation, rainfall, climate, and time series. The third topic involves hydrologic models and simulation; the keywords include model, simulation, calibration, prediction and uncertainty. The fourth topic explores cooperation and conflicts connected with transboundary water resources; the keywords include environment, resource, cooperation and conflict. The fifth topic relates to the effects of water resources and hydropower engineering; the keywords include water, dam, fish and restoration. The sixth topic is river sediment; the keywords include sediment, flow, channel, estuary, etc. The cluster analysis shows that the research themes of international rivers and transboundary environment and resources are relatively fragmented.

The keywords of the retrieved articles were further classified into 13 subjects based on their similarities. The classified subjects are as follows: hydrological and meteorological factors (including precipitation, air temperature, runoff, etc.); water use and water resources management (including water resource, water resources management, water use, water law, etc.); hydrological models and simulation (including hydrological model, simulation, model calibration, model parameters, etc.); ecosystems and ecological environments (including ecosystem, ecological economy, environment, wetland and aquatic lives, etc.); the water cycle and water balance (including surface water, underground water, water balance, evaporation, etc.); hydraulic and hydropower engineering (including dams, reservoirs, hydropower stations, etc.); soil (including soil

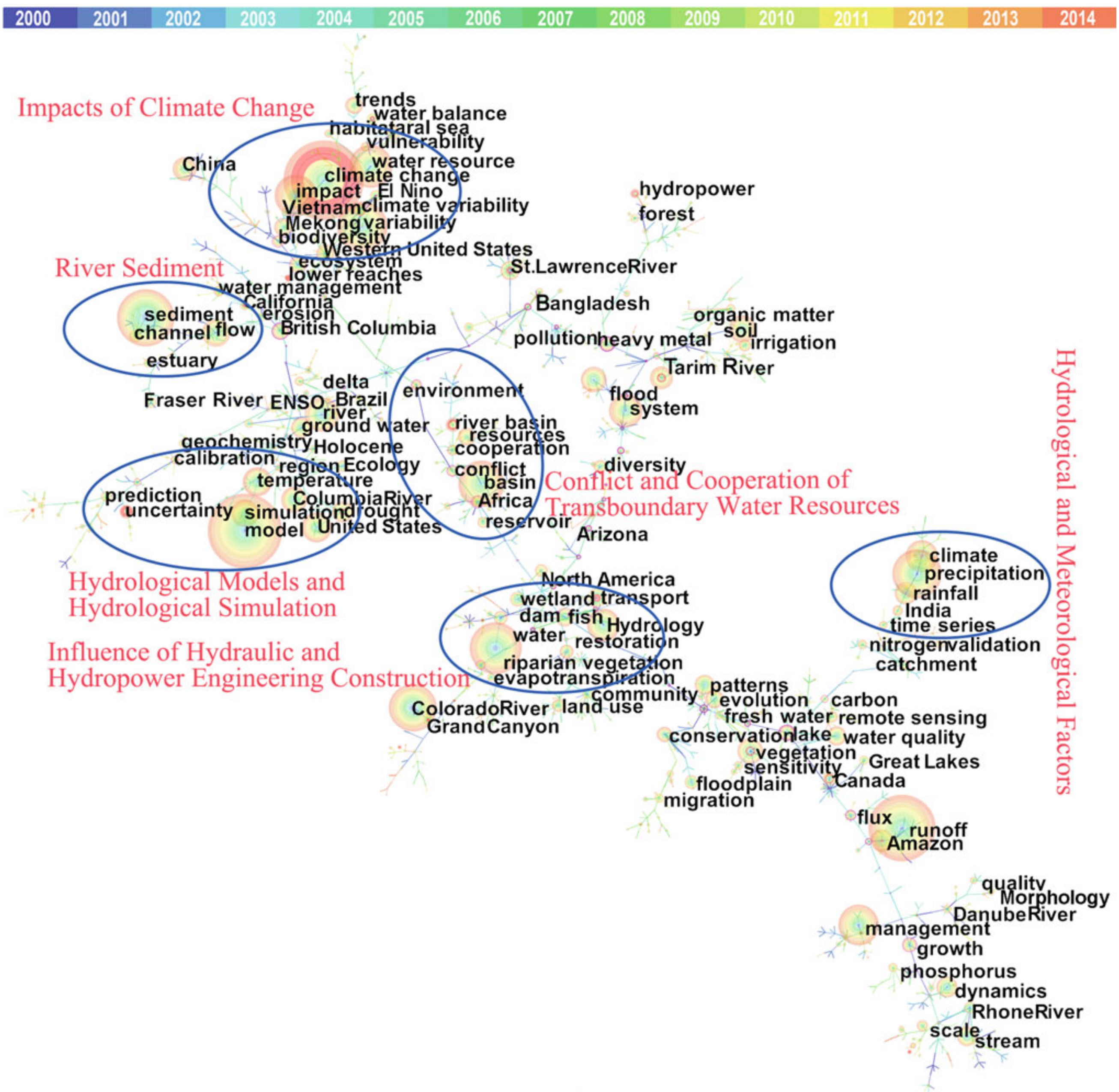

Fig. 22.1 Co-occurrence network of SCI/SSCI-indexed article keywords on "International Rivers and Transboundary Environment and Resources" during the period 2000–2014

chemistry, soil moisture content, soil property, etc.); river sediment and water quality (including sediment, deposition, water chemistry, water pollution, etc.); drought and flood (including drought, flood and other extreme hydro-climate events); remote sensing and geographic information technologies (including remote sensing, spectrum, MODIS, geographic information system, global positioning system, etc.); glacier, snow and permafrost; land use and landscape; and climate change.

Figure 22.2 presents the total frequency of keywords that occurred in each subject. The subject of hydrological and meteorological factors ranks first, reflecting that subject is the hot topic of international river study nowadays. Figure 22.2 also shows Chinese scholars paid relatively less attention than foreign scholars to "hydrological model and simulation", "drought and flood" and "water quality and sediment", but more attention to "water use and water resources management", "ecosystem and environment", "hydrological cycle

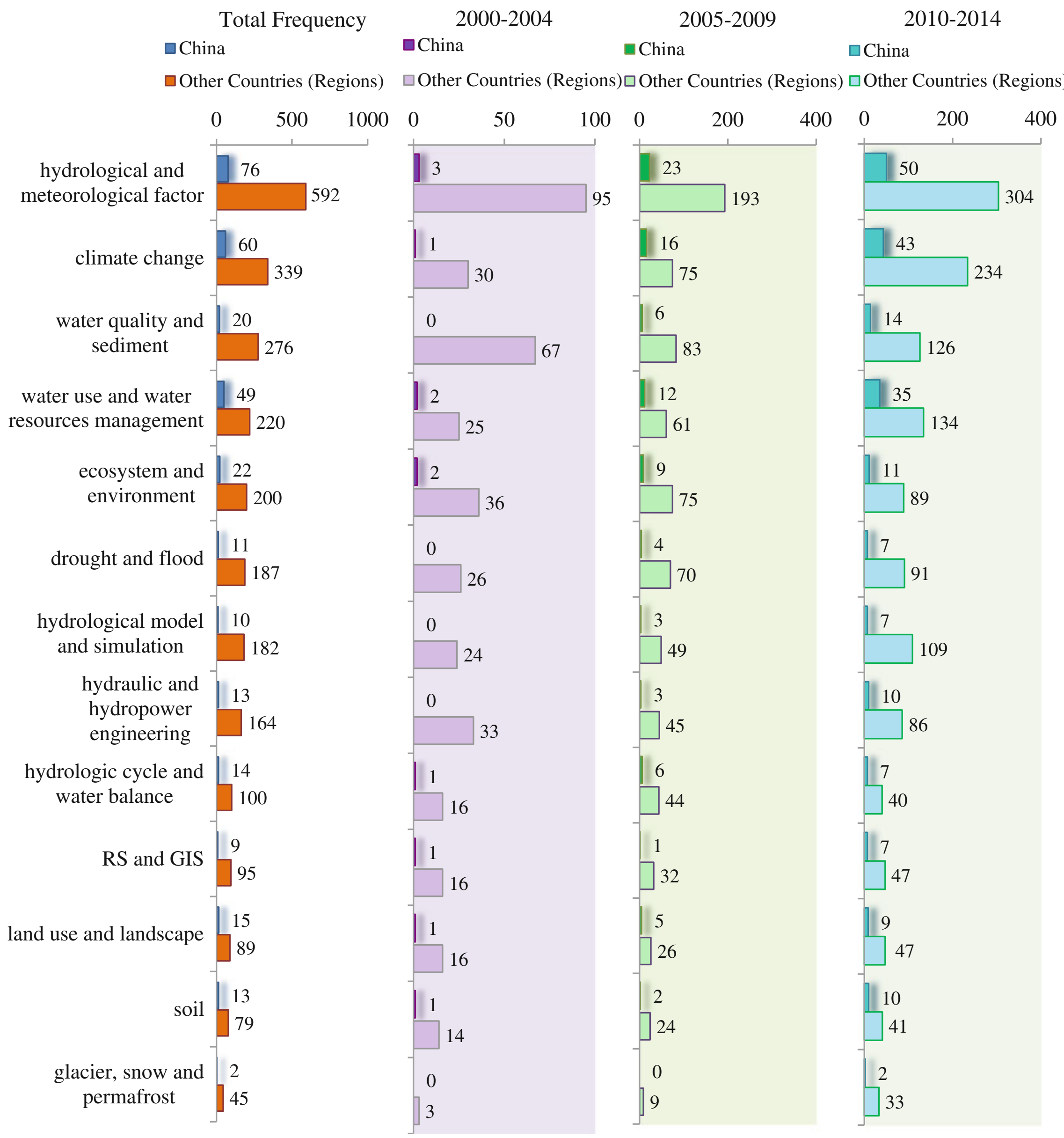

Fig. 22.2 Keyword temporal trajectory graph for SCI/SSCI-indexed articles on "International Rivers and Transboundary Environment and Resources" during the period 2000–2014

and water balance", "hydraulic and hydropower engineering", "land use and landscape" and "soil". As an upstream riparian country of most international river basins, "drought and flood" issues in the Chinese parts of these river systems are not serious. Hence, Chinese scholars paid less attention than foreign scholars to that subject, and the frequency only ranked tenth in articles published by Chinese scholars, compared to sixth among foreigner' articles. Generally, among the research themes of International Rivers and Transboundary Environment and Resources, "hydrological and meteorological factors", "climate change", "hydrological model and simulation", "ecosystem and environment" and "water use and water resources management" are common subjects internationally.

22.1.4 The Role of NSFC in Supporting the Research on International Rivers and Transboundary Environment and Resources

Figure 22.3 shows the frequency and change of NSFC-funded research for the 13 subjects during the period 2000–2014. Generally, projects and CSCD-indexed articles funded by NSFC

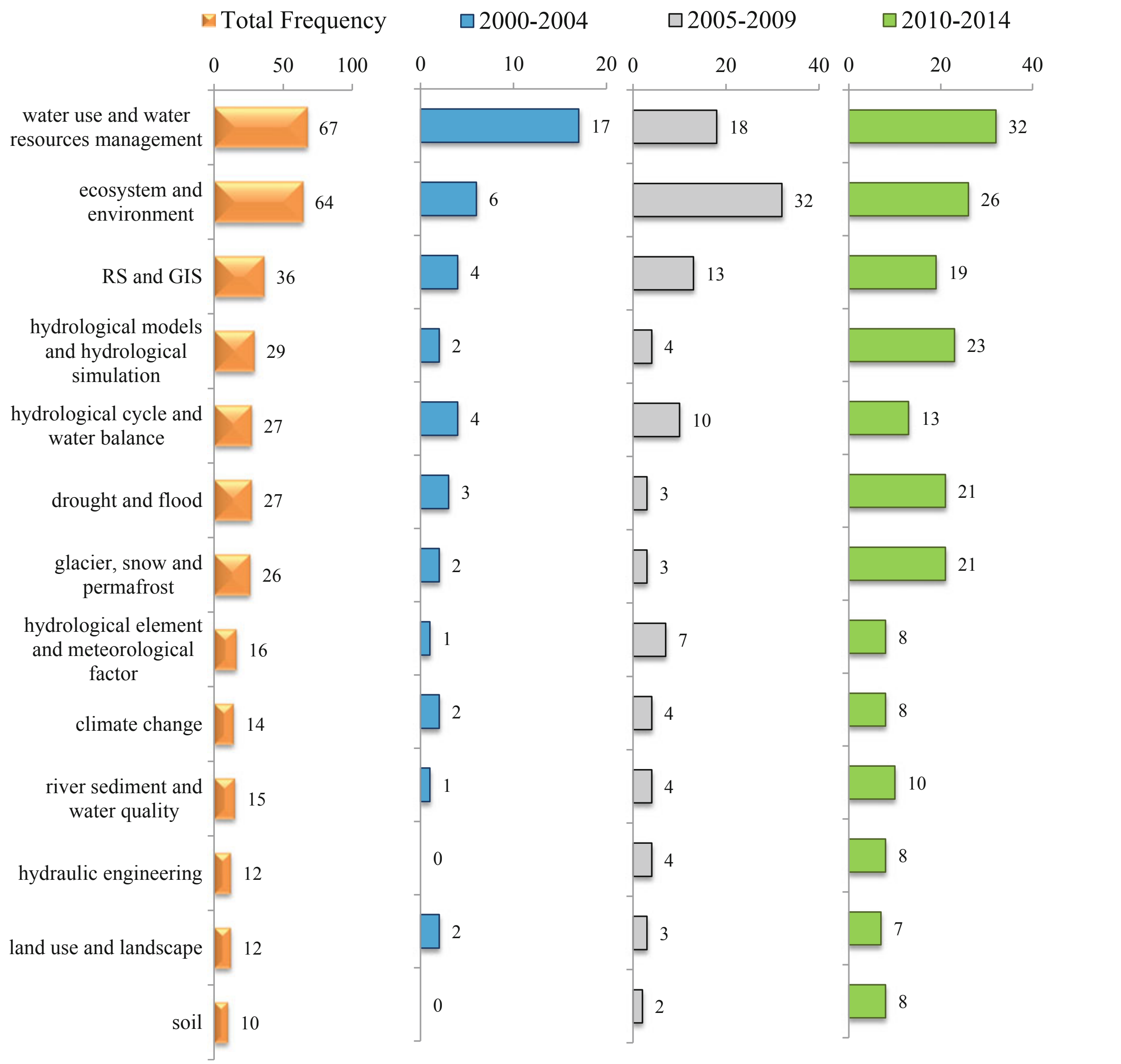

Fig. 22.3 Keyword temporal trajectory graph for NSFC-funded projects on "International Rivers and Transboundary Environment and Resources" during the period 2000–2014

rose for each research theme. For example, the frequencies of the subjects, e.g., hydrological model and simulation, drought and flood, and glacier- snow-permafrost, increased significantly from the period 2005–2009 to the period 2010–2014.

We found that the top issues tackled by NSFC-funded research (Fig. 22.3) are somewhat different from that of research of other countries (regions) (Fig. 22.2). The subject "hydrological and meteorological factors" ranked first for research of other countries (regions) but only eighth for NSFC-funded research, whereas the subject "water use and water resources management" ranked first for NSFC funded research, but fourth globally (Fig. 22.2). This suggests NSFC-funded research paid more attention to water resources management and related themes. Research of other countries (regions) paid more attention to "climate change" and "water quality and sediment" (ranked second and third in Fig. 22.2), whereas NSFC-funded research paid less attention to them (ranked ninth and tenth in Fig. 22.3). NSFC-funded research showed more interest in information and model techniques, such as "remote sensing and geographic information technology" and "hydrological model and simulation", which were ranked third and fourth, respectively. NSFC-funded research related to the ecosystem and environment has increased rapidly in recent years, indicating that eco-security issues of international rivers are getting more attention from Chinese scholars.

During the period 2000–2014, NSFC funded 117 projects in this field with funding reaching 54,986 thousand yuan,

Table 22.2 NSFC-funded projects and SCI/SSCI-indexed articles on "International Rivers and Transboundary Environment and Resources" during the period 2000–2014

SCI/SSCI-indexed articles					NSFC-funded projects			
Periods	Number of articles	% of articles by Chinese authors	% of articles with NSFC funding by Chinese authors	% of articles funded by MOST among those with NSFC funding	Number of projects	Funding (10,000 yuan)	Number of PIs	Number of institutions
2000-2004	643	3.9	20.0	0.0	11	468.0	11	8
2005-2009	1,094	11.0	51.7	17.7	37	1,512.0	36	17
2010-2014	1,737	12.4	76.3	47.6	69	3,518.6	65	26
2000-2014	3,474	10.4	64.2	38.5	117	5,498.6	99	35

which were chaired by 99 Principal Investigators (PIs) from 35 research institutions (Table 22.2). However, these 117 projects only account for 1.1 % of the total projects funded by Department of Earth Sciences, NSFC. The main difficulties are as follows. First, most international rivers in China are located in remote and undeveloped areas, where the former research basis is very weak. Second, the restrictions from State Secrecy Law makes it hard to obtain some basic data of international rivers for research and even prohibits publishing some research results in journals, which contributes to the low competitiveness of scholars in this field, considering the present evaluation system using SCI/SSCI-indexed articles. Third, only a few academic organizations and research teams conduct long-term research in this field, considering its high sensitivity.

Table 22.2 shows that 64.2 % of SCI/SSCI-indexed articles published by Chinese authors were funded by NSFC during the period 2000–2014. The percentage of NSFC funded SCI/SSCI-indexed articles by Chinese authors rapidly increased from 20.0 % during the period 2000–2004 to 51.7 % during the period 2005–2009, and to 76.3 % during the period 2010–2014. Meanwhile, the number of NSFC-funded projects and the total funding also increased rapidly, from 11 projects (4680 thousand yuan) during the period 2000–2004, to 37 (15,120 thousand yuan) during the period 2005–2009, and to 69 (35,186 thousand yuan) during the period 2010–2014.

In terms of the types of the projects funded by NSFC in this field, the Fund for Less Developed Regions (LDR Fund) and Young Scientists Fund (YSF) under Programmes of Talent Training, and General Programme (GP) under Programmes of Research Promotion increased significantly, while Major Programme (MP) and Key Programme (KP) under Programmes of Research Promotion decreased slightly during the period 2000–2014. The number of LDR Fund, YSF, GP, MP/KP awards during the period 2000–2004 was 3, 0, 4 and 3, respectively; then 7, 13, 12 and 3, respectively during the period 2005–2009; and 16, 22, 20 and 2, respectively during the period 2010–2014. In terms of the number of PIs (their host institutions) funded by NSFC, this increased from 11 (8) during the period 2000–2004, to 36 (17) during the period 2005–2009, and then to 65 (26) during the period 2010–2014. Totally, the number of PIs (their host institutions) reached 99 (35), indicating more and more researchers as well as their host institutions obtained NSFC funding to conduct research in the field of "International Rivers and Transboundary Environment and Resources".

In general, NSFC has played an important role in pushing forward the development of this field since 2000, but NSFC funding to this field is still low, notwithstanding the increases in the numbers of NSFC-funded projects, money and PIs during the past 15 years. More and more young scholars in this field were funded by NSFC. However, this field still needs more support from NSFC in the future.

22.2 Research Advances and Problems

22.2.1 Bibliometric Analysis of Contemporary Research

Figure 22.4 (the left part) shows the occurrence frequency of keywords of 3114 articles published by other scholars between 2000 and 2014. "Climate change" was the most popular keyword covered by 153 articles, accounting for 4.9 % of the 3114 articles by other scholars, suggesting that climate change is the most important topic in this field. "Flood" and "drought" were respectively included by 106 and 51 articles, showing that research of hydrometeorology hazards in international river basins is highly valued by non-Chinese scholars. "Sediment", "water resources" and "hydrology" occurred in 81, 73 and 66 articles, respectively. These have long been core research themes in this field. The transboundary effect of dam construction has gradually attracted more attention by scholars of this field, the

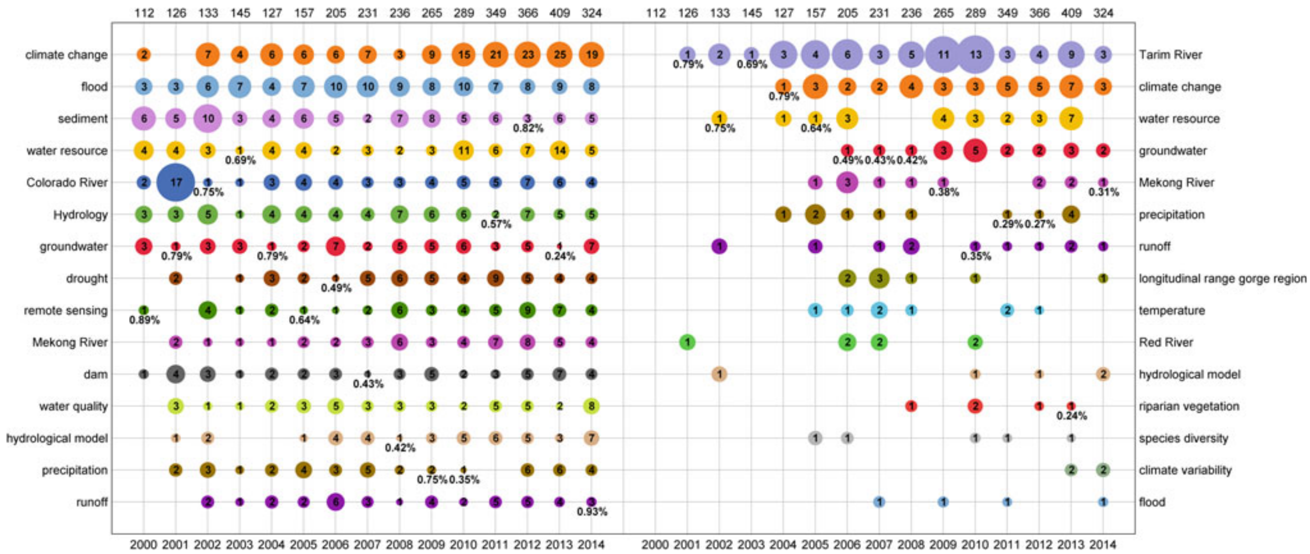

Fig. 22.4 Comparative diagram of prominent keywords on "International Rivers and Transboundary Environment and Resources" by Chinese authors and others in SCI/SSCI-indexed articles during the period 2000–2014. *Note* Right panel shows keywords used by Chinese authors and left panel shows those used by the authors from other countries (regions). Size of circles denotes the ratio of a certain keyword frequency to the total article number in a specific year. The annual total number of articles is shown at the top of the diagram. The frequency of the keyword is shown inside the circle. The size of circles in the diagram for Chinese authors are magnified for clear display

keyword "dam" appeared in 46 articles, accounting for 1.5 % of total articles, higher than some common hydrological research topics, such as "hydrological model" (1.4 %), "precipitation" (1.3 %), and "runoff" (1.3 %). The Colorado River (69 articles) and the Mekong River (49 articles) have been paid high attention by other scholars since 2000.

22.2.2 Contemporary Research

Generally, recent research in this field can be classified as follows. (1) The background of natural environments of international river basins. In recent years, a large number of research projects focused on the environmental backgrounds of international river basins, e.g., the changes to their hydrology and water resources. Data acquisition modes coupling conventional observation with new techniques (e.g. remote sensing) promoted rapid development of this field. (2) Hydrological modeling of international rivers. Hydrological models (especially the physically-based distributed hydrological models for catchments) with new data acquisition modes deepened the studies of hydrological cycles and processes in international river basins. (3) Hydro-ecological processes of international rivers and their responses to climate change and human activities. These works have emphasized the comprehensive and transboundary effects or issues from hydro-ecological changes at the scale of whole international river basin. (4) Allocation, utilization and management of transboundary water resources. Conflicts and cooperation for competitive use of transboundary water resources have been gradually incorporated into geo-political and geo-economic cooperation frameworks. It should be noted that transboundary groundwater resources have become one of the cutting-edge issues in this field, such as the spatial distribution of transboundary groundwater resources (De Stefano et al. 2010), and water allocation of transboundary aquifers (Dinar 2009). (5) Transboundary effects of disasters in international river basins. Disasters in international river basins, e.g. floods, droughts, environmental pollution and biological invasion, often result in obvious transboundary effects.

22.2.3 Bibliometric Analysis of Contemporary Research in China

Figure 22.4 (the right part) also shows the occurrence frequency of keywords of 360 articles published by Chinese scholars between 2000 and 2014. Clearly, "climate change" was also the most popular keyword covered by 38 articles, accounting for 10.6 % of all 360 articles. "Water resource" and "groundwater" were dealt with by 25 (6.9 %) and 20 (5.6 %) articles, respectively, followed by "precipitation" (12 articles), "runoff" (11 articles) and "temperature" (8 articles), indicating that Chinese scholars paid more attention to fundamental hydro-meteorological factors of relevant international rivers. The "Tarim River" was the most cited international river in China and dealt with by 68 articles, followed by "the Mekong Rivers", which was dealt with by 20 articles.

22.2.4 Contemporary Research in China

China is the most important upstream riparian country in Asia. The international rivers and relevant resources in China are crucial for China as well as all downstream riparian and some neighboring countries in Asia, which directly influences the geo-cooperation and geopolitical security between China and Southeast Asia, South Asia, Central Asia and Northeast Asia (He et al. 2014a). Since 2000, international river research in China has made good strides as follows. (1) Study of land surface pattern, regional differentiation and the ecological effects of international river areas. For example, for the study of the international river areas of Southwest China and the Indo-China Peninsula, He et al. (2005) put forward the concept of "the longitudinal range-gorge region (LRGR)" based on land surface pattern of regional mountain ranges and river valleys, and revealed functions and relevant effects of LRGR "corridor-barrier" (Pan et al. 2012; Hu et al. 2011; Feng and Li 2010). (2) Study of climate change and its impacts on relevant international river basins in China. Some studies explored the spatio-temporal patterns and the changing trends of precipitation and temperature in Southwest China, Northwest China and Northeast China, where most international rivers in China originate (Li et al. 2010a, 2012, 2015; Gu et al. 2012; Nie et al. 2012; Sun et al. 2010; Zhang and Li 2012; Xu et al. 2013); some studies revealed the impacts of regional climate change on the melting of glaciers and the snow and river runoff changes of international river basins in northern China (Deng 2012; Yao et al. 2010); Cao et al. (2012) identified the interface between the Indian summer monsoon and the East Asian summer monsoon; and Fan et al. (2013) analyzed regional climate change and potential driving factors in the LRGR region. (3) Studies of water pollution and water quality in international river basins. Earlier studies mainly focused on water environment quality assessment, e.g., Li (1999) assessed the water quality status of the Lancang River. Recently, the development of long-term water environment monitoring of international rivers promoted the research on water quality or environmental changes of international rivers (Li et al. 2010b; Fu 2012). (4) Studies of transboundary water resources. For the transboundary water resources of the international rivers in Southwest China, there were two representative books: "*The Reasonable Utilization and Management of Transboundary Water Resources*" and "*The Utilization of Transboundary Water Resources and Environmental Conservation of International Rivers in Southwest China*". (5) Studies of the hydropower influences on international rivers. Most studies focused on the Lancang-Mekong Rivers (He et al. 2006), e.g. the impacts of dams on the annual distribution and magnitude of river sediment loads (Fu et al. 2007, 2008), impacts of cascade hydropower on ecological environment (Yang et al. 2013) as well as the social and economic influences of large dam building on resettlement (Zhang et al. 2013).

22.2.5 Contributions by Chinese Scholars and Subsequent Problems

Through comparing the occurrence frequencies of keywords of the articles published by Chinese and other scholars, we analyzed the differences of research priorities (Fig. 22.4). Both Chinese and other scholars have paid high attention to "climate change" during the past 15 years. Scholars from other countries (regions) paid much more attention to "flood" than Chinese scholars. Most Chinese authors focused on hydro-meteorological factors of international river basins, such as "precipitation", "temperature" and "runoff", while other scholars focused more on changing trends of the "flood" and "sediment" phenomena associated with international rivers. Another difference was that other scholars paid more attention than Chinese scholars to the effects of dams on international rivers. Major reasons for this include: dam-related information on international rivers was hard to obtain for study, and research results related to dams on international rivers were sensitive topics for publication. Scholars from other countries (regions) focused on the Colorado and Mekong Rivers, while Chinese scholars were concerned more with the Tarim, Lancang-Mekong and Red Rivers.

Currently, China has 5 major issues in this field that need to be pushed forward. (1) The lack of information on the resources and environments of relevant international rivers at the whole basin scale, especially the parts outside of China. This makes it hard to assess the real transboundary effects of the development of international rivers. (2) Comprehensive research related to transboundary waters and eco-security is very weak. The lack of critical data (usually due to the secrecy or lack of transboundary cooperative studies) about the development of international rivers makes it hard to quantitatively analyze transboundary effects of human activities on the water environment, hydro-ecology and hydrological regimes of international rivers. (3) The lack of comprehensive research on transboundary resource and environmental issues at the national level and whole basin scale. It is urgent to push forward the study of some highly sensitive issues, e.g., water rights definitions, classification and water resource allocations of international rivers. (4) The weak study of cooperative management mechanisms for international rivers, transboundary resources and environment. (5) The lack of an open international vision for this field in China. Past studies by Chinese scholars mainly focused on the China part of relevant international rivers.

We need transboundary studies of China's international rivers at the whole basin scale and the study of other international rivers outside of China to learn from a broader range of experiences. It will also be important to publish relevant research results in this field to promote academic exchange and transboundary collaborative research.

22.3 Roadmap for Further Research

Nowadays, the world is stepping into a new era of geopolitics and geo-economics. The development vision of "the Silk Road Economic Belt" and "the 21st Century Maritime Silk Road" (also known as "the Belt and Road") will not only drive large-scale transboundary economic cooperation across Asia and Europe, but also promote comprehensive and geo-cooperative research on international rivers by China's geographers. This will push forward rapid development of relevant branches in Geography (e.g., Geopolitics). It will create the best opportunity to build international river research in the field of Geography.

In view of the long-term strategy of China, research of international rivers and transboundary environment and resources needs to focus on the following.

(1) **Comprehensive Study on Transboundary Environment and Resources in Geo-Political and Geo-Economic Cooperation Areas**

With the process of globalization, the fundamentals of geography, geopolitics and geo-economics will be more essential to support the ever-growing cooperative development among riparian countries of international rivers at regional and continental levels. A brighter future of research on transboundary resources and environment will require more and more international cooperation. Transboundary collaborative and comprehensive research will not only promote reasonable utilization, cooperative development and coordinative management of international rivers, but also strengthen the geopolitical, economic, diplomatic, scientific and technological cooperation among the riparian countries. Relationships of regional interest communities also will be formed and tied by cooperative research on fair and equal development, which will benefit support for sustainable regional development and security.

(2) **Linking the Study of Transboundary Water Security, Food Security and Energy Security**

Water security of international rivers is one of the most critical transboundary issues. Currently, international academia concerns have shifted from traditional water security to the security of the water-food-energy nexus. Transboundary water resources from international rivers in China are abundant, which not only contribute to China's important strategic water resource reserves and resource base for the construction of national hydropower development, but are also very essential for the sustainable development of downstream countries in Central Asia, South Asia and Southeast Asia. Equitable allocation, fair utilization, effective protection and coordinated management of transboundary water resources shared by China and relevant riparian countries are critical for maintaining regional security of food, water and energy, managing regional conflicts, and promoting geopolitical and geoeconomic cooperation. Joint research about the security related to transboundary water-food-energy nexus issues should pay more attention to the uncertainty of the water resources system, water rights, water resources allocation, comprehensive utilization and integrative management of water resources, transboundary conflicts management, transboundary ecological compensation mechanism, dynamics of transboundary aquifers, etc.

(3) **Comprehensive Study of Ecosystem Change Effects and Security Regulation in International River Basins**

The international rivers originating from China play very important ecological roles in Asia's eco-security. Ecosystem change in these transboundary river basins is driven by multiple interactions of monsoon systems, global change and regional human activities, including climate change, land use, hydropower development, mineral exploitation, international navigation, cross-border transportation system development, transnational oil and gas pipeline construction, etc. These activities have caused some negative impacts on the international river basins of China and sharing countries, e.g. landscape fragmentation, ecosystem degradation, transboundary biological intrusion, which directly threaten regional and transnational eco-security.

Therefore, we need to make full use of the advantage of comprehensive analysis and multi-interdisciplinary in Geography to study the topics such as pattern and function of transboundary ecosystems, environmental change and transboundary effects in land border areas, cumulative ecological impacts induced by hydropower development in international rivers. Also transboundary hydrologic and meteorological disasters, transboundary water pollution, biological transboundary invasion, and comprehensive regulation pattern and mechanism of transboundary ecological security should be studied further.

These researches should focus on international river basins, including the Heilong-Amur River, the Ili River, the Lancang-Mekong River, the Yuan-Red River, the Nujiang-Salween River, the Dulong-Irrawaddy River, the Aksu River and Irtysh River, the Yarlung Zangbo-Brahmaputra River, as well as the Aral Sea in Central Asia.

22.4 Summary

Research on international rivers and transboundary environment and resources is a multidisciplinary task. It is closely associated with state sovereignty and geo-security which are extremely complicated and sensitive. However, this field has become one of the hot fields in geography, ecology and environmental sciences since 2000. The cutting-edge research subjects of this field include the background environment and resources, the responses of hydro-ecological processes to climate change and human activities, reasonable utilization and coordinated management of transboundary water resources, comprehensive development and geo-cooperation in transboundary river basins, etc. Among these subjects, water rights and water resources allocation, eco-security, and transboundary groundwater are the most difficult research topics.

The achievements in this field have mainly come from research in developed regions like Europe and the USA, focusing on climate change and its impact on transboundary water resources, hydrological simulation, drought and flood, water quality and other problems. In China researchers paid more attention to water resource utilization and management, ecosystem and environment, the water cycle processes, water conservancy and hydropower development and its transboundary impacts. Although China has achieved rapid development in this field, some important issues need to be solved, e.g., fewer articles with high international influence, weak basis of fundamental studies, lack of open and international visions. With the stronger policy and financial support from national level in the future, geographers could carry out more cooperative projects at the scale of the whole transboundary basin, focusing on critical scientific issues of both the natural environment and human systems, water, ecology, food and energy.

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23 Records of Environmental Changes in Physical Geography

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Abstract

From the viewpoints of physical geography, river and lake terraces, glacial moraines, lake sediments, ice core, stalagmite, tree-rings, loess and paleo-soils, etc. provide broad materials and contain multi-proxies to reconstruct records of environmental changes. During past 30 years, Chinese scholars have achieved many progresses, such as pollen records from lake sediments in the Tibetan Plateau and northwestern arid areas, isotope records of ice cores, climatic factors derived from tree-rings, tectonic and climatic information and their relationships based upon natural sedimentary profiles. Part of them has produced widely international effects. For deeply developing the studies of records of environmental changes, it is important to enhance regional synthesizing, quantitative reconstruction, modern processes of proxies, new technologies for sampling and analyzing.

Keywords

Environmental changes • Proxies • Records • China • Further development

A total of 67,251 SCI/SSCI-indexed articles are analyzed in the research area of records of environmental changes in physical geography. Articles were identified from 89 international journals from 2000 to 2014. The number of journals that have published more than 15 of the relevant articles is 87 (Appendix T). The search query is as follows: "lake" OR "terrace" OR "moraine*" OR "aeolian sediment*" OR "limnology" OR "lacustrine" OR "ice core" OR "stalagmite" OR "sediment*" OR "tree ring" OR "dendroclimatology" OR "pollen" OR "isotope" OR "ostracod*" OR "biomarker" OR "proxies" OR "proxy" OR "alkane" OR "alkenone" OR "gdgts" OR "deposit*" OR "grain-size" OR "dating", "chronology" OR "environmental change*" OR "Holocene" OR "Pleistocene" OR "reconstruction" OR "paleo*" OR "glacier*" OR "timber line" OR "speleothem" OR "leaf wax" OR "geochemical*" OR "geochemistry".

23.1 Overview

23.1.1 Development of Research Questions

Physical geography is a discipline concerned with the Earth surface system and its components, with a research goal of understanding the natural environment of the Earth's surface. This research aims at acquiring and enriching knowledge regarding the characteristics, structures, mechanisms, dynamics and evolution regulations of the natural environment (Cai et al. 2009). Paleo-geography has been one of the most important subdivisions of physical geography since its inception (Zhou 1979). The relationship between physical geography and global change science has strengthened since the 1980s. As a core program of global change science, research on historical global change aims to reconstruct past

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climates and environments and infer response mechanisms of ecosystems to climate changes using key observational and proxy data from Earth's surface.

From traditional paleo-geography to rapidly developing research on historical global change, reconstructing the history of natural environments has always been a crucial task of physical geography from its inception to its modern development. Environmental records are concrete objective archives reflecting natural environmental changes. Therefore, obtaining correct environmental records and scientifically analyzing these records are important tasks for reconstructing natural environmental change histories and elucidating the genesis, processes, and tendencies of such changes.

Over the past 30 years, each step in the remarkable progress of environmental change research has benefitted from innovation in data collection techniques and research methods. Materials used in environmental change records include deep-sea sediment, loess/paleosoils, fluvial and lacustrine terraces, glacial moraines, lake sediments, stalagmites, tree rings, ice cores, coral reefs, historical records, and others (Wei et al. 2013). The research objects involve each key element of physical geography as well as the research contents of marine sedimentology, Quaternary geology and climatology. To acquire abundant data, multiple methods and techniques have been introduced in studies of environmental change records that are widely applied in sedimentology, geochemistry, paleoecology and climatic geomorphology. The data gathered can help produce efficient and accurate reconstructions by offering multiple points of view and reducing uncertainties. However, specific methods may be more suitable for a specific environmental medium and time period. Therefore, spatial distribution, temporal resolution, and environmental implications of multi-proxy techniques should be assessed in terms of both advantages and disadvantages. The integration of multiple methods to collect environmental change records is an essential way to promote development of research on past environmental change.

23.1.2 Contributions by Scholars from Different Countries

Based on 89 physical geographic journals selected from the database of Web of Sciences, literature on studies of environmental change records was identified according to specific keywords. The total number of citations and highly cited articles were then determined for different periods and countries to evaluate the temporal development of studies on environmental change records both in China and abroad. The results of the studies relative to the top 20 countries (regions) from 2000 to 2014 are presented in Table 23.1.

International research groups and their achievements with respect to environmental change records are mainly concentrated in the developed countries. However, developing countries (regions) such as China and India are also in the top 20 countries (regions), illustrating that research on

Table 23.1 Top 20 countries (regions) with the number and citations of SCI/SSCI-indexed articles on "Records of Environmental Changes in Physical Geography" during the period 2000–2014

	Number of articles						Cited frequency						Number of highly cited articles					
	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014
Rank	World	2,607	6,890	15,116	21,326	31,079	World	99,193	4,282	489,536	437,996	171,185	World	316	0	1,353	1,324	1,568
1	USA	685	1,184	3,929	4,870	5,666	USA	31,502	875	144,066	109,129	34,984	USA	102	0	439	356	353
2	China	159	1,286	1,182	1,999	4,900	China	3,955	643	25,576	38,184	22,322	UK	45	0	172	179	180
3	Germany	198	427	1,051	1,436	2,158	UK	13,381	311	58,209	49,977	16,064	China	12	0	63	128	179
4	UK	315	409	1,477	2,033	2,140	Germany	7,430	367	35,352	31,208	14,083	Germany	25	0	103	92	137
5	France	128	356	763	1,079	1,666	France	5,325	237	26,818	24,880	10,866	France	16	0	70	81	120
6	Canada	190	323	982	1,168	1,476	Canada	4,903	169	28,626	23,085	7,242	Switzerland	15	0	53	59	64
7	Spain	62	288	405	776	1,273	Spain	1,735	179	11,460	15,475	7,132	Spain	4	0	28	35	63
8	Italy	69	268	439	810	1,252	Italy	1,942	145	11,448	13,776	6,504	Canada	11	0	69	63	59
9	Australia	84	188	492	732	904	Australia	4,204	119	20,301	16,425	5,812	Italy	2	0	17	26	56
10	Japan	66	143	473	636	721	Switzerland	3,353	137	14,423	14,603	5,513	Australia	17	0	59	55	51
11	India	23	206	196	312	721	Netherlands	3,162	84	14,317	10,318	3,878	Netherlands	13	0	43	37	43
12	Switzerland	72	149	330	504	715	Japan	2,280	57	10,221	9,675	3,148	Sweden	6	0	47	21	36
13	Netherlands	72	104	378	433	534	Sweden	2,002	65	13,838	7,999	2,897	Denmark	6	0	28	24	20
14	Sweden	61	99	373	378	431	India	688	90	3,828	4,907	2,505	Norway	10	0	27	19	20
15	Brazil	18	107	131	317	380	Norway	2,172	50	8,348	5,831	2,191	Belgium	5	0	16	13	20
16	Poland	13	114	106	178	364	New Zealand	867	28	4,943	4,887	2,134	Japan	7	0	18	21	17
17	Norway	45	69	222	257	337	Belgium	1,260	34	5,273	5,806	1,958	New Zealand	0	0	6	10	16
18	Belgium	31	72	155	288	334	Denmark	1,517	36	8,037	5,616	1,748	Austria	1	0	9	8	13
19	New Zealand	29	58	180	247	328	Austria	527	58	3,425	3,699	1,394	India	1	0	5	15	11
20	Denmark	41	42	217	186	252	Finland	733	26	4,134	3,399	1,199	Finland	2	0	8	11	11

Note Countries (regions) ranked by the number of articles, total cited frequency and highly cited articles during the period 2000–2014 environmental change records is a prominent social and scientific interest for both developed and developing countries (regions). In comparing the periods of 2000–2004 and 2010–2014, the research scale (frequency of papers) of Chinese scholars improved in rank from No. 3 to No. 2; in addition, the academic influence (total citations) and prominent achievement (amount of highly cited articles) improved from No. 6 to No. 2 and No. 3, respectively. With increasing investment in science and technology, China is producing a significant body of research on environmental change records with increasing international impact. This indicates that research on environmental change records in China is developing rapidly.

23.1.3 Key Research Topics

Through cluster analysis of keywords in SCI/SSCI-indexed articles published in the past 15 years, the coverage fields and interconnections among these key words reveal prominent foci of environmental change records in physical geography as demonstrated below (Fig. 23.1). (1) The keywords with temporal significance, including "late Quaternary" and "Holocene", are closely associated with those of research content significance, including "climate", "climate change", "record" and "reconstruction", indicating that more attention is being given to the records of climatic and environmental changes in the Quaternary and Holocene eras. (2) Keywords such as "sediment", "lake", "river" and "erosion" are located in the same circle and overlap one another, revealing sediment as the most important method in research on environmental change records. (3) Keywords such as "water", "basin" and "evolution" not only have a certain influence range but also are closely related with each other, while maintaining a certain distance to the circle of "sediment", suggesting that the study of hydrological processes and their basin-scale changes is an important direction

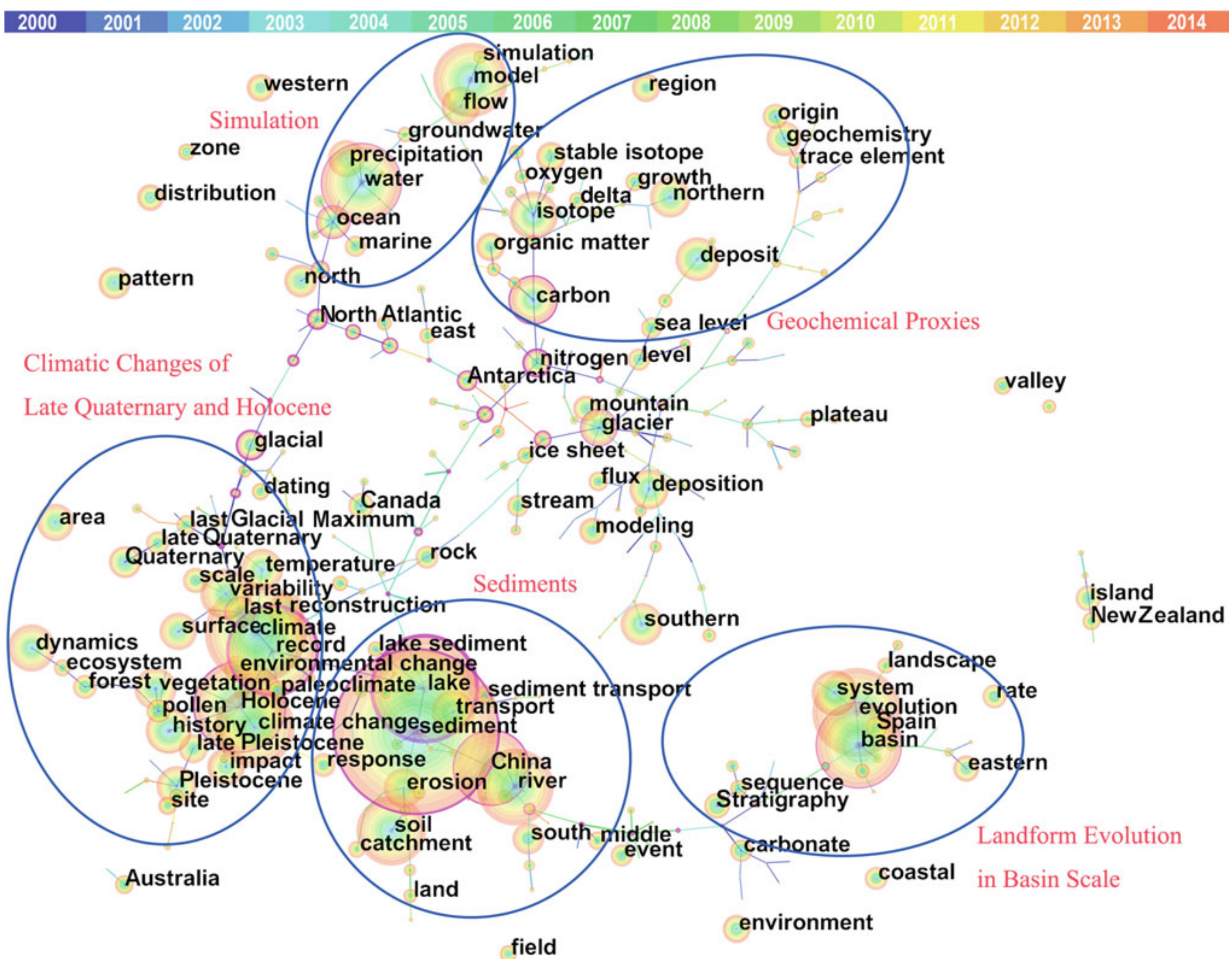

Fig. 23.1 Co-occurrence network of SCI/SSCI-indexed article keywords on "Records of Environmental Changes in Physical Geography" during the period 2000–2014

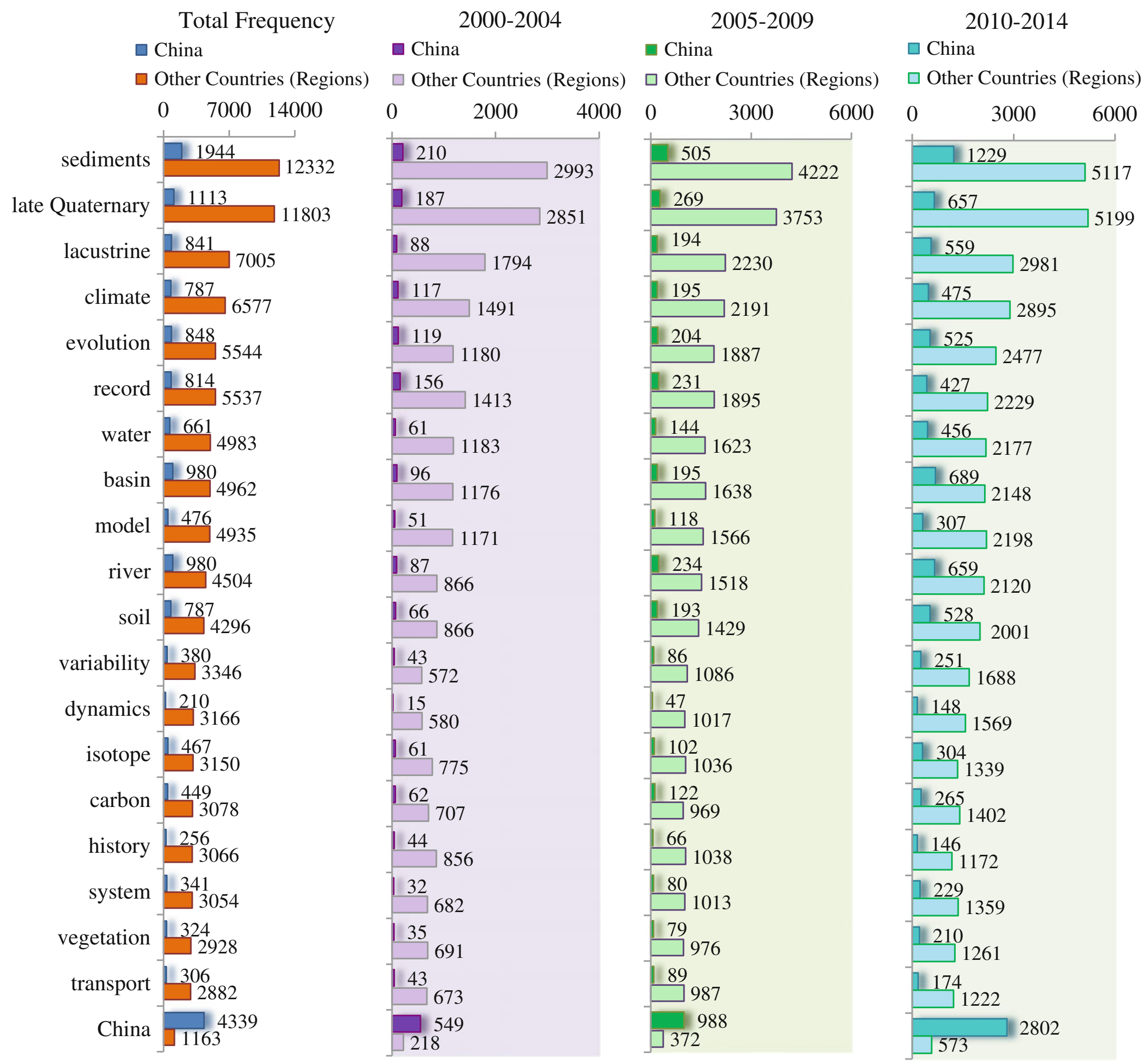

Fig. 23.2 Keyword temporal trajectory graph for SCI/SSCI-indexed articles on "Records of Environmental Changes in Physical Geography" during the period 2000–2014

for the development of research. (4) The keywords "carbon", "organic matter", "isotope" and "geochemistry" are closely linked with one another and maintain some distance from the ranges of keywords focusing on climatic and environmental changes and sediment, but their influence range exceeds that of keywords such as "pollen" and "paleo-ecology" which are closely connected to reconstruction of environmental changes, indicating that the study of geochemical indicators has played an increasingly important role in research on environmental change records. (5) Keywords related to land surface water and atmospheric precipitation ("water", "precipitation", "groundwater", "ocean", etc.) are relatively concentrated and correlated closely with keywords such as "model" and "simulation", indicating that model and simulation research based on water-vapor processes has attracted significant attention, possibly because hydrological processes are dominant in environmental changes recorded by sediments. Thus it is essential to understand the processes, mechanisms and effects of environmental changes from the perspective of the hydrological cycle.

Based on research topics in the literature on environmental change records in different periods, the prominent foci of this research field were determined to be as follows (Fig. 23.2): (1) In the last 15 years, sediment research, especially lacustrine sediment, has been a major research focus; (2) The environmental change records since the late Quaternary have been extensively investigated; (3) The research contents of environmental change records are shifting from obtaining single records to integrative analysis, and great attention has been continuously given to the variability and dynamics of environmental changes; and (4) The number of studies of environmental change records in China has been rapidly increasing, reflecting China's emergence as a key research area.

Table 23.2 NSFC-funded projects and SCI/SSCI-indexed articles on "Records of Environmental Changes in Physical Geography" during the period 2000–2014

SCI/SSCI-indexed articles					NSFC-funded projects			
Periods	Number of articles	% of articles by Chinese authors	% of articles with NSFC funding by Chinese authors	% of articles funded by MOST among those with NSFC funding	Number of projects	Funding (10,000 yuan)	Number of PIs	Number of institutions
2000-2004	15,116	7.8	19.5	0.0	87	5,020.0	79	29
2005-2009	21,326	9.4	37.7	28.2	229	9,987.8	193	65
2010-2014	31,079	15.8	79.9	42.6	370	29,298.5	330	103
2000-2014	67,521	12.0	60.6	38.4	686	44,306.3	471	120

The keyword frequency of SCI/SSCI-indexed journal articles on environmental change records differs between those published by Chinese authors and those by authors from other countries (regions) (Fig. 23.2). The top 2 keywords in the literature from other countries are "sediment" and "late Quaternary". Their frequency far exceeds that of other keywords, indicating a great concentration of literature on Quaternary palaeo-environmental reconstruction with sedimentary records. Other keywords with higher frequencies are "lacustrine", "climate", "evolution" and "record", suggesting that records of lake sediments have been most widely investigated and climatic change is the main focus of research on environmental change records. The next less frequently utilized major keywords are "basin", "water" and "river", respectively, indicating that research on hydrological processes at a watershed scale is an important pattern of environmental change reconstruction. The frequency of "model" falls just below the top 10 keywords in terms of frequency, illustrating that modeling and simulation studies have been used for understanding the mechanisms of environmental changes. "China" is the only word with regional significance, indicating that China has become a key study region.

In analyzing those articles published by Chinese authors, "sediments" and "late Quaternary" are the keywords with the highest frequencies, indicating that scholars from both China and other countries are focused on the studies of environmental reconstruction based upon sediments. Although "Tibetan Plateau" is not in the top 20 keywords of articles published by authors from other countries (regions), it has a higher frequency for articles by Chinese authors, suggesting that research on environmental change records in the Tibetan Plateau has produced a large number of high quality articles. It is worth noting that the frequencies of "basin" and "river" are higher than those of "lacustrine", "evolution", "climate", "record" and "soil". This implies that considerably more Chinese studies are based on terraces and natural profiles, and that qualitative descriptions play a more important role in research of environmental changes in China than does quantitative reconstruction. "Model" is the 11th most frequently utilized keyword, but its frequency is far less than that of the top 10 keywords and is similar to those of "isotope" and "carbon", indicating that in China, more concern is still given to interpretation of environmental proxies as opposed to mechanisms.

23.1.4 The Role of NSFC in Supporting the Research on Records of Environmental Changes in Physical Geography

Within the project classification system of National Natural Science Foundation of China (NSFC), research on environmental change records is also supported in the projects within Quaternary geology and global change research. From the standpoint of physical geography in research on environmental change records, based on NSFC's classification code a total of 686 projects were supported from 2000 to 2014 (Table 23.2).[1]

In comparing articles contributed by Chinese scholars in SCI/SSCI journals and those funded by NSFC projects, we may roughly elucidate the relationship between the input of NSFC and the development of research on environmental change records in China. During 2000–2004, Chinese authors published 1178 articles (7.8 % of the global total) on environmental change records research in SCI/SSCI journals, which ranked second in the world. However, less than 20 % of these publications were funded by NFSC, because of less NSFC input and no attention to funding acknowledgement in publications during this period. In the next five years (2005–2009), the number of articles by Chinese authors in SCI/SSCI journals reached 2004, with the overall proportion rising to 9.4 %, among which 37.7 % were

[1]Projects were first searched according to NSFC classification code among the research fields of geomorphology (D010101), cryosphere geography (D010105), environmental change and prediction (D0104) and applied climatology (D010103) and then manually screened based on project titles and abstracts.

supported by NSFC. During 2010–2014, Chinese scholars authored 4910 articles in SCI/SSCI journals, or 15.8 % of the overall total of selected articles, among which 79.9 % were funded by NSFC. Thus, NSFC projects related to physical geography have become the core impetus in promoting research on environmental change records in China as it moves to the forefront of the international science arena. Relating project funding by NSFC to publication output, funding support during 2010–2014 was 5.8 times that of 2000–2004, while publication output was 17.1 times that of 2000–2004. This reflects the enormous impact of NSFC funding with respect to research on environmental change records. Among Chinese publications supported by NSFC, a considerable part were also funded by China's Ministry of Science and Technology (MOST). MOST-funded projects accounted for 0, 28.5 and 42.6 % during 2000–2004, 2005–2009, and 2010–2014, respectively, indicating that project funding by MOST has been increasing for research on environmental change records in recent years.

With respect to the research theme distribution of the projects during 2000–2014, "sedimentary environment", "late Quaternary" and "climate environmental record (or reconstruction)" were principal research foci, not only in articles contributed by Chinese researchers and those abroad (Fig. 23.2), but also in articles funded by NSFC (Fig. 23.3). "sedimentary environment" rank first in the keyword sorting of the SCI/SSCI publications, implying that sediments were the critical materials for research on environmental change records. "climate change" and "environmental reconstruction" ranked the top 2 position in the keyword distribution of NSFC-funded projects, showing that multiple approaches to research on environmental change records are supported by NSFC, including glacial change, moraine, ice core and tree ring research. The keyword "Tibetan Plateau" ranked 4th in

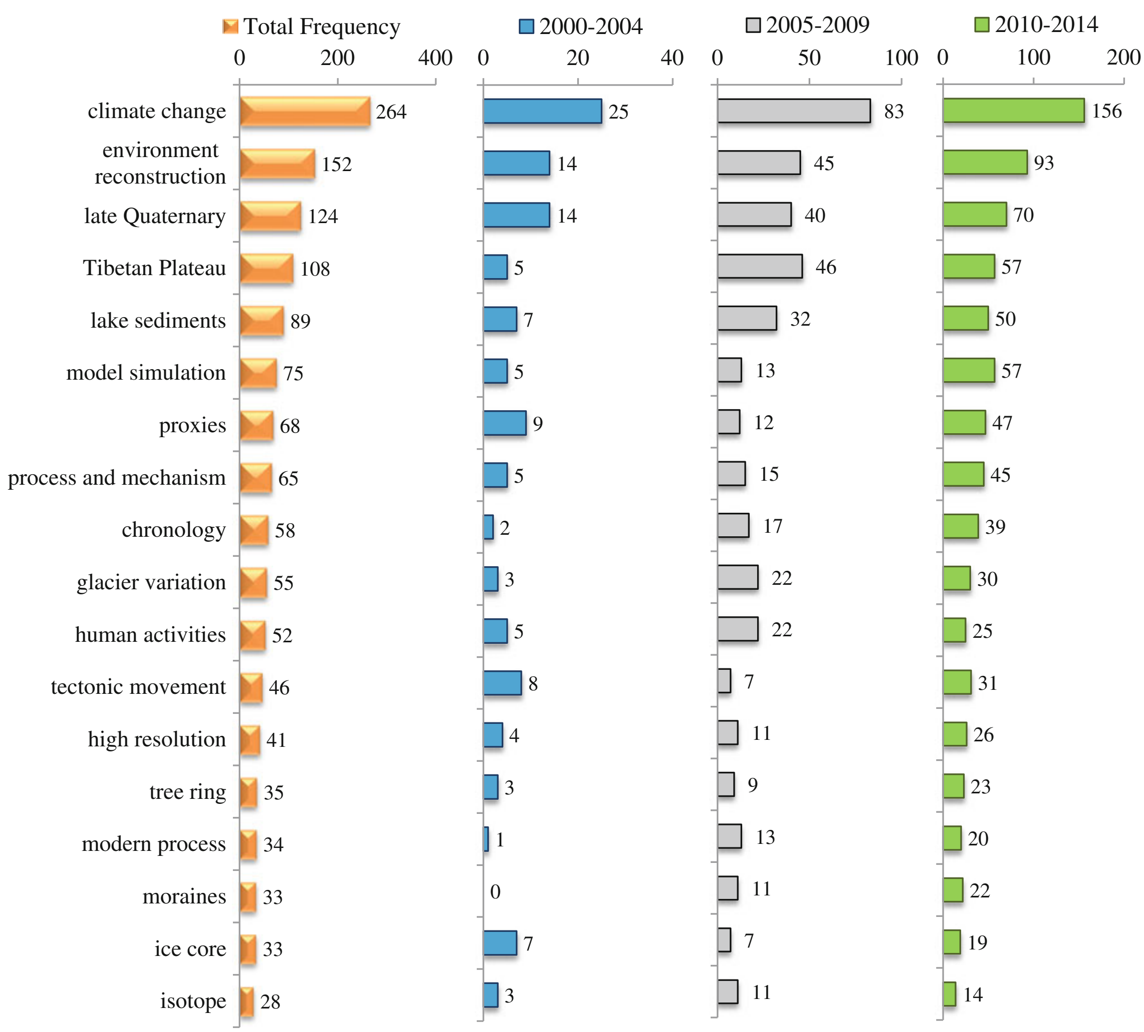

Fig. 23.3 Keyword temporal trajectory graph for NSFC-funded projects on "Records of Environmental Changes in Physical Geography" during the period 2000–2014

NSFC projects, and is the only one word with regional significance. This indicates that Chinese geographers paid more attention to the role of the Tibetan Plateau in research on environmental change records. Keywords including "model simulation", "modern process (mechanism)", "isotope" and "chronology" occurred commonly in NSFC projects, as well as in articles on environmental change by Chinese and international scholars. Their frequencies are nearly equal, demonstrating that the input of NSFC in such research fields was coordinated with the output of publications. The keyword "high resolution" occurred in NSFC projects with high frequency, suggesting that research on environmental change over short time scales received more attention in China.

23.2 Research Advances and Problems

23.2.1 Bibliometric Analysis of Contemporary Research

There were 67,521 SCI/SSCI-indexed articles on past environmental change published around the world from 2000 to 2014 (Table 23.1), among which "Holocene" was the most frequent topic, with 2039 articles accounting for 3.0 % of the total amount (Fig. 23.4). The 2nd-ranked topic was "climate change", with 1475 articles accounting for 2.2 % of the total. Topics with articles accounting for more than 1 % included "paleoclimate", "stable isotope", "sediment", "pollen" and "diatom". Other topics ranked in the top 15 were "paleoecology", "sediment transport", "geochemistry", "erosion", "climate", "Pleistocene", "soil erosion" and "Quaternary", but the overall proportions of these topics were all less than 1 %. According to the top 15 topics of the international articles on past environmental change, it can be seen that the history of climatic and environmental changes has focused primarily on the Holocene period. Sediment is the main research focus in studies with proxy utilization of stable isotopes, pollen and diatoms. Moreover, "sediment transport", "erosion", "soil erosion" and "Quaternary" reflect the fact that long-term climatic evolution had also received much attention in environmental records studies.

23.2.2 Contemporary Research

From an international perspective, studies of environmental change records have made great progress since 2000, as reflected in the reconstruction of facts and records relative to environmental changes, the accuracy of sediments dating, the significance of proxies, and mechanism analyses based upon modeling. Several highlights merit attention. Firstly, the reconstruction of environmental change records has witnessed the most progress. Achievements include: sea level change and sea surface temperature reconstruction based upon benthos foraminiferan at the sea bottom; ice sheet evolutionary history and its environmental effects; regional temperature change through the use of pollen assemblages; paleo monsoon history in East Asia; and confirmation of the existence and regional differences of

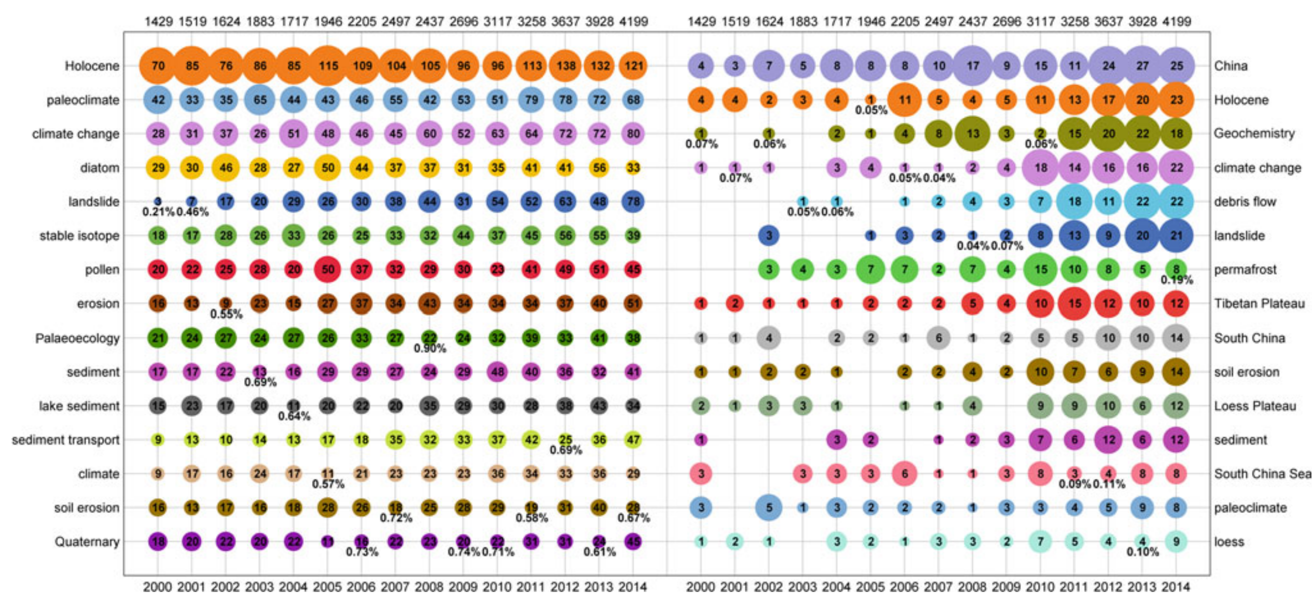

Fig. 23.4 Comparative diagram of prominent keywords on "Records of Environmental Changes in Physical Geography" by Chinese authors and others in SCI/SSCI-indexed articles during the period 2000–2014. *Note* Right panel shows keywords used by Chinese authors and left panel shows those used by the authors from other countries (regions). Size of circles denotes the ratio of a certain keyword frequency to the total article number in a specific year. The annual total number of articles is shown at the top of the diagram. The frequency of the keyword is shown inside the circle. The size of circles in the diagram for Chinese authors are magnified for clear display

Holocene Megathermal (An 2000; Waelbroeck et al. 2002; Davis et al. 2003; Svendsen et al. 2004; Kaufman et al. 2004; Church and White 2006). Secondly, the chronology of sediments dating has been improved. In addition to the upgrading of the radiocarbon dating method, the development of the U-Th method and exposure sample dating (Fairbanks et al. 2005; Balco et al. 2008) has enhanced the temporal accuracy of environmental change records. Thirdly, proxies for reconstructing environmental change have been continually refined and innovated, such as environmental significance excavation of traditional grain-size distribution, isotopes of carbon and nitrogen, trace elements of sediments (Blott and Pye 2001; Leng and Marshall 2004; Tribovillard et al. 2006), and isotopes of tree-rings (McCarroll and Loader 2004). Fourthly, modeling and simulation are playing important roles in elucidating environmental change mechanisms. This research has focused on the influence of tectonic movements on environmental change, environmental processes among land, sea and ice (Mix et al. 2001), paleo-climate simulation from glacial to interglacial periods (Braconnot et al. 2007), and climatic effects of land surface vegetation and atmospheric chemical components under modern climatic conditions (Pearson and Dawson 2003).

A number of international journals focus on past environmental change and have published frontier articles in the field. For example, many articles are concentrated in *Quaternary Science Reviews*, a journal focusing on environmental change studies and related reviews. Other journals focused on environmental proxies and modern processes, such as *Chemical Geology*, *Journal of Geophysical Research* and *Limnology and Oceanography*. The third kind of journal publishes frontier articles that are focused primarily on biogeochemistry, such as *Global Biogeochemical Cycles*, *Biogeochemistry* and *Journal of Biogeography*. A number of frontier articles focused on tectonic movement and environmental changes have been published in journals such as *Journal of Asian Earth Sciences*, *Terra Nova*, and *Earth Surface Processes and Landforms*. It is clear that research on past environmental changes is not only concerned with environmental reconstructions, but also with modern processes of environmental proxies, simulation modeling, and related biogeochemistry.

23.2.3 Bibliometric Analysis of Contemporary Research in China

As shown in Table 23.1, articles on past environmental change in China have rapidly increased since 2000. Chinese scholars have published 8081 academic articles on geomorphology, accounting for 12 % of the world total. For the top 15 themes of these articles, excluding “China” as a regional indicator, “climate change”, “Holocene”, “geochemistry”, “Tibetan Plateau”, “sediment”, “South China”, “heavy metals”, “South China Sea”, “paleoclimate”, “precipitation”, “soil erosion”, “remote sensing”, “carbon isotope” and “loess” rank from 2nd to 15th, respectively. Among these themes, articles focusing on “geochemistry”, “sediment”, “heavy metals”, and “carbon isotope” account for 2.2, 1.9, 1.4 and 0.9 %, respectively, of the total articles published by Chinese scholars. The total percentage of these themes is 6.4 %. Articles on “climate change”, “Holocene”, and “paleoclimate” account for 2.6, 2.5, and 1.3 % of the total articles by Chinese scholars, respectively, with a total percentage of 6.3 %. This indicates that the history and proxies of climatic and environmental changes occupy a similarly important position as the other aforementioned themes. Articles focusing on the “Tibetan Plateau”, “South China” and “South China Sea” account for 2.0, 1.5 and 1.3 % of the total articles by Chinese scholars, respectively, indicating that regional environmental changes have received widespread attention in China. Articles related to erosion processes such as “precipitation”, “soil erosion” and “loess” account for 1.2, 1.0 and 0.9 % of the total articles by Chinese scholars, respectively. This suggests that long-term environmental change has also received considerable attention from Chinese scholars. Compared to the main themes of articles on environmental change by international scholars, in addition to climatic and environmental history, other themes that have received considerable attention in China include proxies and long-term environmental evolution, and the environmental records of regional features, such as the Tibetan Plateau and South China.

23.2.4 Contemporary Research in China

Since the 1980s, the focus of research on environmental change in China has gradually shifted from traditional geomorphology and Quaternary deposition to past climate reconstruction using environmental proxies. Research foci include a variety of media containing information on environmental changes, including river and lake terraces, moraines, lake cores, ice cores, stalagmites, tree rings, loess, and others. Research has focused mainly on the facts of past climatic and environmental changes in China and their comparison with those changes in other parts of the globe, in the process affirming the global or regional significance of these changes.

Investigations of the Yellow River terraces in the Lanzhou region (Li et al. 2001b) and the Huangshui terraces in Huzhu of Xinjiang Province (Lu et al. 2004) revealed multiple phases of uplift in the northeastern Tibetan Plateau. Recent studies revealed that the formation of river terraces in active tectonic regions cannot be explained by a single factor (e.g., tectonic movement or climate). Formation of multiple terraces could be affected by tectonic uplift, whereas the formation of a single terrace is controlled by climate change (Pan et al. 2007). Based on the developmental relationship between loess and paleosols in each terrace, researchers found that river terraces in the Qilian Mountains developed during glacial-interglacial transitions. In such tectonically active regions, tectonic deformation drives long-term fluvial incision, whereas climate variations determine when terraces will form (Pan et al. 2003).

Terraces of closed lakes show that a Pan-lake period occurred in the late stage of the Interstadial of the Last Glacial Period (40–20 ka BP) on the Tibetan Plateau (Li and Zhu 2001). During the early Holocene (11–9 ka BP), many lakes of the plateau reached their highest levels (Li et al. 2001a). During the middle Holocene, the third lake terrace widely developed in lakes of the southern and central plateau regions. During the late Holocene, Lake Terrace variation in the southern and northern plateau reflected a decrease in lake levels by 10–20 m and disintegration of some large lakes, reflecting the general retreat of lakes under cooling climatic conditions (Zheng et al. 1989).

Shi and Yao (2002) summarized the paleo-glacial changes in 23 regions from five continents of the world and found a significant glacier advance in marine oxygen isotope stage 3b, with the glacier advance scale even larger than that in the Last Glacial Maximum (LGM). Study of developmental characteristics of glaciers since the Last Glacial Period in Asia found that glacier development exhibited regional differences due to location, hydrothermal conditions and atmospheric circulation (Cui and Zhang 2003). Integration of chronology data from moraines for the Little Ice Age (LIA) on the Tibetan Plateau and adjacent mountain areas revealed that the timing of glacier activity during the LIA varied in different regions. The glacier fluctuations responded more strongly to temperature than to precipitation (Xu and Yi 2014).

Lake core proxies can record climatic and environmental changes at resolutions from a million years to a millennium scale. A 666 m long sediment core from Heqing Basin in Yunnan Province revealed Indian summer monsoon (ISM) variability at a glacial-interglacial time scale over the past 2.6 million years (An et al. 2011). Environmental change records from the LGM to the early Holocene are mainly concentrated in western China. A sediment core from Nam Co Lake on the Tibetan Plateau revealed that the lake area remained small under cold and dry climatic conditions during 24–20 ka BP (Kasper et al. 2015). However, ostracoda in the core from Balikun Lake in Xinjiang Province revealed a high lake level occurring during 30–24 ka BP (Han et al. 1993). The climate tended to be warm during the Late Glacial period. Records of lake cores in northwestern China and the Tibetan Plateau showed that precipitation/glacier melt water increased with increasing lake water supply (Yang and Wang 1994; Pachur et al. 1995; Zhu et al. 2009) and the subsequent Younger Dryas Event (YD) (Gasse et al. 1991; Gu et al. 1993; Lü et al. 2011). Most of the climatic and environmental records from lake sediments are focused on the Holocene. The highest lake level, lowest lake level and salification stage occurred successively during the early, middle and late Holocene on the Tibetan Plateau and the Yunnan-Guizhou Plateau (Shen et al. 2004, 2005; Zhu et al. 2010). Lake sediment records in northwestern China indicated that temperature increased during the early Holocene, reached a maximum during the middle Holocene, and decreased during the middle to late Holocene (Zhou and Shen 2007). Integration research of lake sediment records in arid central Asia revealed a humid climate during the middle and late Holocene in the Westerly dominant region, which differed significantly from the strong monsoon domination during the early and middle Holocene in the Asian monsoon region (Chen et al. 2008a, b). Although lake sediment records have the disadvantage of a lower resolution in millennial-scale climatic reconstruction, they can still reflect some important climate events, including the Medieval Warm Period (MWP) and the Little Ice Age (LIA). These records were obtained from the Tibetan Plateau (Shen et al. 2001; Zhu et al. 2003), the Yunnan-Guizhou Plateau (Chen et al. 2008a, b), the arid regions in northwestern China (Chen et al. 2000), the northern farming-pastoral transitional zone (Cao et al. 2000) and the eastern plain region (Su 1992). Recently, quantitative reconstructions of climatic parameters and hydrological factors have been developed based on biological indicators such as pollen, ostracoda, diatoms, chironomids, and others (Lu et al. 2011; Mischke et al. 2007; Yang et al. 2004; Zhang et al. 2006).

Although ice cores can be used to trace environmental changes back hundreds of thousands of years (Yao et al. 1995), most ice core records in China are concentrated in the past hundreds to thousands of years. The positive correlation between $\delta^{18}O$ of ice cores and temperature exists over long time scales (Thompson et al. 2000), based on those temperature records in different regions on the Tibetan Plateau that have been reconstructed (Yao et al. 2006). Glacial accumulation is positively associated with precipitation and data on this relationship can be used for constructing precipitation information. Glacial accumulation variations in the southern Tibetan Plateau differ from those from the Guliya ice core and Dunde ice core in northern Tibet (Duan et al. 2000), which may reflect differences in precipitation source areas. Particles and trace elements in ice cores can also record major environmental events (Wang et al. 2012) and sensitively reflect pollution events and processes caused by human activities (Xu et al. 2009). Microbial characteristics recorded by the Malan ice core and Purog Kangri ice core indicated that microbial community density exhibits a strong relationship with cooling events. Compared with temperature changes reflected by $\delta^{18}O$, microbial community density showed a certain lag (Yao et al. 2003).

Chinese scientists have published important articles on the climatic significance of stalagmite $\delta^{18}O$ in the Asian monsoon region. Information therein consists of variations of summer/winter precipitation ratios (Wang et al. 2001); water vapor residual ratios of air masses in different periods in the migration process from the tropical Indian-Pacific ocean to southeastern China (Yuan et al. 2004); the relative variations in intensity of summer/winter monsoons (Johnson et al. 2006); an index of East Asian monsoon intensity and summer solar radiation changes of the Northern Hemisphere at an orbital scale (Wang et al. 2008); precipitation changes caused by summer monsoon intensity on decade to inter-annual scales (Zhang et al. 2008); and circulation effects on decadal to century scales (Tan 2009). Based on these studies, scientists have reconstructed paleoclimatic histories in different regions and on different time scales. In addition to stalagmite $\delta^{18}O$, variations of stalagmite trace elements are mainly controlled by external temperature over decadal to annual temporal scales (Tan et al. 2014). Changes in stalagmite trace elements can indicate cave environments and seasonal variations of external climatic conditions (Huang et al. 2000).

Climatic records from tree rings in China have focused on the Tibetan Plateau and arid northwestern China. In the eastern Tibetan Plateau, Zhu et al. (2011) described a summer temperature reconstruction series with low-frequency climate variability using the Regional Curve Standardization method. Based on living trees, dead trees and archaeological wood in tombs, Shao et al. (2010) developed a tree-ring width chronology in the northeastern Qaidam Basin extending from 1580 BC to AD 2005. This is by far the longest tree-ring width chronology in Asia, indicating that the East Asian summer monsoon possibly affected the eastern Qaidam Basin. Using the relationships among tree rings, precipitation and runoff, scientists have conducted research on river runoff in northwestern China (Liu et al. 2010) and found widely-distributed events over the historical period (Gou et al. 2010). Based on studies of tree growth and the settling environment on moraines after glacial retreat, glacial advance and retreat since the LIA in the southeastern Tibetan Plateau was reconstructed by the dating of lateral and terminal moraines using tree rings (Xu et al. 2012). Recently, dendroclimatic investigations have given more attention to the relationships between wood formation and climatic factors in microscopic tree physiology (Li et al. 2013).

Global environmental changes from Chinese loess records have been successfully determined. Since most of these studies were focused primarily on Quaternary geology, as a progress and perspective analysis from the view of physical geography, we did not provide further analysis on this topic.

23.2.5 Contributions by Chinese Scholars and Subsequent Problems

As evidenced by the articles on environmental change records in China and abroad over the past 15 years (Table 23.1), significant progress has been made in the total number of articles, total citations, and highly cited articles. The last 15 years can be divided into three stages: I (2000–2004), II (2005–2009) and III (2010–2014). The total number of articles in China was ranked 3rd among all countries in stage I and stage II and then reaches 2nd in stage III. However, the growth rate of articles in China in stage II and III are 1.7 and 4.1 times of that in stage I, respectively, whereas the world average growth rates are 1.4 and 2.1, respectively. The USA, ranked first in terms of number of articles, has growth rates of 1.2 and 1.4 in stage II and stage III compared with that of stage I. With respect to total citations, China has greatly increased its influence, improving its ranking from 6th to 3rd and then 2nd in the world. Influenced by the publishing cycle, the ratio of total citations among the three stages in China is 1:1.5:0.9, whereas the world average and that for the USA are 1:0.9:0.4 and 1:0.8:0.2, respectively. Regarding the number of highly cited articles, China ranked 6th in stage I, and reached 3rd in stages II and III, with growth rates of 2.0 and 2.8 compared to that of stage I, whereas the world average growth rates were 1.0 and 1.2, and those of the USA were 0.8 and 0.8, respectively. The trends in total citations and highly cited articles indicate that research on environment change records in China is rapidly increasing from the stages of learning from and tracking international trends to parallel advancement and even competition toward assuming the leading status.

It is evident from the above that the maturation process for research on environmental change records in China has occurred via a process in which Chinese scholars first learned methods from abroad, then applied them in local research, and then performed successful studies of local features. However, only some research has assumed top prominence in the international mainstream. In terms of research content, early cooperative research has been dominated by scholars from other countries, but Chinese scholars are currently producing increasingly more articles, including those of high quality and widespread influence. In terms of research foci, Chinese scholars have paid more attention to issues within China, and considered other areas of the world when comparing the degree of accordance between regional and global results.

23.3 Roadmap for Further Research

Past global change is becoming quite an important research field because it can help provide an accurate understanding of the history and mechanisms of climate and environment changes. With in-depth development of research on past global change, environmental change records provide solid scientific evidence of the facts underlying climate and environment changes. Further understanding of mechanisms and regularities of climate and environment changes has become an increasingly important concern, and modern process research for environmental change records is undoubtedly an important direction of research in physical geography. Environmental change records help provide further facts regarding past environmental changes, and systematic interpretations of the mechanisms driving environmental changes will thus play a more important role in research on earth system processes and their impacts on human society.

Research on environmental change records in China has led to a large amount of environmental reconstructions using multiple materials. In particular, pollen assemblages and geochemical indices have been utilized over different time scales and in different areas. The total number of articles, citations and highly cited articles contributed by Chinese scholars rank second in the world, just after the United States. Considering the developmental trend of research on environment change records in China and abroad, in order to play a better role in comprehending global changes and in developing earth system science theory, some key issues need to be addressed. Several aspects that need to be strengthened include the following.

(1) Integration of Regional Environmental Change Records

Environmental change records are based on the analysis of environmental proxies. Substantial evidence of past climate change has been obtained through a variety of such proxies. Although this evidence has been used to describe the history of environmental change in different regions and with different foci, inconsistencies remain in terms of the timing and scale of key environmental events. If such contradictions in reconstruction results cannot be resolved at a regional scale, it will be difficult to consolidate the regional reconstruction results. Integration of physical geography can help us integrate the results of environmental change records and validate the reconstructions resulting from different indices. In so doing, the credibility of reconstruction at a regional scale will be enhanced, and a better understanding of the relationship among regional climate change, atmospheric circulation and global change will be attained.

(2) Modern Process Research for Environmental Proxies

Although most proxies have very clear environmental implications, uncertainties still exist when applied in environment change reconstruction in different regions. For example, the environmental significance of many proxies are based on sediment reconstruction in low elevation and humid regions from abroad; thus, the reliability should be verified when they are introduced in the Tibetan plateau as to whether and how the proxies can reflect high altitude environmental changes. Because more attention is given to process research in physical geography, modern process research of proxies can be effectively conducted to help understand the environmental significance of formation mechanisms, which can thus lay a solid foundation to establish quantitative relationships between proxies and climatic factors.

(3) Quantitative Reconstruction of Environmental Changes

Quantitative reconstruction of environment changes can not only provide a scientific basis for the evaluation of such changes in historical periods and the prediction of future extreme environmental events, but is also an essential boundary condition for simulation studies which help provide an understanding of environment change mechanisms. Simulation models can play an important role in analyzing the mechanisms of environmental changes and predicting future trends. Because such models are established based on quantitative relationships under modern climate conditions with limited ranges of variation, their applicability may need further verification with respect to past climate change records with larger environmental ranges. These models also need quantitative boundary conditions to simulate climate changes during different periods. In this light, quantitative reconstruction of environmental change is the foundation for in-depth understanding of the mechanisms of environmental change and predicting future trends.

(4) Methods of Past Environmental Change Reconstruction

To reconstruct past climate changes accurately, we must obtain ideal samples and proxies that can reflect environmental changes. Relevant concerns here include the integrity of the samples, temporal continuity of proxies, the extent of quantification, and so on. Existing proxies have played an important role in research on environmental change records, but some proxies with limited environmental significance are less effective in quantitative reconstructions or discovering driving mechanisms. Technology plays a critical role in scientific discovery. Therefore, we need to constantly develop new technology, obtain more reliable samples, seek new proxies that can sensitively reflect environmental changes, and improve the accuracy of environmental change reconstruction.

23.4 Summary

Research on environmental change records is an important field for the understanding of past global change. Lacustrine terraces, glacial deposition, lake sediments, stalagmites, tree rings, ice cores, loess, paleosols, and other entities provide a wide range of materials for research on environmental change records and proxies reflecting environmental parameters. Over the past 30 years, with the development of techniques for acquiring research materials and innovations in proxy analyses, environmental change reconstructions in China have been extensively performed. Significant achievements with regional features have been accomplished, and environmental change reconstruction has become a major developing direction in physical geography. Especially under the support of NSFC, from the perspective of physical geography Chinese scholars have made significant progress in many respects, such as reconstructing environmental change histories using lake sediment pollen records, oxygen isotopes in ice cores and tree rings, and the determination of the relationship between tectonic movement and climate derived from the natural profiles in the Tibet Plateau and arid northwestern areas. Some achievements have had international influence. To further enhance research on environmental change records from the perspective of physical geography, there is a need for strengthening the integration of regional environmental change records, as well as for quantitative reconstructions of environment change, modern process research on environmental proxies, and development of new sampling techniques and analysis methods. These actions would benefit the depth and breadth of research on environmental change records, enhance their influence on the development of earth system science theory, and help guide China to a leading position in this field of study through cutting edge research on key issues.

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24 Detection and Attribution of Changes in Land Surface Sensitive Components

Fulu Tao, Shilong Piao, Qiuhong Tang, and Wenjiao Shi

Abstract

Detection and attribution are essential to understand the roles of natural and anthropogenic factors in changes of land surface sensitive components such as terrestrial ecosystem, water resources and crop yield. In this chapter, we review the research progress on detection and attribution using the literature statistics and analyses based on 240 international SCI/SSCI journals in the related fields such as geographical sciences, ecology, atmospheric science, hydrology and agriculture. We also review the research progress on detection and attribution in China. We conclude that Chinese scientists have had great progresses on detection and attribution in the past three decades; nevertheless more novel studies are needed to obtain high quality observation data on land surface dynamics and develop human and natural systems coupled models.

Keywords

Climate change • Human activities • Impact • Detection • Attribution

A total of 12,748 SCI/SSCI-indexed articles are analyzed in the research area of detection and attribution of changes in land surface sensitive components. Articles were identified from 240 international journals from 2000 to 2014. The number of journals that have published more than 15 of the relevant articles is 151 (Appendix U). The search query is as follows: ("climate change" OR "climate" OR "climatic") AND ("human*" OR "anthropogenic" OR "management" OR "policy" OR "natur*" OR "*forestation" OR "land*" OR "non-climatic*" OR "over graz*" OR "irrigation" OR "practices") AND ("contributions" OR "roles" OR "impacts" OR "effects" OR "detection" OR "attribution" OR "attributing" OR "cause*" OR "driver") AND ("land surface" OR "land cover" OR "cropland" OR "hydrological*" OR "water*" OR "runoff" OR "streamflow" OR "flow" OR "evapotranspiration" OR "ET" OR "agriculture" OR "crop" OR "phenology" OR "yield" OR "vegetation" OR "forests" OR "distribution" OR "ecosystem" OR "productivity" OR "LAI" OR "NDVI" OR "NPP" OR "grassland" OR "pasture" OR "drying" OR "degradation" OR "desertification" OR "disasters" OR "droughts" OR "floods" OR "glacier" OR "ice sheet" OR "cryosphere" OR "*systems") NOT ("project*" OR "scenarios").

24.1 Overview

24.1.1 Development of Research Questions

Global temperature was found to increase in the 1970s. Since then, whether climate is changing and what are the causes of climate change have become key research questions (Singer 1999, 2008). Scholars try to find evidence of climate change, and to understand the roles of anthropogenic and natural drivers in climate change, which is the early stage of detection and attribution. The detection and attribution studies develop quickly with the international global environmental change programs. Detection and attribution is concerned with assessing the causal relationship between one or more drivers and a responding system. "Detection of

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climate change is defined as the process of demonstrating that climate or a system affected by climate has changed in some defined statistical sense without providing a reason for that change. An identified change is detected in observations if its likelihood of occurrence by chance due to internal variability alone is determined to be small" (Hegerl et al. 2010). Attribution is defined as "the process of evaluating the relative contributions of multiple causal factors to a change or event with an assignment of statistical confidence". Detection and attribution has further been applied to other fields such as climate change impacts. "Detection of impacts" of climate change addresses the question of whether a natural or human system is changing beyond a specified baseline that characterizes its behavior in the absence of climate change (Stone et al. 2013). "Attribution of impacts" addresses the question of the magnitude of the contribution of climate change to a change in a system. Attribution requires the evaluation of the contributions of all external drivers to the system change. Separation of drivers from a responding system is a crucial element of formal detection and attribution analysis. Many external drivers may influence any system, including the changing climate and other confounding factors (Hegerl et al. 2010). The reliable detection and attribution of changes in climate, and their impacts, is fundamental to our understanding of the scientific basis of climate change and in enabling decision makers to manage climate-related risk.

In recent decades, with the development of global change research, new scientific instruments, satellite and remote sensing technology, the Earth Observing System is well developed. Many observation networks (e.g., Global Surface Network, Global Upper Air Network, satellite observations of Earth Radiation Budget and FLUXNET) provide large volumes of information and data on the Earth system with high resolution and large temporal and spatial extent. These have improved our understanding on the physical, chemical and biological aspects of the Earth system notably. Furthermore, earth system simulation models such as global climate models (GCMs), regional climate models, land surface models, ecosystem models, hydrological models and agricultural system models have been improved substantially. For example, a new set of simulations from a greater number of GCMs have been performed as part of the Coupled Model Intercomparison Project Phase 5 (CMIP5). These new simulations incorporate some moderate increases in resolution, improved parameterizations, and better representation of aerosols (IPCC 2014). Most of the GCMs can simulate the climate response of single anthropogenic and natural radioactive forcing, as well as global mean temperature change in the past century, reasonably well. The wealth of observation data and the improved models now permits the application of quantitative tools for synthesis assessment of detection and attribution (Root et al. 2005). Detection and attribution has become an important topic in the assessment reports of the Intergovernmental Panel on Climate Change (IPCC). In the past decades, detection and attribution of climate change has extended from temperature to other climate variables such as precipitation, atmospheric humidity and extreme climate events, and from the global scale to continental or regional scales. Detection and attribution of climate change impact now covers natural and human systems, including the hydrological cycle and water resources, the cryosphere, terrestrial ecosystems, food production systems, coastal and marine ecosystems, droughts and floods, and human health and well-being. Detection and attribution methods have also been improved notably, as detailed in the IPCC Good Practice Guidance Paper (Hegerl et al. 2010) and IPCC assessment report (IPCC 2014).

24.1.2 Contributions by Scholars from Different Countries

This section analyzes the number of academic articles on detection and attribution published in SCI/SSCI-indexed journals and their citations (see Table 24.1). Based on the statistics during the period 2010–2014, we found the top five countries that published the most SCI/SSCI-indexed articles were the USA, China, UK, Australia and Germany. The top five countries that had the most SCI/SSCI citations were the USA, UK, Australia, China and Germany. The top five countries that had the highly-cited SCI/SSCI-indexed articles were the USA, UK, Australia, Canada and Germany. China ranked seventh. USA ranked first in all three lists. From 2010 to 2014, China made great progress in detection and attribution, as indicated by the increases in the numbers of SCI/SSCI-indexed articles and SCI/SSCI citations (see Table 24.1). In terms of the number of SCI/SSCI-indexed articles, China ranked fifth during the period 2000–2004 and ranked second during the period 2010–2014. In term of the number of SCI/SSCI citations, China ranked ninth during the period 2000–2004 and ranked fourth during the period 2010–2014. Nevertheless, China was still lags far behind the USA. For example, during 2000–2004, 2005–2009 and 2010–2014, respectively, the USA scholars published 741, 1,326 and 2,067 SCI/SSCI-indexed articles and by contrast, Chinese scholars published 78, 270 and 931 SCI/SSCI-indexed articles. The mean citations per article were 80.5, 47.4 and 10.0 times for the USA scholars, and 31.4, 20.3 and 4.2 times for Chinese scholars during the same periods. The number of highly cited SCI/SSCI-indexed articles was 173, 200 and 151 for the USA, and 4, 10 and 15 for China. In sum, Chinese scholars need to improve the quality of their SCI/SSCI-indexed articles.

Table 24.1 Top 20 countries (regions) with the number and citations of SCI/SSCI-indexed articles on "Detection and Attribution of Changes in Land Surface Sensitive Components" during the period 2000–2014

	Number of articles						Cited frequency						Number of highly cited articles					
	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014
Rank	World	276	1,604	1,742	3,557	7,449	World	19,405	833	112,521	136,145	61,860	World	61	0	326	409	398
1	USA	132	432	741	1,326	2,067	USA	11,435	298	59,673	62,892	20,729	USA	35	0	173	200	151
2	China	8	244	78	270	931	UK	2,188	72	12,560	13,404	7,052	UK	7	0	33	54	51
3	UK	32	108	140	283	531	Australia	189	44	3,242	6,672	4,931	Australia	0	0	8	18	29
4	Australia	7	100	70	169	499	China	391	80	2,452	5,409	3,922	Canada	2	0	10	17	21
5	Germany	11	89	81	185	386	Germany	845	53	4,889	6,987	3,370	Germany	3	0	17	18	19
6	Canada	17	67	97	200	347	Canada	717	21	4,243	6,503	3,091	Spain	0	0	3	8	18
7	Spain	4	46	43	114	257	Spain	142	20	2,007	3,775	2,509	China	1	0	4	10	15
8	France	7	42	50	114	234	France	574	27	2,631	3,267	1,935	France	2	0	9	8	15
9	Italy	3	51	21	72	198	Netherlands	305	27	2,816	2,835	1,604	Netherlands	2	0	14	7	13
10	Netherlands	7	49	33	101	177	Switzerland	429	24	2,583	3,346	1,433	Denmark	0	0	4	5	8
11	Switzerland	8	30	36	63	155	Italy	154	24	945	2,369	1,281	Switzerland	2	0	9	16	7
12	Sweden	2	21	40	59	126	Sweden	281	13	1,660	2,315	958	Italy	1	0	2	4	6
13	Norway	3	16	17	37	101	Norway	66	6	917	1,741	847	Norway	0	0	2	5	5
14	India	1	20	8	31	100	Denmark	224	7	1,461	1,153	788	Austria	0	0	2	1	5
15	Japan	5	19	31	69	92	Austria	0	6	524	562	605	New Zealand	0	0	6	3	4
16	Belgium	2	20	12	36	79	New Zealand	38	7	1,106	1,129	532	Sweden	1	0	5	10	3
17	Denmark	4	15	18	24	73	Belgium	58	12	499	980	485	South Africa	0	0	3	2	3
18	Finland	3	19	20	30	72	Japan	350	13	1,615	1,599	484	Czech Republic	0	0	1	3	2
19	New Zealand	2	14	25	23	69	South Africa	108	3	730	761	440	Brazil	1	0	2	1	2
20	South Africa	2	10	13	30	57	Finland	88	8	663	906	371	Japan	2	0	5	3	1

Note Countries (regions) ranked by the number of articles, cited frequency and the number of highly cited articles during the period 2010–2014

24.1.3 Key Research Topics

Based on the keywords cluster of SCI/SSCI-indexed articles during the period 2000–2014 (Fig. 24.1), we have identified six popular research themes in detection and attribution: detection and attribution of climate change/variability, detection and attribution of climate change impacts, detection and attribution of land use change, detection and attribution of ecosystem change, detection and attribution of hydrological cycle change, and detection and attribution of crop yield change. The research methods included model, remote sensing and long-term observation data. The influence of human activities was represented by policy, management, land use, deforestation and fire.

We further investigated the temporal changes in the popular topics during the period 2000–2014 by analyzing the keywords sequential variation of SCI/SSCI-indexed articles (Fig. 24.2). For foreign scholars, the "climate change", "vegetation change", "ecosystem", "agriculture", "hydrology", "climate change impacts", "model", "human activities" and "land use change" have been the most frequently used keywords since 2000. The frequencies of these keywords increase obviously, but their consistency suggests that the major topics in this field have been investigating the impacts of climate change and human activities on vegetation, ecosystem, hydrological cycle and agricultural production since 2000. Chinese scholars followed and made great progress with these topics as well. The frequent keywords from Chinese scholars are almost the same as those from other countries, including "climate change", "vegetative change", "hydrology", "climate change impact", "agriculture", "land use change", "ecosystem", "hydrology", "climate change impact" and "land use change" during the period 2010–2014. This suggests that the key research topics in this field are the same in China. Chinese scholars have more studies on detection and attribution of basin hydrological cycle change, land use change, and permafrost change, but less studies on detection and attribution of environment change and land surface change. The study methods mainly include models, remote sensing and long-term observation data. Chinese scholars have made substantial progress in using these methods from 2000 to 2014.

24.1.4 The Role of NSFC in Supporting the Research on Detection and Attribution of Changes in Land Surface Sensitive Components

National Natural Science Foundation of China (NSFC) has played a crucial role in detection and attribution studies, as indicated by NSFC-funded projects and outcomes (Table 24.2). During the period 2000–2014, NSFC provided 124,915

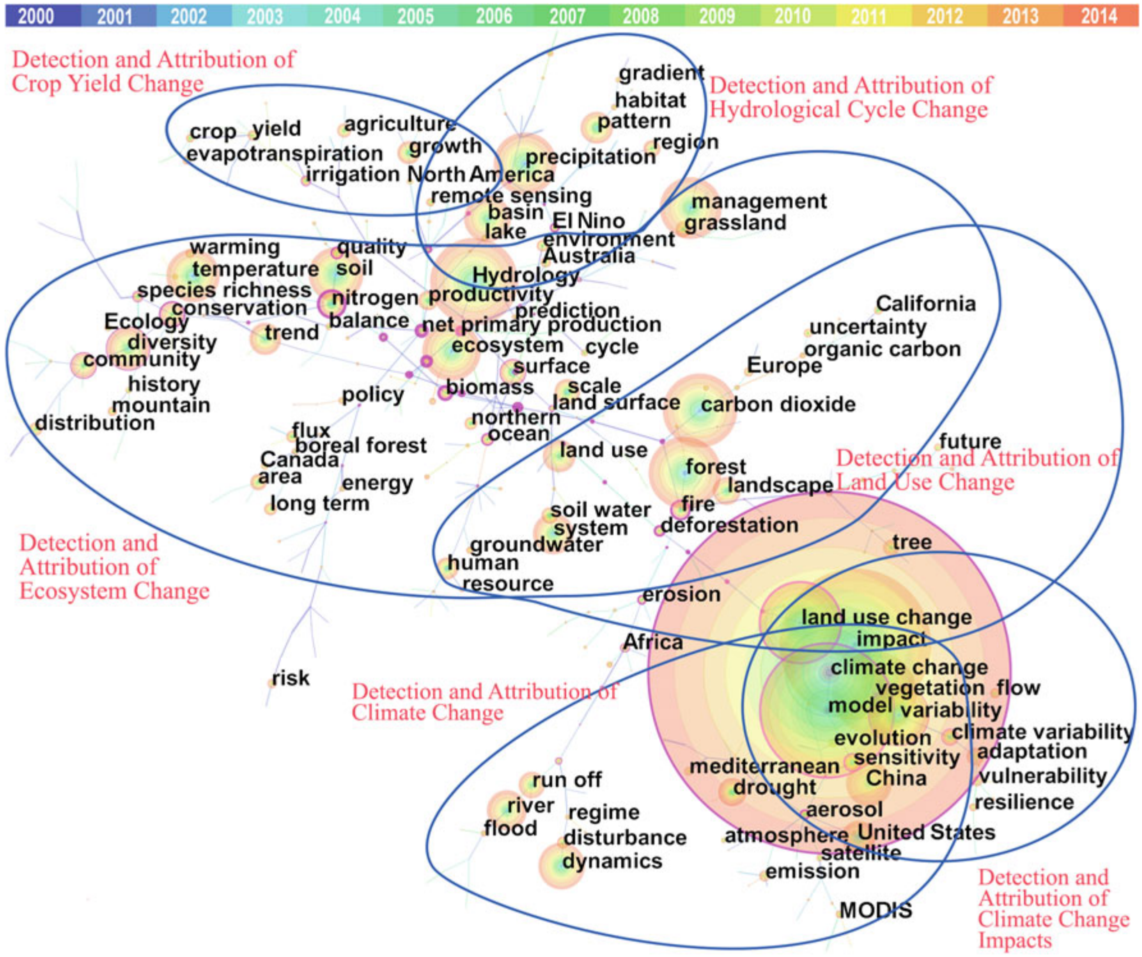

Fig. 24.1 Co-occurrence network of SCI/SSCI-indexed article keywords on "Detection and Attribution of Changes in Land Surface Sensitive Components" during the period 2000–2014

thousand yuan to 186 projects for 169 principal investigators in 70 research institutions or universities. In every five year period from 2000 to 2014, the amount of funds, number of projects, principal investigators and research institutions or universities increased notably. For example, from 2000–2004 to 2010–2014, the number of NSFC-funded projects increased from 21 to 97, the amount of funds increased from 22,650 thousand yuan to 74,306 thousand yuan, the number of principal investigators increased from 19 to 96, and the number of research institutions or universities funded increased from 12 to 53. In addition, NSFC supports also laid the foundation for Chinese scholars to launch or participate in international global environmental change research programs.

The outcomes from NSFC-funded projects were fruitful (Table 24.2). 10.0 % of the identified 12,748 SCI/SSCI-indexed articles were from Chinese scholars during the period 2000–2014. The proportion increased from 4.5 % during the period 2000–2004 to 12.5 % during the period 2010–2014, suggesting that the impacts of Chinese scholars in this field have increased gradually. Two-thirds (65.1 %) of the identified SCI/SSCI-indexed articles from Chinese scholars were funded by NSFC during the period 2000–2014. The proportion increased notably from 28.2 % during the period 2000–2014 to 73.7 % during 2010–2014.

The keywords temporal trajectory graph for NSFC-funded projects on "Detection and Attribution of Changes in Land Surface Sensitive Components" during the period 2000–2014 shows that "climate change", "response mechanism", "attribution of water resources change", "attribution of ecosystem change", "model simulation", "observation data", "attribution of Tibet Plateau Change", "attribution of environment evolution", "attribution of agro-pastoral transitional zone change", "human activities", "temporal and spatial change", "remote sensing monitoring" and "attribution of crop yield change" are the most frequent keywords (Fig. 24.3). The keywords whose frequency increased notably from 2000 to 2014 include "climate change", "response mechanism", "water resources change", "ecosystem change" and "model simulation". These keywords represent the topics, subjects and methods, as well as the characteristics, of studies in this

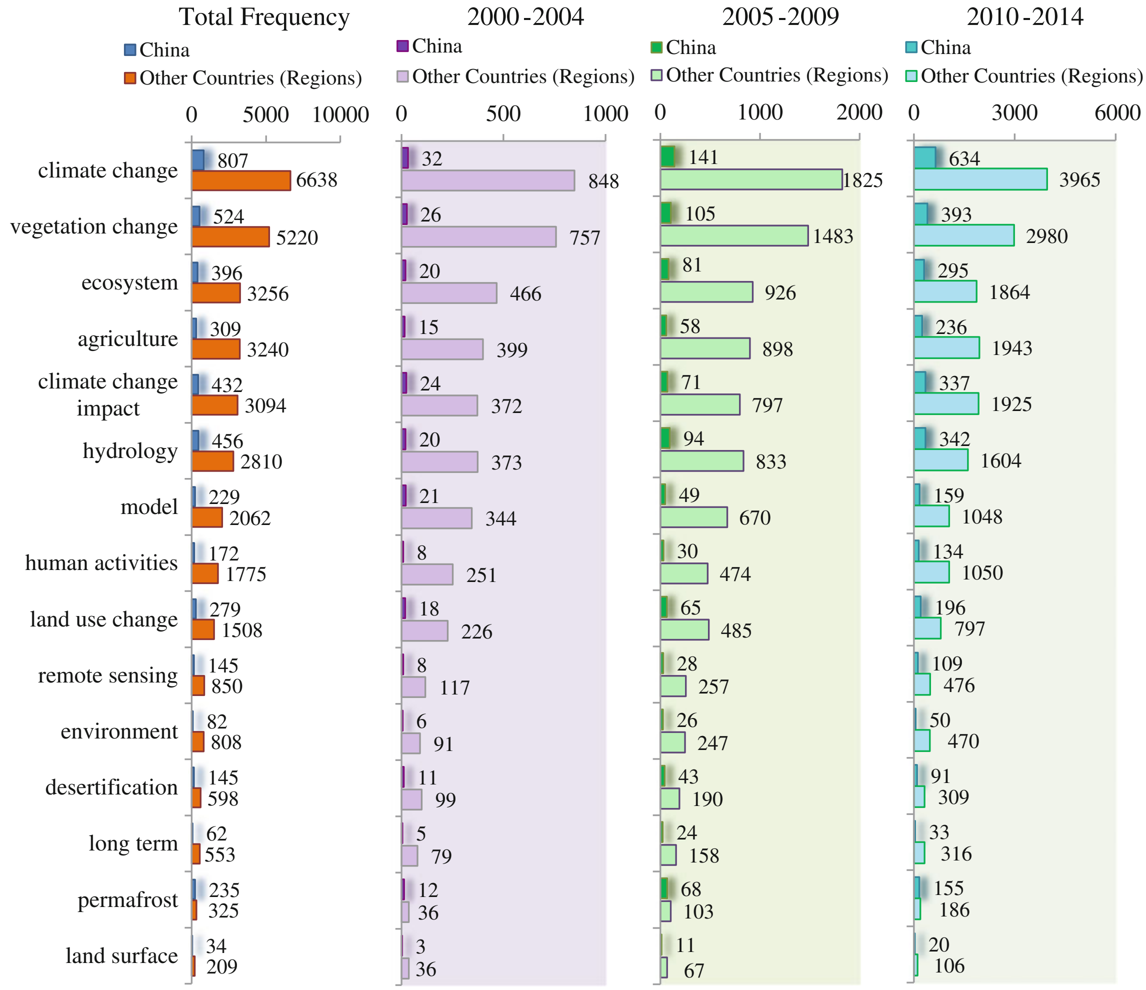

Fig. 24.2 Keyword temporal trajectory graph for SCI/SSCI-indexed articles on "Detection and Attribution of Changes in Land Surface Sensitive Components" during the period 2000–2014

Table 24.2 NSFC-funded projects and SCI/SSCI-indexed articles on "Detection and Attribution of Changes in Land Surface Sensitive Components" during the period 2000–2014

SCI/SSCI-indexed articles					NSFC-funded projects			
Periods	Number of articles	% of articles by Chinese authors	% of articles with NSFC funding by Chinese authors	% of articles funded by MOST among those with NSFC funding	Number of projects	Funding (10,000 yuan)	Number of PIs	Number of institutions
2000-2004	1,742	4.5	28.2	0.0	21	2,265.0	19	12
2005-2009	3,557	7.6	46.1	25.0	68	2,795.9	66	29
2010-2014	7,449	12.5	73.7	55.2	97	7,430.6	96	53
2000-2014	12,748	10.0	65.1	49.3	186	12,491.5	169	70

field in China. The typical research topics include investigating the impacts of climate change and human activities on terrestrial ecosystem change, land use change, vegetation and plant phenology change, vegetation and glacier change on the Tibet Plateau, agro-pastoral transitional zone change, water resource change in the Yellow River basin, crop phenology and yield change. These studies mainly investigate the impacts of climate change and human activities on land surface sensitive components, including impact mechanisms, degree and temporal and spatial pattern, using model

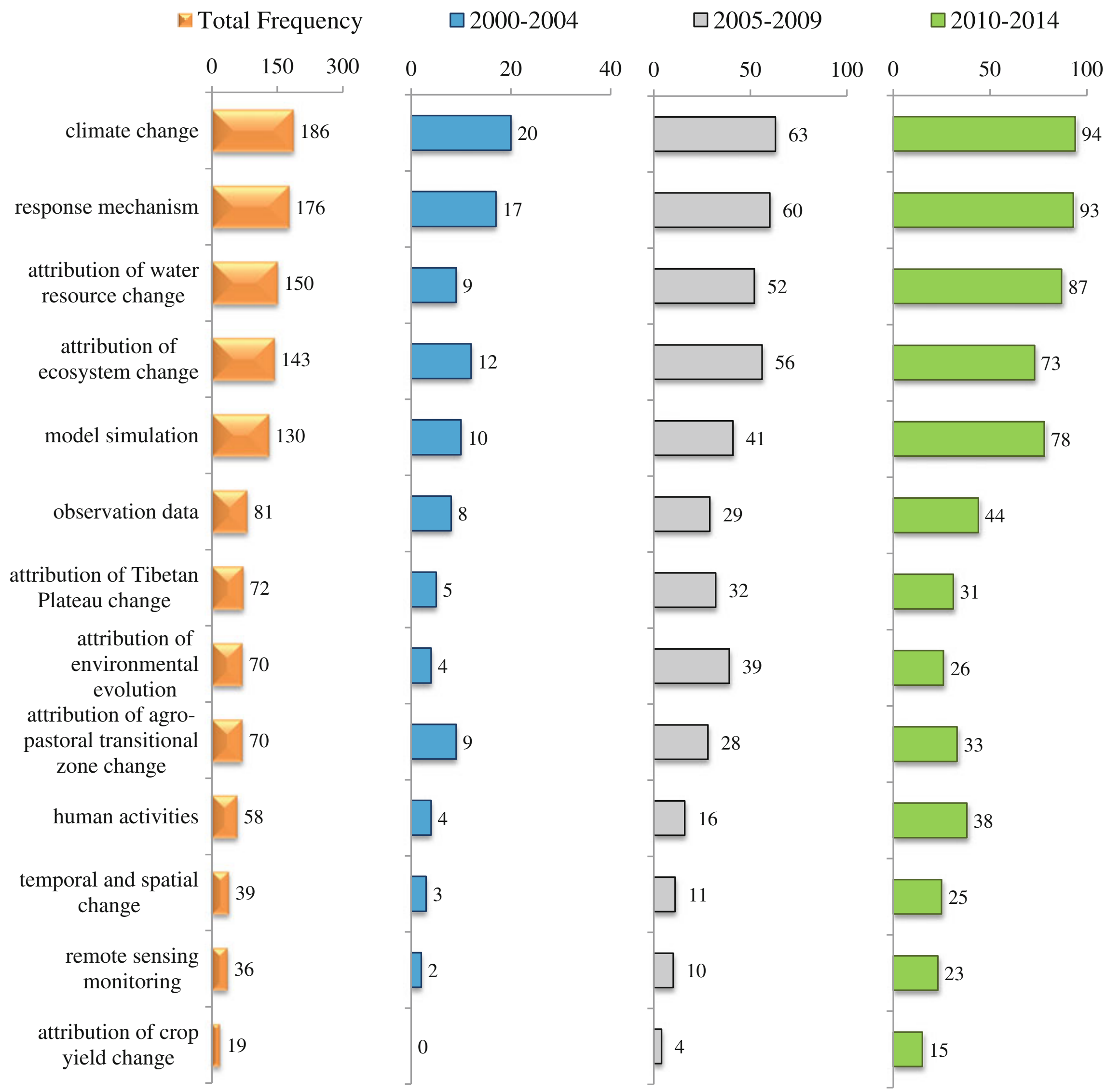

Fig. 24.3 Keyword temporal trajectory graph for NSFC-funded projects on "Detection and Attribution of Changes in Land Surface Sensitive Components" during the period 2000–2014

simulation, remote sensing and long-term observation data, and further analyze the relative contributions of climate change and human activities to the changes in land surface sensitive components.

In sum, the statistics on NSFC-funded projects and outcomes indicate that NSFC has played a crucial role in promoting this research field in China in terms of developing research teams, guiding research directions and increasing research outcomes. Owing to the support of NSFC, the impacts of Chinese scholars have been gradually increasing in the detection and attribution field.

24.2 Research Advances and Problems

As shown in the keywords cluster graph for the period 2000–2014 (Fig. 24.1), there are about six key research topics in the field of detection and attribution. Here, we review the research advances and problems in the world and in China for three key research topics, based on both bibliometric analysis and literature reviews. The three key research topics are detection and attribution of ecosystem change, hydrological cycle change, and agricultural system change.

24.2.1 Detection and Attribution of Terrestrial Ecosystem Change

Bibliometric Analysis of Contemporary Research

There has been 11,469 articles on detection and attribution published since 2000 (excluding those published by Chinese scholars), in which 6638 (57.9 %) articles use "climate change" as one of keywords, 3094 (27.0 %) articles use "climate change impact" as one of keywords, 5220 (45.5 %) articles use "vegetation change" as one of the keywords, 3256 (28.4 %) articles use "ecosystem" as one of keywords, and 1775 (15.5 %) articles use "human activities" as one of keywords. In addition, the articles use the keywords "permafrost" (2.8 %), "desertification" (5.2 %) and "land surface" (1.8 %) as well. The articles using the keywords "climate change", "climate change impact" and "human activities" increased sharply 3–4 times from 2000 to 2014, suggesting detection and attribution of ecosystem change should be one of key research topics in this field. Vegetation and ecosystem change have been traditionally popular research topics, but recently attributions of vegetation and ecosystem change to climate change (climate change impact) and human activities have become increasingly popular.

Contemporary Research

Major progresses in "detection and attribution of ecosystem change" in recent decades include (1) new and longer term observations, improved models and more extensive analyses of existing data provide new or stronger evidence that impacts of recent changes in climate on ecosystem occur on all continents (IPCC 2014). Long-term plant phenology observation data, land-atmosphere fluxes of carbon dioxide, latent heat, and sensible heat from eddy covariance observations, and satellite-based high resolution land surface biophysical parameters such as daily gross primary production (GPP), annual net primary production (NPP), leaf area index (LAI) and NDVI, have increasingly become available. These improved detection and attribution studies substantially. (2) Impacts of extreme climate events (heat and drought stress), atmospheric carbon dioxide (CO_2), ozone (O_3), nitrogen (N), and human interventions such as land use, overgrazing, reforestation and deforestation on ecosystem change are increasingly quantified. Free-air CO_2 enrichment (FACE) experiments, temperature free-air-controlled enhancement (T-FACE) experiments, as well as elevated ozone concentration experiments, have been extensively conducted. (3) Land surface models and ecosystem models have gradually improved with increased land surface data and experimental data. For example, land surface models have evolved from simple, unrealistic schemes into credible representations of the global soil-vegetation-atmosphere transfer system as advances in plant physiological and hydrological research, advances in satellite data interpretation, and the results of large-scale field experiments have been exploited. This progress has provided important data and model tools for detection and attribution. For examples, Ciais et al. (2005) used measurements of ecosystem carbon dioxide fluxes, remotely sensed radiation absorbed by plants, and country-level crop yields, together with a terrestrial biosphere simulation model, to assess continental-scale changes in primary productivity during 2003, and their consequences for the net carbon balance. They found that the productivity reduction in Eastern and Western Europe can be explained by the rainfall deficit and extreme summer heat, respectively. Tian et al. (2011) evaluated the effects of multiple environmental factors (climate, atmospheric CO_2, ozone pollution, nitrogen deposition, nitrogen fertilizer application, and land cover/land use change) on net carbon balance in terrestrial ecosystems of China for the period 1961–2005. Forkel et al. (2015) assessed the performance of a newly developed phenology module within the LPJmL (Lund-Potsdam-Jena managed Lands) DGVM with a comprehensive ensemble of three satellite data sets of vegetation greenness and ten phenology detection methods, thoroughly accounting for observational uncertainties, quantified the relative importance of environmental controls on interannual variability and trends of land surface phenology and greenness at regional and global scales.

Bibliometric Analysis of Contemporary Research in China

There have been 1279 articles on detection and attribution published since 2000 by Chinese scholars, in which 807 (63.1 %) articles use "climate change" as one of keywords, 432 (33.8 %) articles use "climate change impact" as one of keywords, 524 (41.0 %) articles use "vegetation change" as one of keywords, 396 (31.0 %) articles use "ecosystem" as one of keywords, 172 (13.4 %) articles use "human activities" as one of keywords. In addition, the articles use the keywords "permafrost" (18.4 %), "desertification" (11.3 %) and "land surface" (2.7 %) as well. The numbers of articles using these keywords increased 15–20 times from 2000 to 2014, suggesting Chinese scholars have made great progress working on these topics.

Contemporary Research in China

Major progresses in China include: (1) establishing the Chinese Ecosystem Research Network (CERN), Chinese Terrestrial Ecosystem Flux Observational Research Network (China FLUX) and China phenology observation network, which provides long-term data of ecosystem change. CERN was established in 1988 to conduct long-term ecological monitoring on the biological and environmental elements of the major terrestrial and aquatic ecosystems, including cropland, forest, grassland, desert, marshes, lakes, and bays (Fu et al. 2010). ChinaFLUX, established in 2002, applies the eddy covariance technique and the chamber method to continuously measure the exchanges of CO_2, water vapor and energy between terrestrial ecosystems and the atmosphere across diurnal, daily, seasonal and interannual time scales over typical forest, grassland and cropland ecosystems in China (Yu et al. 2006). (2) Establishing the NorthEast Chinese Transect (NECT) and North-South Transect of Eastern China (NSTEC) in 1993 and 1999, respectively. NECT and NSTEC are mainly driven by moisture and temperature, respectively. Four field surveys and samplings along NECT were conducted in 1995, 1997, 1999 and 2001, respectively. These surveys were conducted over 107 sites across forests and grasslands in northeast China. In addition, two extensive surveys were carried out along NSTEC in 2006 and 2007, respectively. The NSTEC survey covered all forest types in eastern China using 125 sites (Fu et al. 2010). (3) Conducting detection and attribution of ecosystem change, aridification and desertification in northern China. NSFC and the China Ministry of Science and Technology (MOST) have launched several large research projects in the past decades to investigate ecosystem and environment change, as well as the human and natural causes. These projects have provided fruitful results. For example, the key research plan "China west environmental and ecological science (2001–2010)" funded by NSFC made important progress on environment evolution, hydrological cycle and water resource sustainable unitization, ecological processes and their regulation, and modern human activities and their impacts (Leng et al. 2011). The National Basic Research Program of China "Predictive Study of Aridification in Northern China in Association with Life-Supporting Environment Changes (1999–2004)" accelerated the understanding on aridification in Northern China, obtained new evidence on aridification in Northern China and the roles of human activities in aggravating aridification (Ye and Fu 2004). The National Basic Research Program of China "Aeolian Desertification Processes and Its Control in the Northern China (2000–2005)" and "The Processes of Oasification-Desertification and Their Responding to Human Activities & Climate Change and Their Regulation in the Arid Region of China (2009–2013)" advanced our understanding of desertification processes, evolution, pattern and driving mechanisms, as well as the human and natural causes in the past 2000 years and most recent 50 years (Wang et al. 2006b). (4) Conducting environment-controlled experiments and human intervention experiments. These experiments include FACE experiments, OTC (Open-Top Chamber) experiments, T-FACE experiments, elevated ozone concentration experiments, overgrazing experiments, and nitrogen addition experiments (Wan et al. 2007; Bai et al. 2012). (5) Conducting detection and attribution studies based on long-term observation data, remote sensing data and modeling at large scales. More and more scholars applied remote sensing and ecological models to conduct detection and attribution of ecosystem change at national or regional scales. For example, Fu and Wen (1999) investigated the variations of ecosystems in the Asian region and their relationships with the monsoon climate. The results show that the spatial and temporal variability of ecosystems are characterized by their strong response to variations in monsoon rainfall. The high rate of variation in monsoon climate strongly influences variation in Asian ecosystems. Lü et al. (2015) analyzed trends in vegetation change using remote sensing and linear regression. Climate and socioeconomic factors were included to screen the driving forces for vegetation change using correlation or comparative analyses. The results indicated that China experienced both vegetation greening (restoration) and browning (degradation) with great spatial heterogeneity. Socioeconomic factors, such as human populations and economic production, were the most significant factors for vegetation change. Piao et al. (2015) used three different satellite-derived LAI datasets for detection as well as five different process-based ecosystem models for attribution. Rising atmospheric CO_2 concentration and nitrogen deposition are identified as the most likely causes of the greening trend in China. The models generally agree on the negative impacts of climate change in north China and Inner Mongolia and the positive impact in the Qinghai–Tibet Plateau. Fang et al. (2014) quantified the growth enhancement due to environmental changes (CO_2 concentration, nitrogen deposition, temperature, and precipitation) and its contribution to the biomass carbon sink in Japan's forests, using a unique time series of an age-class dataset from six national forest inventories in Japan.

Contributions by Chinese Scholars and Subsequent Problems

Chinese ecosystems are diverse, with extensive impacts from human activities. The studies conducted by Chinese scholars on various ecosystems including cropland, forest, grassland, desert, marshes, lakes, and bays in contrasting geographical and climate zones, provide plenty of evidence and interesting case studies, greatly enriching the studies on detection and attribution. Generally, Chinese scholars are following the studies of their colleagues abroad, as indicated by changes in keywords such as climate change, land use, remote sensing and drought (Fig. 24.4). The important and

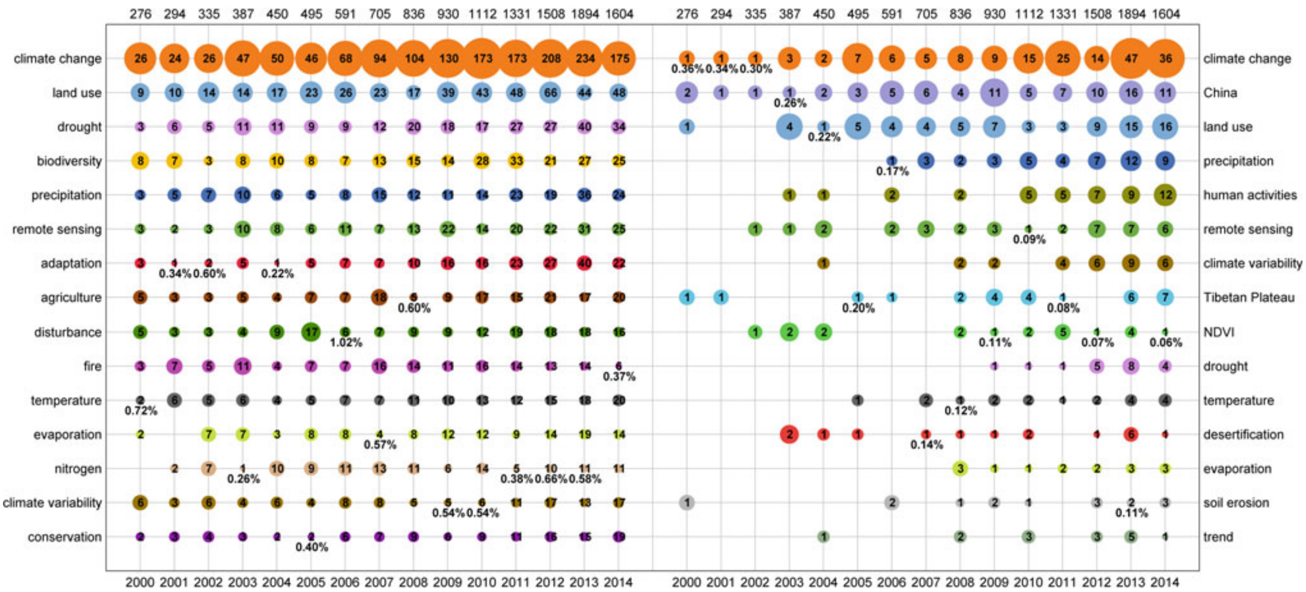

Fig. 24.4 Comparative diagram of prominent keywords on "Detection and Attribution of Changes in Land Surface Sensitive Components" by Chinese authors and others in SCI/SSCI-indexed articles during the period 2000–2014. *Note* Right panel shows keywords used by Chinese authors and left panel shows those used by the authors from other countries (regions). Size of circles denotes the ratio of a certain keyword frequency to the total article number in a specific year. The annual total number of articles is shown at the top of the diagram. The frequency of the keyword is shown inside the circle. The size of circles in the diagram for Chinese authors are magnified for clear display

novel ideas, technologies, instruments and ecosystem models applied in China usually originated from abroad, for example, the satellite and remote sensing technology, the eddy covariance observations technology, FACE and T-FACE experiments, as well as the most popular ecosystem models.

24.2.2 Detection and Attribution of Hydrological Cycle Change

Bibliometric Analysis of Contemporary Research

Among the 11,469 articles on detection and attribution published since 2000 (excluding those published by Chinese scholars), 2810 (24.5 %) articles use "hydrology" as one of keywords.

Contemporary Research

In the past decades, improvements have been made to observational data sets, taking more complete account of systematic biases and heterogeneity in observational systems, further developing uncertainty estimates, and correcting detected data problems (IPCC 2014). Earth water cycle observations have improved. Orbiting satellites are now collecting data relevant to all aspects of the hydrologic cycle, including evaporation, transpiration, condensation, precipitation, and runoff. NASA even has one satellite, Aqua, named specifically for the information it is collecting about the many components of the water cycle. The Terra satellite also has MODIS and CERES instruments onboard, and several other spacecraft have made or are making unique water-cycle measurements. The Ice, Cloud, and Land Elevation Satellite (ICESat) collects data on the topography of the Earth's ice sheets, clouds, vegetation, and the thickness of sea ice. The Gravity Recovery and Climate Experiment (GRACE) scientists are able to derive information about changes in the mass of ice sheets and glaciers and even changes in groundwater around the world. CloudSat is advancing scientists' understanding of cloud abundance, distribution, structure, and radiative properties (how they absorb and emit energy, including thermal infrared energy escaping from the Earth's surface). CloudSat's radar allows the detection of the much smaller particles of liquid water and ice in the large cloud masses that contribute significantly to our weather. These have improved our understanding on the physical, chemical and biological aspects of the Earth system notably. Increasing in situ and satellite observations contribute substantially to progresses in detection and attribution of changes in cryosphere, snow cover, permafrost, evapotranspiration, runoff and water resources (Roderick and Farquhar 2002; IPCC 2014). Impacts of climate change on the hydrological cycle and the availability of freshwater resources have been observed on all continents and many islands. Combined in situ and satellite observations indicate a decline of 8 % in northern hemisphere spring snow cover extent since 1922. Glaciers are detected to have shrunk worldwide, as a result of climate change, affecting runoff and water resources downstream. Climate change is the main driver of permafrost warming and thawing in both high-latitude and high-elevation mountain regions. Hydrological systems changed in many regions because of changing precipitation or melting cryosphere, affecting water resources, water quality, and sediment transport. At the same time, land surface data and hydrological models are improving and increasingly applied for detection and attribution. For example, Gedney et al. (2006) use a mechanistic land surface model and optimal fingerprinting statistical techniques to attribute observational runoff changes to climate change, solar dimming, CO_2 and land use change. Piao et al. (2007) using historic land-use data, together with a biogeography–biogeochemistry model, show that land-use change plays an additional and important role in controlling regional runoff values, particularly in the tropics. Land-use change has been strongest in tropical regions, and its contribution is substantially larger than that of climate change. Detection and attribution have been conducted for changes in a number of hydrological variables, including precipitation, heavy precipitation, atmospheric humidity, oceanic surface salinity, cryosphere, glaciers, snow cover, permafrost changes, evapotranspiration, runoff, droughts and floods. The majority of studies have focused on quantifying attributable risk. For example, Pall et al. (2011) provide an example of multi-step assessment of attributable risk using a physically based model, applied to the floods that occurred in the UK in the autumn of 2000. The results show that including the influence of anthropogenic greenhouse warming increases flood risk at the threshold relevant to autumn 2000 by around a factor of two in the majority of cases, but with a broad range of uncertainty. IPCC (2014) concludes that it is likely that human influence has affected the global water cycle since 1960. This assessment is based on the combined evidence from the atmosphere and oceans of observed systematic changes that are attributed to human influence in terrestrial precipitation, atmospheric humidity and oceanic surface salinity through its connection to precipitation and evaporation. However, remaining observational and modelling uncertainties, and the large internal variability in precipitation, preclude a more confident assessment at this stage.

Bibliometric Analysis of Contemporary Research in China

There have been 1279 articles on detection and attribution published since 2000 by Chinese scholars, in which 456 (35.7 %) articles use “hydrology” as one of keywords.

Contemporary Research in China

China has launched FY-3 satellites, China’s second generation polar-orbiting meteorological satellites, with substantively enhanced functionalities and technical capabilities. They are designed to enhance China’s three dimensional atmospheric sounding capability and global data acquisition capability, in an effort to collect more cloud and surface characteristics data, from which meteorologists may infer out atmospheric, land surface and sea surface parameters that are global, all-weather, three-dimensional, quantitative, and multi-spectral. Chinese scholars have developed GCMs (i.e. BCC, LASG-IAP, LASG-IAP) involved in CMIP5, and conducted detection and attribution of change in climate variables such as temperature, precipitation and extreme climate events (Sun et al. 2014). Chinese scholars have also conducted great works on detection and attribution of cryosphere, glaciers and permafrost on the Tibet Plateau (Li et al. 2010; Yao et al. 2012). Detecting runoff change and attributing it to climate change and human activities (dams and reservoirs, land use change, water withdrawn for living, agricultural and industrial purposes) has been one of major research topics in China. Some scholars investigate the roles of temperature, precipitation, solar radiation, vapor pressure and wind speed in evapotranspiration and runoff changes (Tang et al. 2013). A number of studies investigate the hydrological and sediment change in the Yellow River basin and tried to attribute the zero-flow phenomenon to climate change and human activities using hydrological models, together with long-term runoff observation data from gauging stations (Yang et al. 2004; Zheng et al. 2009; Wang et al. 2016). Such studies first use calibrated and validated hydrological models to reconstruct natural runoff time series data, and then use the difference between the annual observed runoff and the reconstructed natural runoff, i.e. the additional runoff reduction, as a result of local human activities (Liu et al. 2010; Wang et al. 2010). For example, Wang et al. (2016) use an attribution approach to analyze 60 years of runoff and sediment load observations from the traverse of the Yellow River over China’s Loess Plateau—the source of nearly 90 % of its sediment load. They find that landscape engineering, terracing and the construction of check dams and reservoirs were the primary factors driving reduction in sediment load from the 1970s to the 1990s, but large-scale vegetation restoration projects have also reduced soil erosion from the 1990s onwards. Chinese scholars have also investigated water resource shortages in the Huang-Huai-Hai Plain (Wang et al. 2010; Tang et al. 2013). The water requirements for ecosystems, agriculture, industry and living, as well as the roles of climate change and human activities in changes in the water cycle components, have been extensively studied (Yang et al. 2008; Liu et al. 2010). Process-based hydrological models are increasingly applied for robust attribution. Chinese scholars have developed hydrological models such as GBHM, WEP-L, WEB-DHM, HIMS and DBH model. Based on analyses of the interaction between socio-economic development and the evolution of hydrological cycle, Wang et al. (2006a) propose the nature-society dualistic hydrological cycle theory that emphasizes the driving effect of socio-economic development on the natural hydrological cycle and its response mechanism on water hydrological processes. Then a dualistic hydrological model was developed by coupling between the socio-economic calculable general equilibrium model and the distributed hydrological model called WEP (Water and Energy Transfer Processes). NSFC has launched a key research plan on the integrated study of the water-ecosystem-economy of the Heihe River Basin (Cheng et al. 2014). An integrated platform, which incorporates monitoring, modeling and data manipulation, has been developed to support the integrated study of the basin. Integrated models have been used for understanding complex interactions within the 'water-soil-air-plant-human' continuum and some decision support systems (DSSs) have been developed and used in small-scale water management, such as irrigation water allocation. Future work will develop a fully integrated water–ecosystem–economy model and a spatially explicit DSS that takes integrated scientific models as its framework for supporting sustainable development of the river basin.

Contributions by Chinese Scholars and Subsequent Problems

Water resource is a major problem in many regions of China. Human activities such as land use change, agricultural, industrial and human water use have intensive impacts on regional water resources. Chinese scholars have tackled the detection and attribution of water hydrological change, and this work has resulted in several excellent case studies such as in the Huang-Huai-Hai Plain, the Yellow River basin and the Tibet Plateau. They have also developed hydrological models and integrated river basin studies. Chinese scholars are following the key research topics in the world, as indicated by changes in the keywords such as drought, precipitation and evaporation (Fig. 24.4). In comparison to scholars from the remainder of the world, Chinese scholars are generally weak at the novel and fundamental research focused on earth water cycle observations and earth system modelling. Most studies are limited to basin, regional or national scales; studies at the global scale are scarce. The water cycle observation network is not well developed, in particular in remote and poor regions to monitor the impact of human activities. More work are needed to improve the hydrological models. The integrated studies that take into account human activities such as water withdraw and dams and the roles of social-economic factors such as policy and water prices are still scarce.

24.2.3 Detection and Attribution of Agriculture System Change

Bibliometric Analysis of Contemporary Research

There are 11,469 articles on detection and attribution published since 2000 (excluding those published by Chinese scholars), in which 3240 (28.2 %) articles use "agriculture" as one of keywords.

Contemporary Research

Climate change impacts on agriculture have been a research priority for a long time. The early work used crop models, driven by future climate change scenarios, to project future climate impacts on crop yields. Then, the studies are increasing to detect historical crop yield change and attribute it to climate change and agronomic management, using census crop yield data and statistical regression methods (Lobell and Asner 2003; Tao et al. 2008, 2012; Ray et al. 2015). Later, improved datasets and statistical methods, such as long-term observation data on crop phenology and yield data at experiment stations, have been used for detection and attribution of crop yield change, including the impacts of mean climate change and climate extremes (Peng et al. 2004; Lobell et al. 2011; Tao et al. 2013a, 2014). These studies indicate that ongoing climate change has had significant impacts on crop phenology and yields across broad regions of the world, although the impact mechanisms and patterns are quite complex and heterogeneous. Furthermore, climate impacts are compounded by shifts in cultivars and agronomic management (Liu et al. 2010). Therefore, some studies try to disentangle the roles of climate change, cultivar renewal and agronomic management improvement, as well as each climate variable, in crop yield change, using a combination of crop models and long-term field experiment data (Xiao and Tao 2014). Environment-controlled experiments, such as FACE experiments, T-FACE experiments, as well as elevated ozone concentration experiments, have also been extensively conducted for major crops including rice, wheat, maize and soybean (Kimball et al. 2008). These experiments accelerate the understanding of the impact mechanisms and magnitude of elevated CO_2, elevated O_3 and extreme temperature on crop growth and grain formation. Agricultural system models are important tools for attribution of crop yield change; however, they incorporate uncertainties in simulating elevated CO_2, elevated O_3, extreme temperature, pests and diseases. The international community launched the Agricultural Model Intercomparison and Improvement Project (AgMIP), which is a major international effort linking the climate, crop, and economic modeling communities with cutting-edge information technology to produce improved crop and economic models (Rosenzweig et al. 2013).

Bibliometric Analysis of Contemporary Research in China

There have been 1279 articles on detection and attribution published since 2000 by Chinese scholars, in which 309 (24.2 %) articles use "agriculture" as one of keywords.

Contemporary Research in China

In the past decades, China has established a number of comprehensive agricultural experimental stations and agricultural meteorological experimental stations, where the long-term experimental observations are gathered. Chinese scholars have used long-term census crop yield data at the provincial and county scales to conduct detection and attribution of crop yield change, using statistical and regression methods (Tao et al. 2008, 2012). The Chinese Agricultural Meteorological Observation Network provides unique long-term observation data on crop growth and yields at hundreds of stations across China. This unique observation dataset covers a larger number of experiment stations and a longer time period (Tao et al. 2006, 2013a). The greater scope of the dataset in both spatial and temporal dimensions positions us to estimate the effects of climate change on crop yields more precisely and with less bias than prior studies (Tao et al. 2013a). Climate change impacts are compounded by cultivar renewal, improved technology and agronomic management. Chinese scholars have developed methods to disentangle the roles of climate change, cultivar renewal and improved agronomic management, as well as each climate variable, in crop yield change, based on long-term detailed experimental data on crop cultivars, management, crop growth and yield, together with crop models (Liu et al. 2010; Xiong et al. 2012; Yu et al. 2012; Zhang et al. 2013; Xiao and Tao 2014). Chinese scholars also conducted FACE experiments, T-FACE experiments, as well as elevated ozone concentration experiments for major crops including rice, wheat and maize (Zhu et al. 2009). In addition, Chinese scholars used to apply crop models from abroad, but recently, several groups have developed new models such as the MCWLA family of crop models, Agro-C, VIP model and RiceGrow model. These models have been published in top international journals and some of them are involved in the AgMIP. In addition, Chinese scholars have also contributed work on detection and attribution of changes in cropland (Liu et al. 2014; Shi et al. 2014), cropping systems (Dong et al. 2009; Yang et al. 2015) and agricultural disasters (Tao et al. 2013b).

Contributions by Chinese Scholars and Subsequent Problems

Chinese agricultural production and food security have been of key concern worldwide. China has established a number of agricultural comprehensive experimental stations and an excellent agricultural observations network for long-term observations and experiments on diverse agricultural ecosystems. Chinese scholars have used these unique datasets, developed new approaches and conduced great work in detection and attribution of changes in crop growth and yields in contrasting geographical and climate zones across China. Chinese scholars also conduct environmental controlled experiments on crops such as FACE experiments, T-FACE experiments, as well as elevated ozone concentration experiments. These works contribute greatly to detection and attribution of changes in agricultural systems. In comparison to the scholars from other countries, Chinese scholars are generally weak at the novel and fundamental research such as the interactions between genotypes, the environment and management, as well as agricultural system modeling. Most studies are limited to the site, regional or national scales; studies on global scales are scarce. In addition, the studies on the impacts of social-economic factors such as agricultural policy, economy, markets and trade are scarce, and integrated studies that take into account agronomic management, and agricultural economics and policy factors are scarce as well.

24.3 Roadmap for Further Research

With global climate change and social-economic development, the impacts of human activities and climate change on land surface sensitive components are becoming more intensive, which poses challenges for the sustainable development of human society. Detection and attribution of changes in land surface sensitive components are essential to understand the mechanisms and trends in changes of land surface sensitive components. Based on the key research topics, the research frontiers, the comparisons between China and other countries, as well as the requirements of China's national development strategy, future research should pay more attention to building capacity for data observations and the development of natural and human system coupled models.

(1) **Building Capacity for Obtaining High Temporal and Spatial Resolution Data on Land Surface Sensitive Components, Providing a Solid Data Foundation for Detection and Attribution**

High quality data are essential for robust detection and attribution. More efforts are needed to conduct quantitative observation experiments on changes in land surface sensitive components, and to develop novel technologies, methods and instruments to obtain high quality data with high temporal and spatial resolution on land surface sensitive components. New technologies such as radar, satellite and remote sensing need to be developed and applied for land surface observations, particularly in remote and less developed regions with sparse data. In addition, observation technologies for land surface processes, such as heat, carbon and water flux between ocean-land-atmosphere, the internet of things and wireless data transfer technology for real-time monitoring, need to be further developed. These are important to provide big data for detection and attribution, and for understanding the drivers and mechanisms in changes of land surface sensitive components. In addition, conducting quantitative observation experiments of human impacts on land surface sensitive components, as well as developing data assimilation and scales matching methods for multiple sources and interdisciplinary data on natural and human factors, should be priority. For example, for detection and attribution of terrestrial ecosystem change, the high temporal and spatial resolution data on climate, CO_2 concentration, and human interventions such as deforestation, afforestation and land use change should be obtained. For detection and attribution of hydrological cycle change, high temporal and spatial resolution data on climate, land use change, water withdrawn for agricultural, industrial and human use, as well as water conservancy and hydropower engineering, are required. For detection and attribution of agricultural disasters, high temporal and spatial resolution data on extreme climate events, cropping system patterns, as well as agronomic cultivation and management practices, are required.

(2) **Developing Human and Natural Systems Coupled Models, Providing Robust Models, Methods and Tools for Detection and Attribution**

Due to combined influences of natural and human factors, the dynamics and processes of land surface sensitive components are extremely complicated. Future studies should focus on the interactions between these factors and their integrated impacts on land surface processes, investigating the impact mechanisms of human activities and natural factors, and disentangling the roles of human activities and natural factors in land surface dynamics. To do so, the land surface process models such as land surface models, ecosystem models, hydrological models and agricultural system models should be improved. Particularly, the human factors, and the integrated impacts of human and natural factors, should be better taken into account. The human and natural systems coupled process models, such as watershed ecosystem, hydrology and social-economy integrated models, should be developed. The impact mechanisms of multiple natural factors (water, soil, climate and biological factors) and human factors on land surface process should be investigated across scales in representative regions, by integrating the long-term observation data, remote sensing and models. The models should be further improved to better represent the integrated impacts of human and natural factors on land surface processes based on the improved data, knowledge and integrated studies. Finally, by integrating the detailed mechanism studies at site scale, high temporal and spatial resolution data on human and natural factors at regional scale, conducting scale transformation, and modeling the integrated impacts of human and natural factors on land surface processes and dynamics temporally and spatially, robust models to disentangle the relative contributions of human and natural factors to changes in land surface sensitive components can be developed at regional scales.

24.4 Summary

With the development of global change studies and the national strategy promoting sustainable development, "detection and attribution of changes in land surface sensitive components" have been developing quickly and becoming one of the major research fields in geographical science. Detection and attribution of changes in land surface sensitive components involves the detection of the changes in ecosystem, hydrology, land use, agricultural yield and disasters, investigation of the drivers and mechanisms of the change, involving the relative roles of human activities and natural processes. In the past decades, earth system observations using radar, satellite, remote sensing and ocean-land-atmosphere fluxes have provided large volumes of new observation data for detection and attribution studies. The development of earth system models, such as global climate models, regional climate models, land surface models, ecosystem models, hydrological models and agricultural system models, provides robust modeling tools for detection and attribution studies. Chinese scholars have made great progresses on detection and attribution of changes in plant phenology, NDVI, LAI, NPP, aridification, desertification, ecosystem function, evapotranspiration, runoff, droughts and floods, cropland and crop yield. Nevertheless, they are relatively weak at developing novel methods and technologies for earth system observations, and at developing novel earth system models, in comparison with the scholars from other countries. Future studies should focus on developing novel technologies, methods and instruments for earth system observations to obtain long-term, high quality and high resolution observation data; understanding the impact of human activities and natural factors on land surface sensitive components; as well as developing novel human and natural systems coupled models.

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Uncertainty of Spatial Information and Spatial Analysis

25

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Abstract

Uncertainty of spatial information and spatial analysis is one of the most essential and fundamental issues in geographical information science, and spatial data quality plays a critical role in geographical applications and decision-making. This chapter adopts a bibliometric quantitative analysis to study the history of international development in this field, to study the state and evolution of hot issues, and to analyse the position of China in this field as well as the contribution of NSFC with respect to gross, process and source. The result shows that the research of Chinese scholars in this field is overall top-ranked worldwide. However, there exists a gap of high-influence achievement in this field between our country and international developed countries. Therefore, further efforts should be made to strength the fundamental researches on uncertainty and trust in spatial information and to associate with the strategic requirements of national development.

Keywords

Error of spatial data • Uncertainty of spatial data • Trust in spatial data • Spatial data quality control • Application of uncertainty analysis in geosciences

A total of 17,465 SCI/SSCI-indexed articles are analyzed in the research area of uncertainty of spatial information and spatial analysis. Articles were identified from 68 international journals from 2000 to 2014. The number of journals that have published more than 15 of the relevant articles is 63 (Appendix V). The search query is as follows: ("GIS" OR "remote sensing" OR "geographical information system" OR "geographical analysis" OR "spatial analysis" OR "image" OR "imagery" OR "mapping" OR "cartography" OR "spatial information" OR "spatial" OR "surveying") AND ("uncertainty" OR "uncertainties" OR "accuracy" OR "accuracies" OR "positional accuracy" OR "error" OR "errors" OR "data quality" OR "reliability" OR "sensitivity analysis" OR "trust*" OR "validation" OR "calibration" OR "sampling" OR "inconsistency" OR "adjustment" OR "bias*").

25.1 Overview

The uncertainty of spatial information and spatial analysis is one of the basic core themes in geographic information science. Spatial data are the basic data used in earth system science, global change, geoscience analysis, and deep space exploration. They are also typical "big data". The quality of the spatial data is a necessary prerequisite for spatial data applications. Therefore, the quality and uncertainty of spatial data directly affects the information applications and decision-making, and is a major part of applications such as national geographic information infrastructures, smart city construction, and lunar exploration.

The uncertainty of spatial information and spatial analysis has always been part of the international academic frontier in the field of geographic information science. Since 1991, the American National Center for Geographic Information and Analysis (NCGIA) has listed "accuracy of spatial database" as the first of the 12 priority research subjects and the University Consortium for Geographic Information Science (UCGIS) has listed the "uncertainty of spatial data and spatial analysis" as one of the 10 priority research subjects since 1996. The European Union countries and Canada cooperated on the "uncertainty theory of geographic information" from 1998 to 2004. In 1997, academician **Li Deren** listed the "theory of quality and uncertainty of spatial data" as one of

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the 12 basic theories for priority development in China. National Natural Science Foundation of China (NSFC) listed the "uncertainty of geographic information" as one of the priority funding areas of the 10th Five-Year Plan in geographic information science. The "trust processing, data model, and error system of geographic information" is also listed as one of the major basic research topics and frontier exploration subjects of the 12th Five-Year Plan of surveying, mapping, and geo-information technology. The International Cartographic Association (ICA) set up the "data quality commission" to focus on the uncertainty and quality of spatial data. Recently, the Spatial Statistics and Uncertainty Modeling (WG-II/4) working group of the International Society for Photogrammetry and Remote Sensing (ISPRS) listed the "trust in spatial data and modelling" as one of the most important research topics (2012–2016).

25.1.1 Development of Research Questions

The uncertainty and quality of spatial data is a common problem in geoscience data acquisition, processing, analysis, and applications. In general, the development of the uncertainty of spatial information has consisted of three stages.

Since the 1960s, with the emergence and application of GISystems, researchers have found that errors occur in spatial data during map data acquisition, processing, and spatial analysis, and they began to focus on spatial data error (Perkal 1956; Blakemore 1983; Burrough 1986). The accuracy of spatial databases was listed as one of the most important problems of the basic theory of GISystems by the NCGIA (Goodchild and Gopal 1989; NCGIA 1989). Usually, the error of spatial data is defined as the difference between the real value and its observation. Spatial data error is classified into three categories. The first is systematic error, which has a regular magnitude and sign (positive and negative). The second is random error, which is random in the magnitude and sign, but with a statistical regularity. The third is gross error, which is the outliers in a set of data. For spatial data, the quality cannot only be measured by the magnitude of the error. For example, if the spatial data only contain random errors, the quality is usually measured by the accuracy, which reflects the degree of closeness of the measurement of a quantity to that quantity's true value (Huang et al. 1995; Liu et al. 1996).

Since the 1990s, researchers have tried to reveal the causes of spatial data errors in GISystems, and spatial data quality and uncertainty has been listed as one of the basic themes of geographic information science (Goodchild 1992; Shi 2005). With respect to the research in spatial data quality and uncertainty, there have been a number of important international conferences on the subject of spatial data uncertainty: the International Symposium on the Spatial Accuracy of Natural Resource Data Bases (ASPRS 1994) and the annual International Symposium on Spatial Data Quality (ISSDQ) (Shi et al. 1999). The uncertainty of spatial data refers to the extent that the "true value" of the data cannot be confirmed. Therefore, in a broad sense, it is a kind of generalized error, which includes the random error, systematic error, and gross error. It also consists of both measurable and immeasurable error (Liu et al. 1996). Uncertainty is a very wide concept, which includes the data error and randomness, and the incompleteness and ambiguity of the concept and the data (Caspary and Scheuring 1993; Shi 1994, 2005; Guptill and Morrison 1995; Heuvelink 1998; Zhang and Goodchild 2002; Ge and Wang 2003; Bai and Wang 2003; Cheng et al. 2004; Liu et al. 2010; Li et al. 2013; Tong et al. 2013). In 2002, the International Organization for Standardization (ISO) classified the uncertainty of spatial data as positional uncertainty, attribute uncertainty, logical consistency, data completeness, and data sources, according to the elements of geographic information data quality.

In recent years, researchers have gradually realized that the uncertainty of spatial data mainly involves the generation mechanism of the uncertainty, the mathematical expression model, and the propagation mechanism of spatial analysis and data mining. The uncertainty in the spatial data, analysis, and processing should be paid more attention. Furthermore, the uncertainty of spatial data involves the scientific understanding of the geographic entities and phenomena. With the development of geographic information science and earth observation system applications, it has been found that the trust, reliability, and usability of spatial data are the important foundation of spatial data quality control, analysis, and applications. As a result, the definitions of the basic concepts, scientific connotation, and theoretical framework of trust in spatial data according to the actual requirements of applications, have become the latest development in spatial data quality, and represent a shift from the understanding of the problem to solving the problem. The concept of trust in spatial data refers to the expectation of some match between the observed and the real object. Spatial data with a matching degree within the expectation range are called trusted spatial data. The degree of trust in spatial data is a quantitative evaluation of the quality of the spatial data. "Trust in spatial data and modelling" is now one of the most important research topics in the ISPRS WG-II/4.

25.1.2 Contributions by Scholars from Different Countries

Research in the uncertainty of spatial information and spatial analysis is one of the most active areas in geographic information science. In this section, we use the "quantitative analysis of literature" method to study the evolution of the research situation and the hot topics in this area, and to analyze the status of China in this area and the contributions of NSFC.

Using the literature retrieval and quantitative analysis, the research in the uncertainty of spatial information in China and other countries is compared and analyzed. Furthermore, the global situation and the status of China in this research area are evaluated. The keywords of remote sensing, geographic information, and uncertainty are used to retrieve the SCI/SSCI-indexed articles published from 2000 to 2014. The number of published articles, citations, and the number of highly cited articles are analyzed based on the retrieved articles. The top 20 countries (regions) for the SCI articles on "uncertainty" from 2000 to 2014 are shown in Table 25.1.

From the statistical results in Table 25.1, it can be seen that: (1) From the total number of published SCI/SSCI-indexed articles from 2000 to 2014, Chinese researchers ranked second only to USA in the world. However, the growth rate of published SCI/SSCI-indexed articles in China exceeded that of USA. There were 662 published SCI/SSCI-indexed articles by Chinese researchers in 2014, and the world ranking of China rose to first place. (2) China ranked fourth (behind the USA, Canada, and UK) in terms of cited frequency of SCI/SSCI articles published from 2000 to 2014. However, the number of citations showed a rapid increase over this time period. In 2000, China ranked 16th in terms of total citations (83 citations). By 2014, China ranked first, when the total citations increased to 224. (3) In terms of the quality of the research in the uncertainty of spatial information, China ranked fifth in terms of the number of highly cited articles, with a big gap from the USA, and at a similar level to Canada, UK, Italy and France. From the above analysis, we can see that, in general, the research in spatial data uncertainty in China tops the world list with respect to published articles. However, there is still a lack of high-impact research results. International academic influence and peer attention to the research in China lags behind the increasing number of published articles.

25.1.3 Key Research Topics

Figure 25.1 shows the relationships between the keywords of published SCI/SSCI-indexed articles on the "uncertainty of spatial information and spatial analysis" from 2000 to 2014, based on the data from Table 25.1. From Fig. 25.1, we can see that there are two large keyword clusters in the research in spatial information uncertainty over the 15 years. The first keyword cluster consists of three types of keywords and reflects the basic theoretical issues and the most important geographic applications. The first type of keyword indicates the main research topics in spatial data uncertainty, which are "information", "remote sensing", and "imagery". The second type of keyword refers to the basic theoretical issues of uncertainty, including "uncertainty", "accuracy",

Table 25.1 Top 20 countries (regions) with the number and citations of SCI/SSCI-indexed articles on "Uncertainty of Spatial Information and Spatial Analysis" during the period 2000–2014

	Number of articles						Cited frequency						Number of highly cited articles					
	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014	Countries (Regions)	2000	2014	2000-2004	2005-2009	2010-2014
Rank	World	413	2,208	2,697	5,159	9,609	World	20,731	918	114,433	108,391	45,383	World	58	0	344	361	494
1	China	5	662	157	506	2,258	USA	9,710	185	56,238	39,421	12,619	USA	27	0	188	155	152
2	USA	174	397	1,003	1,558	1,995	China	83	224	2,481	6,092	6,449	China	0	0	5	9	48
3	Germany	16	106	75	266	501	Germany	518	57	2,218	5,575	3,055	Germany	3	0	5	17	38
4	Italy	29	84	151	248	427	Italy	1,610	50	6,359	5,925	2,346	France	1	0	7	24	31
5	Canada	32	68	235	361	418	France	577	32	4,000	4,963	2,059	Italy	5	0	16	18	29
6	Spain	7	91	59	185	381	Canada	1,303	15	8,174	6,896	1,991	Canada	5	0	24	21	23
7	UK	34	57	187	247	333	Spain	424	46	2,674	3,971	1,939	Netherlands	3	0	10	12	23
8	Australia	5	72	88	144	305	UK	1,058	18	8,241	5,327	1,746	Spain	1	0	8	8	21
9	France	20	60	114	194	293	Netherlands	607	21	2,969	3,674	1,424	UK	4	0	26	17	18
10	India	6	60	43	117	255	Australia	206	33	3,487	3,368	1,377	Australia	1	0	13	9	18
11	Netherlands	10	33	60	152	190	Finland	22	23	1,379	1,783	929	Finland	0	0	5	6	10
12	Japan	11	35	60	122	161	Switzerland	3,018	15	4,899	2,743	820	Switzerland	3	0	9	13	8
13	South Korea	2	40	28	69	153	Belgium	271	9	1,265	1,736	685	Austria	0	0	0	4	7
14	Taiwan, China	6	18	34	70	148	India	80	10	762	1,091	591	Portugal	0	0	0	1	7
15	Finland	2	29	35	86	133	Japan	157	10	1,183	2,807	571	Belgium	2	0	5	8	6
16	Iran	0	31	3	24	128	Austria	37	30	122	1,369	545	Singapore	0	0	0	3	6
17	Brazil	0	31	13	49	126	Taiwan, China	121	5	828	858	521	Turkey	1	0	3	3	5
18	Belgium	3	24	36	69	123	South Korea	13	12	563	957	401	Denmark	0	0	0	4	4
19	Switzerland	6	29	35	103	122	Turkey	94	1	494	987	398	Japan	0	0	2	9	3
20	Turkey	4	17	19	73	87	Greece	175	8	445	954	243	Israel	1	0	5	1	1

Note Countries (regions) ranked by the number of articles, cited frequency and the number of highly cited articles during the period 2010–2014

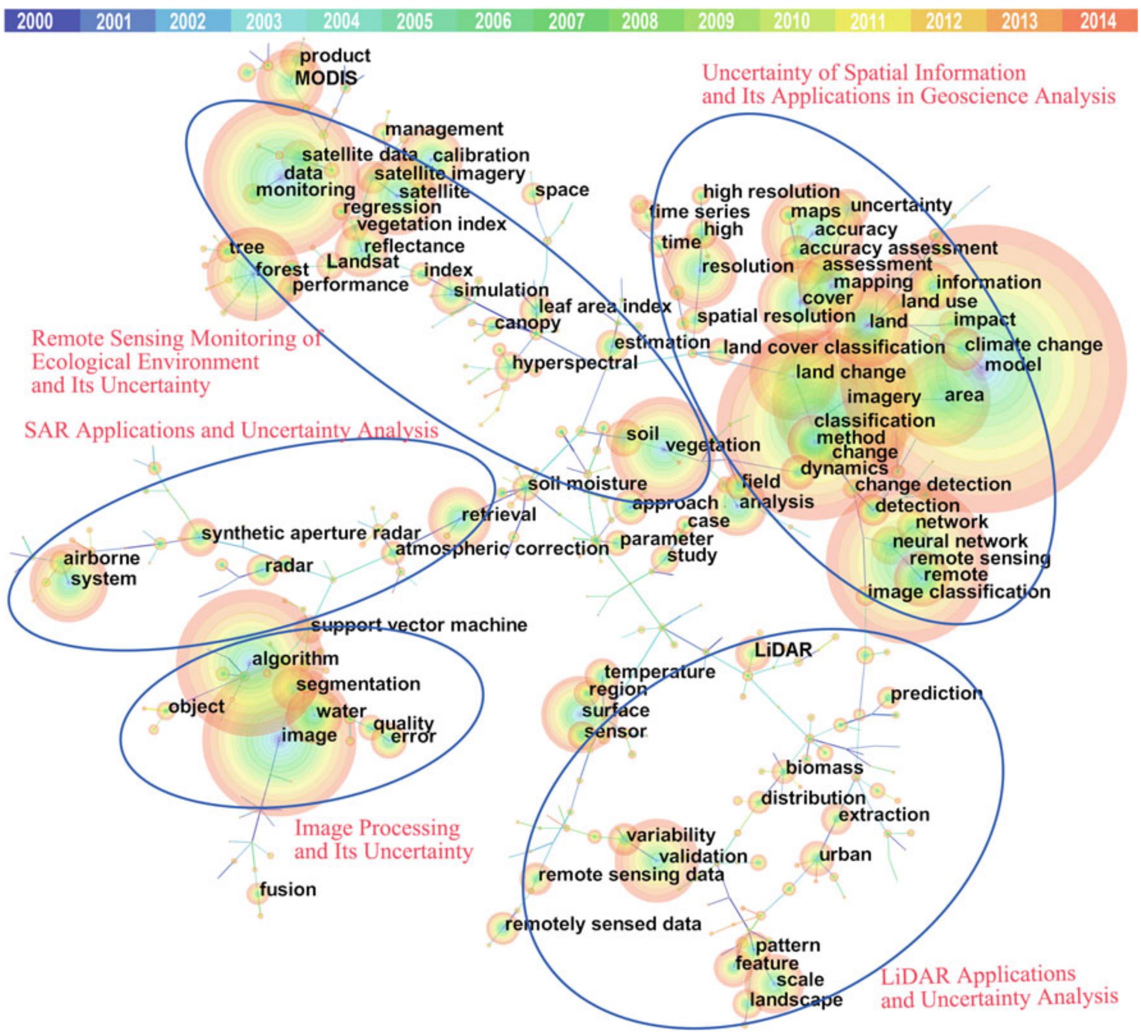

Fig. 25.1 Co-occurrence network of SCI/SSCI-indexed article keywords on "Uncertainty of Spatial Information and Spatial Analysis" during the period 2000–2014

and "assessment". The third type of keyword indicates the essential geographic applications, including "classification", "mapping", "land change", "cover", and "climate change". The second keyword cluster reflects the uncertainty in ecology, vegetation, soil, and other remote sensing applications, including "estimation", "satellite imagery", "hyper spectral", "forest", "canopy", "vegetation", and other keywords. This cluster indicates that spatial data uncertainty is common in ecological, environmental, and remote sensing studies.

In addition to these two large clusters, the research in spatial information uncertainty also presents three relatively loose sub-clusters, which are closely related to the current developments in three new earth observation technologies. These new earth observation technologies are represented by "airborne sensor system", "light detection and ranging (LiDAR)", "synthetic aperture radar (SAR)", and "algorithm", "image", "quality", "validation", and other uncertainty algorithms. The three sub-clusters indicate that the rapid development of new airborne and satellite observation systems, laser and radar technologies, and image processing technology has also been affected by the problem of uncertainty in spatial information and analysis.

The temporal variations of the research topics in the SCI/SSCI journals on "uncertainty of spatial information and spatial analysis" from 2000 to 2014 are studied (Fig. 25.2) in order to analyze the evolution of the research focus in spatial information uncertainty. According to the relationships among the retrieved research topics from SCI/SSCI journals, the research topics of "uncertainty of spatial information and spatial analysis" are classified into 15 categories: geographic information, which includes spatial data, mapping, GISystems, etc.; remote sensing, including various types of sensors and remote sensing data (optical imaging, SAR data, LiDAR point cloud, etc.); uncertainty, including the uncertainty of spatial data, sampling, statistics, etc.; accuracy, including the

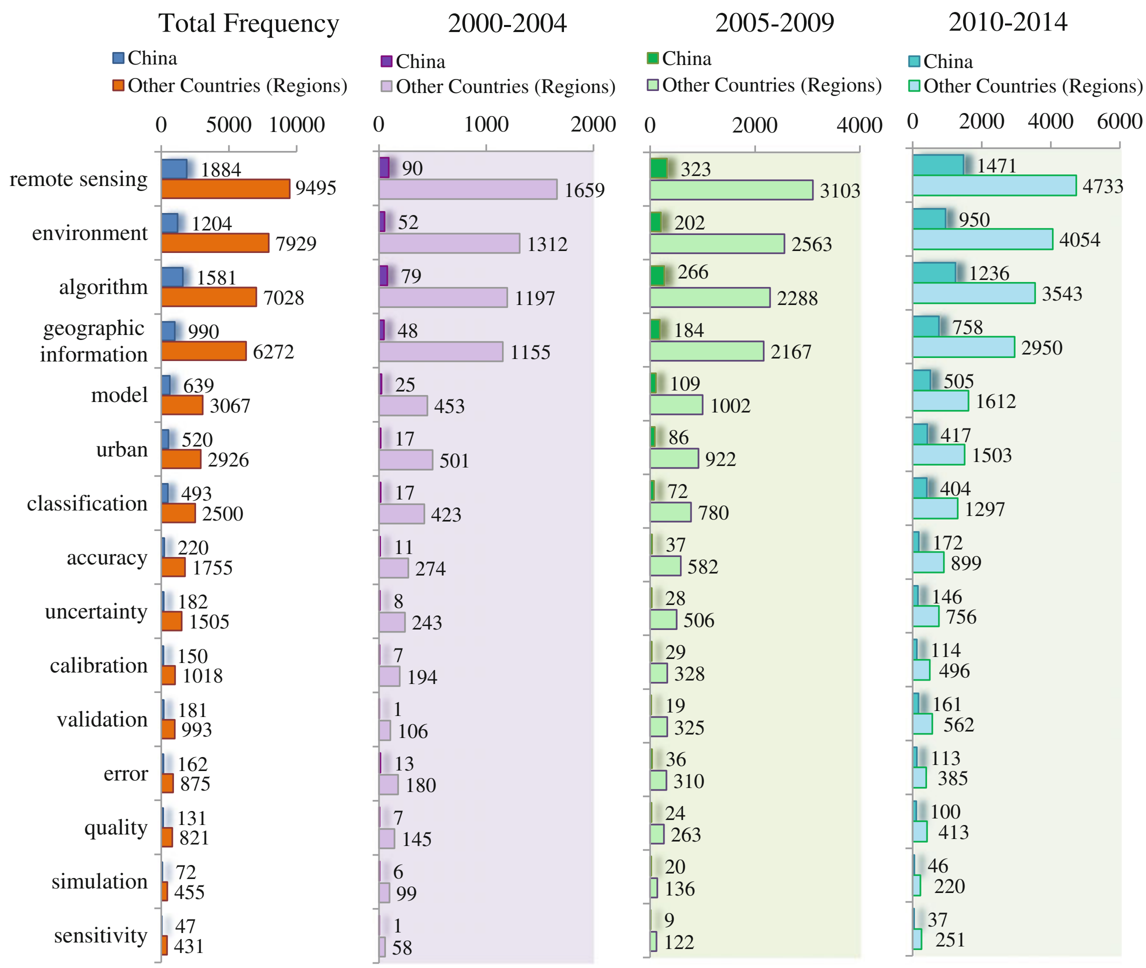

Fig. 25.2 Keyword temporal trajectory graph for SCI/SSCI-indexed articles on "Uncertainty of Spatial Information and Spatial Analysis" during the period 2000–2014

accuracy of spatial data, spatial data products, and processing methods; error, including the various types of spatial error, noise, deviations, and error processing methods; sensitivity, including data sensitivity, sensitivity analysis, etc.; validation, including various data verifications; calibration, including radiation calibration, sensor calibration, model calibration, geometric calibration, etc.; quality, including data quality, quality assessment, reliability, trust, etc.; models, including various spatial data models and their parameters, time series, regression models, data assimilation models, etc.; algorithms, including inversion, segmentation, remote sensing index, neural network, optimization, and other algorithms; simulation, including various types of simulation models; urban, including land cover, change detection, urban area, landscape, etc.; environment, including the various types of land cover, climate change, environment, etc.; classification, including image classification, classification algorithms, etc.

Figure 25.2 shows the sequential variations of the research topics in SCI/SSCI journals on "uncertainty of spatial information and spatial analysis" from 2000 to 2014. From this figure, we can see that the frequency of keywords of "uncertainty of spatial information and spatial analysis" are increasing year by year. Specifically, the keywords of "remote sensing", "algorithm", and "environment" have always ranked in the top three. Therefore, the research in the uncertainty of spatial information and spatial analysis has mainly focused on the uncertainty of remote sensing, spatial data applications, and various algorithms.

Furthermore, from Fig. 25.2, it can be seen that the listed research topics appeared 7999 times in those articles authored by other countries (regions) from 2000 to 2004, while they appeared 382 times in the articles of Chinese authors, which is only 4.6 % of the total number of appearances. The listed research topics appeared 15,387 times in other countries (regions) authored articles from 2005 to 2009, which is double the level of the previous five years. At the same time, the listed research topics appeared 1444 times in the articles of Chinese authors, which is three times the level of the previous five years, and is 8.6 % of the total appearances. From 2010 to 2014, the listed research topics appeared 23,674 times in the articles of other countries (regions), which is an increase of 8287 over the level of the previous five years. In the Chinese authors' articles, the listed research topics appeared 6,630 times, which is an increase of 3.6 times the level of the previous five years, accounting for 21.9 % of the total appearances.

25.1.4 The Role of NSFC in Supporting the Research on Uncertainty of Spatial Information and Spatial Analysis

Figure 25.3 shows the sequential variations of the research topics funded by NSFC on the "uncertainty of spatial information and spatial analysis" from 2000 to 2014. The keywords of "remote sensing", "algorithm", "environment", "geographic information", and "model" appeared more frequently than the other keywords. These frequent keywords can be divided into two categories: the first category is the uncertainty of remote sensing, geographic information, and environmental applications, and the second category is the uncertainty of algorithms and models. This indicates that NSFC not only funded uncertainty studies in remote sensing and geographic information, but also focused on the algorithms of spatial data processing and models, which significantly contributed to the growth rate in the appearance of related keywords. At the same time, we can see that during the three periods 2000–2004, 2005–2009, and 2010–2014, the research in uncertainty theory, which is represented by the keywords of "uncertainty", "accuracy", "error", and "quality", increased markedly. These data indicate that the "uncertainty of spatial information and spatial analysis" is becoming a hot research topic attracting more and more researchers. The development of the theories of spatial data uncertainty have promoted research in the algorithms and models of remote sensing and geographic information processing, which have obtained more and more funding from NSFC. However, compared to the uncertainty research of geographic applications, there is still a lack of research in uncertainty theory itself, which therefore requires more support from NSFC. The above data indicate that NSFC's funding is essential to research in uncertainty theory, research output, the uncertainty of geographic applications, etc.

The statistical results of the projects and published articles on the "uncertainty of spatial information and spatial analysis" funded by NSFC from 2000 to 2014 are shown in Table 25.2. The total number of published articles in this research area in international journals was 17,465. Articles from Chinese authors accounted for 16.8 %, of which 57.9 % were funded by NSFC. From 2000 to 2014, in each five-year period, the share of the Chinese authors' published articles increased

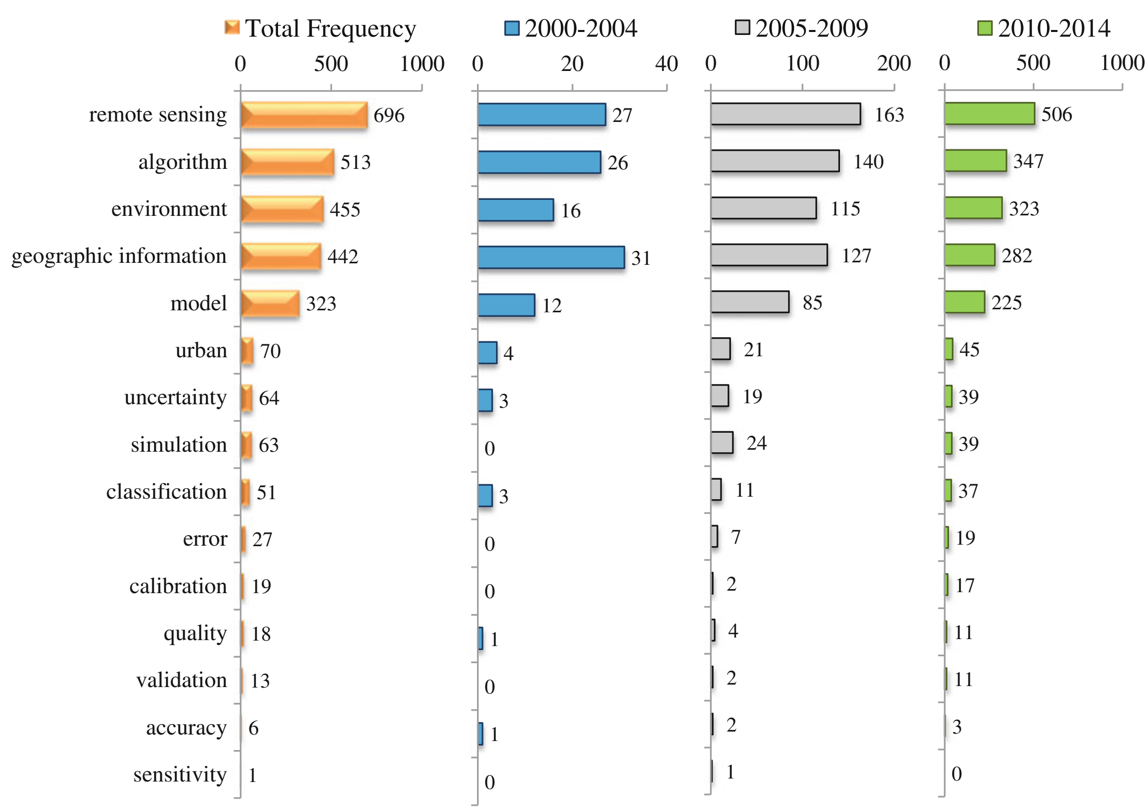

Fig. 25.3 Keyword temporal trajectory graph for NSFC-funded projects on "Uncertainty of Spatial Information and Spatial Analysis" during the period 2000–2014

Table 25.2 NSFC-funded projects and SCI/SSCI-indexed articles on "Uncertainty of Spatial Information and Spatial Analysis" during the period 2000–2014

SCI/SSCI-indexed articles					NSFC-funded projects			
Periods	Number of articles	% of articles by Chinese authors	% of articles with NSFC funding by Chinese authors	% of articles funded by MOST among those with NSFC funding	Number of projects	Funding (10,000 yuan)	Number of PIs	Number of institutions
2000-2004	2,697	5.8	13.4	0.0	24	768.0	23	11
2005-2009	5,159	9.8	32.1	33.1	142	4,303.5	138	55
2010-2014	9,609	23.5	66.8	49.2	367	18,702.8	355	121
2000-2014	17,465	16.8	57.9	47.1	533	23,774.3	479	136

dramatically. The proportion increased from the initial 5.8 % to the most recent level of 23.5 %. The percentage of articles funded by NSFC increased from 13.4 to 66.8 %. The proportion of published articles funded by NSFC exceeded that of the other domestic projects. This illustrates that NSFC is the most important source of support for Chinese authors in basic research in spatial data uncertainty. In addition, among the articles funded by NSFC, the articles funded by the Ministry of Science and Technology increased from 0 to 49.2 %, indicating that more and more research is funded by the Ministry of Science and Technology.

As can be seen from the statistical results of NSFC-funded projects, from 2000 to 2014, NSFC funded 533 projects, which involved a total of 237,743 thousand yuan, 479 project leaders, and 136 support organizations. During the period 2000–2014, the number of funded projects and the amount of funding increased significantly every five years. The average funding level per project also grew. For example, from 2000 to 2004, the average funding per project was 320 thousand yuan. From 2010 to 2014, the average funding per project increased to about 510 thousand yuan. In general, both the number of projects funded by NSFC and the level of funding showed significant growth. At the same time, the research teams funded by NSFC expanded each year, which greatly promoted the development of outstanding young scholars and teams studying the basic theories of spatial data uncertainty.

In summary, NSFC's funding has played a very important role in the promotion of research in "uncertainty of spatial information and spatial analysis" in China.

25.2 Research Advances and Problems

In this section, based on the retrieved articles published on the "uncertainty of spatial information and spatial analysis", the main research topics and the progress of the research in uncertainty in spatial information are analyzed. By comparing these results with the research in spatial data uncertainty in foreign countries, the characteristics, status, and the main problems of the research in spatial data uncertainty in China are further analyzed.

25.2.1 Bibliometric Analysis of Contemporary Research

Figure 25.4 compares the keyword frequencies of foreign authors and Chinese authors for the SCI/SSCI-indexed articles on spatial data uncertainty published from 2000 to 2014. There were a total of 14,519 published articles on spatial data uncertainty from 2000 to 2014, excluding those published by Chinese scholars, in which 1311 articles focused on the topic of remote sensing. Subsequently, the most popular keywords were MODIS (437 articles), Landsat (326 articles), and LiDAR (293 articles), which represent the major earth observation technologies. Following these three keywords, research attention has been focused on the remote sensing image processing methods of classification (285 articles), calibration (251 articles), and change detection (198 articles). This indicates that spatial data quality is one of the most important problems in remote sensing. The keywords on spatial data error, which are uncertainty (145 articles) and accuracy (125 articles), appeared less frequently than those related to image processing. However, the published articles with the keywords of uncertainty and accuracy increased year by year from 2000 to 2014, which indicates that more and more authors have begun to pay attention to the spatial data uncertainty problem.

25.2.2 Contemporary Research

The global research in spatial data uncertainty can generally be divided into three types. The first type is the study of the basic problems of uncertainty in geographic information science, which includes the basic theory of trust in spatial data, the uncertainty of spatial relations, scale effects, the

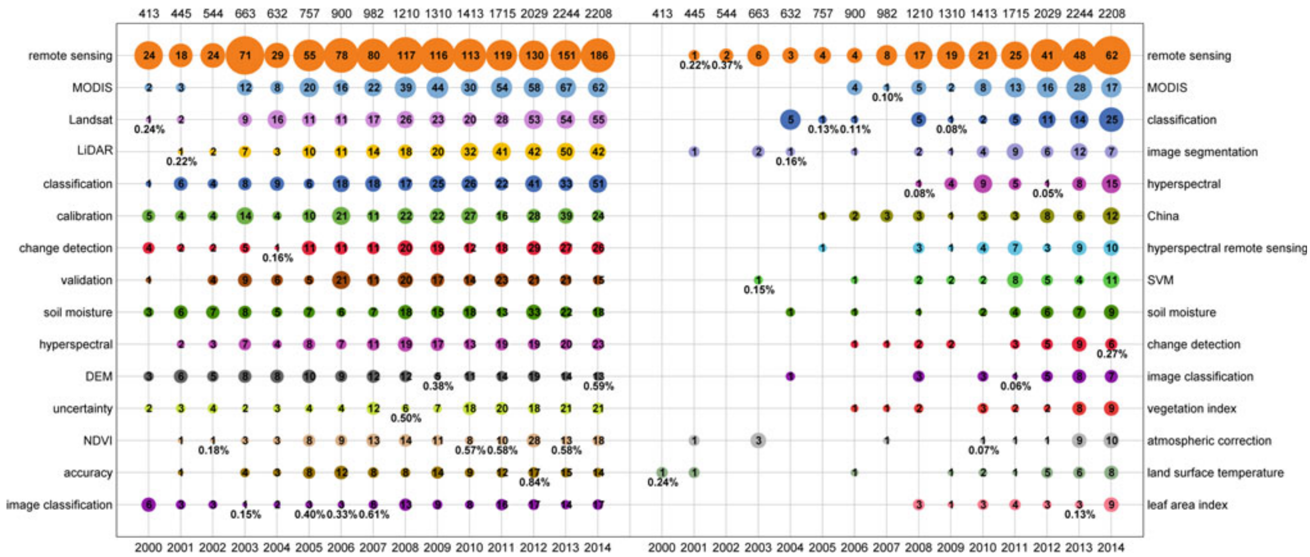

Fig. 25.4 Comparative diagram of prominent keywords on "Uncertainty of Spatial Information and Spatial Analysis" by Chinese authors and others in SCI/SSCI-indexed articles during the period 2000–2014. *Note* Right panel shows keywords used by Chinese authors and left panel shows those used by the authors from other countries (regions). Size of circles denotes the ratio of a certain keyword frequency to the total article number in a specific year. The annual total number of articles is shown at the top of the diagram. The frequency of the keyword is shown inside the circle. The size of circles in the diagram for Chinese authors are magnified for clear display

uncertainty of temporal geographical information, the uncertainty in multi-scale representations, the uncertainty in the conflation of multi-source spatial data, spatial data sampling, the uncertainty of digital elevation models, error propagation, spatial data quality assessment, the uncertainty of automatic map generalization, etc.

The second type is the uncertainty issues in remote sensing, which includes the uncertainty in remote sensing principles, classification, remote sensing scale, the geometric uncertainty of remote sensing, the quality evaluation of remote sensing information, etc. Such as remote sensing information uncertainty analysis, the uncertainty evaluation of classification information, the reliability evaluation of remote sensing information, and the scale effect in remote sensing classification. With the launch and application of independently developed high-resolution satellites in China, the associated uncertainty problems have attracted much research attention, such as self-calibration bundle adjustment for high-resolution satellite linear charge-coupled device (CCD) array images, the correction of the periodic error of satellite attitudes based on ground control points, the band registration error of multi-channel satellites and its impact on the data products, high-resolution satellite jitter detection and correction, etc.

The third type is the uncertainty of geographic science applications, which includes land-surface processes, ecology, the carbon cycle, assimilation, etc. In these geoscience applications, uncertainty has always been a key scientific issue, in applications such as the error estimation of assimilation systems of land-surface data, the calibration of remote sensing observation experiments, the uncertainty analysis of land-surface process models, the uncertainty estimation and control of carbon cycle model simulations, remote sensing inversion, and multi-scale verification based on vegetation leaf area indexes.

25.2.3 Bibliometric Analysis of Contemporary Research in China

In China, uncertainly studies have rapidly developed since 2000. Chinese researchers have published 2946 academic articles on uncertainly, accounting for 16.9 % of the total. Remote sensing was the most popular research topic, which contributed 261 articles. The other important keywords in the publications (in descending order) were MODIS (94 articles), classification (70 articles), image segmentation (46 articles), hyperspectral (43 articles), China (42 articles), hyperspectral remote sensing (38 articles), SVM (36 articles), soil moisture (31 articles), change detection (29 articles), image classification (28 articles), and vegetation index (28 articles), showing that remote sensing data processing and algorithm research have received a great deal of attention from Chinese scholars.

25.2.4 Contemporary Research in China

Over the past 15 years, with the support of NSFC, Chinese scholars have made a series of innovative contributions to research in spatial information uncertainty. Specifically, Chinese scholars are highly regarded by their international peers for their research in the uncertainty of spatial data models, spatial sampling and unbiased estimation, high surface modeling and error estimation, the modeling and estimation of space-time point processes, and the theory of trust in spatial data.

Wenzhong Shi and his team have systematically established theoretical models of the positional uncertainty of spatial data (including vector spatial data, digital elevation models, and satellite remote sensing images), attribute uncertainty, spatial relation uncertainty, spatial analysis uncertainty, spatial data uncertainty processing, and quality control. Based on the mechanisms, spatial distribution, expression models, communication mechanisms, and the quality control of uncertainty, they established a new error band theory for line features (including the confidence region, the G-band, the maximum error band, and the error distribution model), the general N-dimensional confidence region model for line features, and the S-band model integrating attribute and position uncertainties. They derived an accuracy estimation of the irregular triangulation surface model, and established a spatial analysis uncertainty model for the spatial overlap, buffering, feature extraction, etc. They established theories and methods of reliability analysis and the quality control of geographic national condition monitoring and spatio-temporal dynamic modeling (Shi1994, 1998, 2005; Shi and Liu 2000, 2007; Shi et al. 2004, 2012; Tong et al. 2005; Zhu et al. 2005; Tong and Shi 2010).

On the basis of classical sampling and spatial sampling, **Jinfeng Wang** and his team have systematically established the spatial sampling and unbiased estimation theory for heterogeneous land surfaces. They proposed the principle of "trinity" for the interaction between land-surface types, spatial sampling, and the statistical inference. They established the model of "mean of surface with non-homogeneity" (MSN), the "biased sentinel hospital based area disease estimation" (B-SHADE) model, "single point area estimation" (SPA), and the "sandwich" model of heterogeneous surface interpolation (Li et al. 2008; Wang et al. 2009a, b, 2010, 2013a, b; Xu et al. 2013).

Tianxiang Yue and his team have systematically established a high-precision fitting theory system for the earth's surface, which is driven by global approximation data and controlled by local high-precision data. They proposed the high-accuracy surface modeling (HASM) method, a multi-grid method, an adaptive method, and an adjustment algorithm. They derived the high-accuracy fitting surface by obtaining uniform grid points based on the numerical equations of the uniform orthogonal subdivided region, with the constraints of local sampling data. HASM has been applied in the establishment of digital elevation models, the trend analysis and future simulation of climate change, and the simulation analysis of ecosystem service functions (Yue et al. 2010a, b, 2011, 2012; Yue and Wang 2010; Yue 2011).

With respect to the spatio-temporal variations and interactions of geographic point-events, **Tao Pei**, **Chenghu Zhou**, and colleagues established a theoretical model of data mining based on the spatial statistics of spatio-temporal point processes. Firstly, this method presents the complex point sets as the integration of several uniform Poisson distributions by regarding the complex geographic processes as overlays of several single geographic processes. Secondly, the nonparametric discriminate analysis and scale estimation of point clusters is undertaken by converting the spatio-temporal point processes into the mixed density function of the *k*th-order adjacent distance. Lastly, by obtaining the uniform point processes with different densities from the mixed density function, the arbitrary spatio-temporal point set is extracted (Pei et al. 2006, 2009, 2010, 2011; Pei 2011; Wan et al. 2012).

Xiaohua Tong and his team put forward the concept of "trust in spatial data and modelling", and established a theoretical system of trust measurement, trust modelling, and trust control. In this theoretical system of "trust in spatial data", the trust measurement represents the measurement of the degree of trust in spatial data. The trust modelling improves and enhances the degree of trust in spatial data, in order to satisfy the application requirements. The trust control is an integrated process of trust measurement, modelling and dynamic control, in order to ensure the degree of trust in spatial data (Tong 2010, 2011, 2012; Tong et al. 2010, 2011a, b, 2014a, b, 2015; Xie and Tong 2014; Chen et al. 2015). The proposed theory of "trust in spatial data" has been applied in major national scientific projects, such as the soft landing of the "Chang'e-3" lunar exploration mission, jitter detection and compensation for the "ZY-3" satellite platform, and the verification of global land-cover products.

25.2.5 Contributions by Chinese Scholars and Subsequent Problems

Chinese scholars have shown a lot of similarity in research topics with scholars in other countries over the last 15 years. Figure 25.4 shows that remote sensing has been the most popular topic, not only for scholars in China, but also for those in other countries; however, the relative importance of these topics have shown contrasting trends in the different periods between China and the other countries. The study of remote sensing showed an increasing trend from 2000 to 2003 and from 2007 to 2014 in foreign countries, while it showed a continuously increasing trend from 2008 to 2014 in China. Similar trends exist for the keywords of MODIS, classification, etc. The ratio between the frequency of keywords and the total number of articles in Fig. 25.4 for China lags approximately 3–5 years behind the other countries. The other hot topics for uncertainty studies include Landsat, LIDAR, classification, calibration, change detection, validation, soil moisture, and hyper spectral. Overall, China has made a significant contribution to the study of spatial data uncertainty problems. The keywords of "accuracy" and "uncertainty" are in the list of top keywords, while the number of published articles with the keywords of "accuracy" or "uncertainty" by Chinese scholars lags behind. Therefore, there is a requirement to further promote the theoretical study of uncertainty in geographic information science and remote sensing in China.

25.3 Roadmap for Further Research

As mentioned above, China has made considerable progress in research in spatial information uncertainty. Furthermore, Chinese scholars have led the world in some of the important research topics in this area. The current research in spatial information uncertainty provides theoretical support for the trusted application of spatial data and analysis. However, compared with the international research in this area, there is still a lack of high-impact, significant innovations in China. Therefore, it is necessary to strengthen China's contributions to innovations in spatial data uncertainty. According to the current research and problems in this area, the following topics need to be further studied in the research in spatial data uncertainty:

(1) **The Theories and Methodologies of Spatial Information Uncertainty Need to Be Strengthened**

The global research in the uncertainty of spatial information has, to date, focused on the generation mechanism of uncertainty, the spatial distribution of uncertainty, and the propagation of uncertainty. With the development of geographic information science and earth observation systems, the trust, reliability, and usability of spatial data has emerged as an important topic in spatial information uncertainty research. Therefore, the most important basis for the research in spatial data uncertainty is to establish a complete theoretical system of the trust in spatial data, reliability and usability of spatial data. The key research topics include the cognition of spatial information uncertainty, the scientific connotation of trusted spatial data, the trust measurement of spatial data, the quality evaluation of spatial data based on sampling, and trust modelling and quality control.

(2) **Given the Strategic Demand for National Development, the Major National Applications Based on Trusted Spatial Data Need to Be Supported**

One of the important research topics is the uncertainty in global land cover, climate change, urbanization, and other geographic analyses. Therefore, the research in spatial data uncertainty in China should solve the problem of uncertainty in global land cover, surface processes, climate change and sustainable development, smart cities, national condition monitoring, and other major needs of the country, in order to promote the development of the related subjects and industries which are based on trusted spatial data. The key research topics are the trust validation of global geographic information products, especially the verification theory and methods of high-resolution global land-cover data and product systems developed by China, improvement of the geometrical, spectral, and radiometric quality of high-resolution earth observation systems, the uncertainty problems of the applications of multi-source remote sensing data in land-surface systems and processes, the development of urbanization, and the deep space exploration of the Moon and Mars.

25.4 Summary

Uncertainty of spatial information and spatial analysis is one of the basic core themes of geographic information science. It is also an essential requirement in applications based on trusted spatial data. The research in spatial data uncertainty has undergone stages that have focused on spatial data error, spatial data uncertainty, and the reliability, usability, and trust in spatial data. To date, the research has focused on two main aspects: The first is the basic theory of spatial information uncertainty, including the sources of uncertainty, the propagation of uncertainty, uncertainty processing, and assessment. The second is the uncertainty in geoscience applications, which includes the uncertainty analysis of ecological, environmental, remote sensing, and other applications. Chinese scholars lead the world with respect to the research topics and methods of spatial data uncertainty. The published articles on spatial data uncertainty funded by NSFC account for nearly 60 % of the total published articles on uncertainty by Chinese scholars. Therefore, NSFC plays an important role in promoting the development of the research in spatial data uncertainty in China. On the other hand, there is still a gap between China and developed countries with respect to high-impact research results in this area. Therefore, in order to encourage research progress, it is necessary to strengthen the basic research in spatial data uncertainty in China. At the same time, it is necessary to take into account the strategic needs of national development, in order to better address the uncertainty problems in major national applications as well.

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Appendix A
List of 307 Mainstream SCI/SSCI Journals in Geographical Sciences

Code	Journal name	Impact factor	Type	Subdiscipline	Index type
1	Acta Geographica Slovenica-Geografski Zbornik	0.306	2	1	SCI
2	Advances in Meteorology	0.946	2	1	SCI
3	Aeolian Research	2.309	2	1	SCI
4	Agricultural and Forest Meteorology	3.762	1	1	SCI
5	Agriculture Ecosystems & Environment	3.402	1, 2	1, 4	SCI
6	Alpine Botany	1.458	2	1	SCI
7	Ambio	2.641	1, 1	1, 4	SCI
8	Annales de Limnologie-International Journal of Limnology	1.042	2	1	SCI
9	Annals of Glaciology	2.378	2	1	SCI
10	Annals of Regional Science	0.651	2	2	SSCI
11	Annals of the Association of American Geographers	2.291	1	2	SSCI
12	Annals of Tourism Research	2.685	2	2	SSCI
13	Annual Review of Environment and Resources	5.892	2	4	SCI/SSCI
14	Antarctic Science	1.606	1	1	SCI
15	Antipode	2.104	1	2	SSCI
16	Applied Ecology and Environmental Research	0.557	2	1	SCI
17	Applied Geography	2.494	1	2	SSCI
18	Applied Soil Ecology	2.644	2	1	SCI
19	Applied Spatial Analysis and Policy	0.844	2	2	SSCI
20	Aquatic Toxicology	3.451	2	4	SCI
21	Archives of Environmental Contamination and Toxicology	1.895	1	4	SCI
22	Archives of Environmental Protection	0.855	2	4	SCI
23	ARCTIC	1.174	2	1	SCI
24	Arctic Antarctic and Alpine Research	1.515	1	1	SCI
25	Area	1.203	1	2	SSCI
26	Arid Land Research and Management	0.804	1	1	SCI
27	Asia Pacific Journal of Tourism Research	1.023	2	2	SSCI
28	Atmospheric Environment	3.281	1	4	SCI
29	Australian Geographer	1.160	2	2	SSCI
30	Basic and Applied Ecology	1.942	2	1	SCI
31	Biodiversity and Conservation	2.365	2	1	SCI
32	Biogeochemistry	3.488	1	4	SCI
33	Biogeosciences	3.978	2	1	SCI
34	Biological Conservation	3.762	2	1	SCI

(continued)

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Code	Journal name	Impact factor	Type	Subdiscipline	Index type
35	Boreas	2.658	1	1	SCI
36	Cambridge Journal of Regions Economy and Society	1.148	1	2	SSCI
37	Canadian Geographer-Geographe Canadien	1.179	1	2	SSCI
38	Canadian Journal of Remote Sensing	1.727	1	3	SCI
39	Canadian Water Resources Journal	1.333	2	1	SCI
40	Cartographic Journal	0.299	2	3	SSCI
41	Cartography and Geographic Information Science	0.944	1	3	SSCI
42	Catena	2.820	2	1	SCI
43	Chemosphere	3.340	1	4	SCI
44	Chinese Geographical Science	0.877	1	1	SCI
45	Chinese Journal of Oceanology and Limnology	0.657	2	1	SCI
46	Cities	1.728	2	2	SSCI
47	Clean Technologies and Environmental Policy	1.934	2	4	SCI
48	Climate Dynamics	4.673	2	1	SCI
49	Climate of the Past	3.382	2	1	SCI
50	Climatic Change	3.430	2	1	SCI
51	Cold Regions Science and Technology	1.367	1	1	SCI
52	Computers & Geosciences	2.054	1	3	SCI
53	Computers Environment and Urban Systems	1.537	1, 2	2, 3	SSCI
54	Continental Shelf Research	1.892	2	1	SCI
55	Cryosphere	5.516	2	1	SCI
56	Cultural Geographies	1.887	1	2	SSCI
57	Disaster Advances		2	1	SCI
58	Earth Observation and Remote Sensing		2	3	SCI
59	Earth Science Informatics	0.743	1	3	SCI
60	Earth Surface Processes and Landforms	2.845	1	1	SCI
61	Ecography	4.774	1	1	SCI
62	Ecohydrology	2.426	2	1	SCI
63	Ecological Applications	4.093	2	1	SCI
64	Ecological Complexity	1.931	2	1	SCI
65	Ecological Engineering	2.580	2	1	SCI
66	Ecological Indicators	3.444	2	1	SCI
67	Ecological Informatics	1.727	2	1	SCI
68	Ecological Modelling	2.321	2	1	SCI
69	Ecological Monographs	6.980	2	1	SCI
70	Ecological Research	1.296	2	1	SCI
71	Ecology and Society	2.774	2	1	SCI
72	Economic Geography	2.735	1	2	SSCI
73	Ecoscience	0.975	2	1	SCI
74	Ecosystems	3.943	2	1	SCI
75	Ecotoxicology	2.706	2	4	SCI
76	Ecotoxicology and Environmental Safety	2.762	2	4	SCI
77	Energy & Environmental Science	20.523	1	4	SCI
78	Environment and Development Economics	1.169	2	2	SSCI
79	Environment and Planning A	1.604	1	2	SSCI
80	Environment and Planning B-Planning & Design	0.983	1, 2	2, 3	SSCI
81	Environment and Planning C-Government and Policy	1.535	1	2	SSCI
82	Environment and Planning D-Society & Space	1.515	1	2	SSCI
83	Environment and Urbanization	1.324	2	4	SSCI
84	Environment International	5.559	1	4	SCI

(continued)

Code	Journal name	Impact factor	Type	Subdiscipline	Index type
85	Environmental Conservation	2.368	2	1	SCI
86	Environmental Geochemistry and Health	2.566	2	4	SCI
87	Environmental Health	3.372	2	4	SCI
88	Environmental Health Perspectives	7.977	2	4	SCI
89	Environmental Impact Assessment Review	2.400	2	4	SSCI
90	Environmental Management	1.724	1, 2	1, 4	SCI
91	Environmental Modeling & Assessment	0.980	2	4	SCI
92	Environmental Modelling & Software	4.420	2	4	SCI
93	Environmental Monitoring and Assessment	1.679	2	4	SCI
94	Environmental Pollution	4.143	1	4	SCI
95	Environmental Research	4.373	1	4	SCI
96	Environmental Research Letters	3.906	1	4	SCI
97	Environmental Science & Policy	3.018	2	4	SCI
98	Environmental Science & Technology	5.330	1	4	SCI
99	Environmental Science and Pollution Research	2.828	1	4	SCI
100	Environmental Science-Processes & Impacts	2.171	2	4	SCI
101	Environmental Toxicology	3.197	2	4	SCI
102	Environmental Toxicology and Chemistry	3.225	1	4	SCI
103	Erde	0.324	2	1	SCI/SSCI
104	Erdkunde	0.512	2, 2	1, 2	SCI/SSCI
105	Estuarine Coastal and Shelf Science	2.057	2	1	SCI
106	Eurasian Geography and Economics	0.623	1	2	SSCI
107	European Journal of Public Health	2.591	2	4	SCI/SSCI
108	European Planning Studies	1.228	2	2	SSCI
109	Folia Geobotanica	1.778	2	1	SCI
110	Fresenius Environmental Bulletin	0.378	2	4	SCI
111	Frontiers in Ecology and the Environment	7.441	1, 1	1, 4	SCI
112	Frontiers of Environmental Science & Engineering	1.357	2	4	SCI
113	Gender Place and Culture	1.183	1	2	SSCI
114	Geoforum	1.759	1	2	SSCI
115	Geografisk Tidsskrift-Danish Journal of Geography	0.788	2	2	SSCI
116	Geografiska Annaler Series A-Physical Geography	1.150	1	1	SCI
117	Geografiska Annaler Series B-Human Geography	0.844	1	2	SSCI
118	Geographical Analysis	1.543	1, 1	2, 3	SSCI
119	Geographical Journal	1.926	2	2	SSCI
120	Geographical Research	1.101	2	2	SSCI
121	Geographical Review	0.514	2	2	SSCI
122	Geography	0.786	2	2	SSCI
123	Geoinformatica	0.745	1	3	SCI
124	Geomatics Natural Hazards & Risk	1.310	2	1	SCI
125	Geomorphologie-Relief Processus Environnement	0.660	2	1	SCI
126	Geomorphology	2.785	2	1	SCI
127	Geopolitics	0.923	2	2	SSCI
128	Geospatial Health	1.194	2	3	SCI
129	GIScience & Remote Sensing	1.770	1	3	SCI
130	Global and Planetary Change	2.766	1	1	SCI
131	Global Biogeochemical Cycles	3.965	2	1	SCI
132	Global Change Biology	8.044	1	1	SCI
133	Global Ecology and Biogeography	6.531	1	1	SCI
134	Global Environmental Change-Human and Policy Dimensions	5.089	1	2	SCI/SSCI

(continued)

Code	Journal name	Impact factor	Type	Subdiscipline	Index type
135	Global Networks: A Journal of Transnational Affairs	1.586	2	2	SSCI
136	GPS Solutions	2.918	2	3	SCI
137	Grassland Science	0.627	2	1	SCI
138	Ground Water Monitoring and Remediation	0.944	2	1	SCI
139	Growth and Change	0.642	2	2	SSCI
140	Habitat International	1.746	2	2	SSCI
141	Holocene	2.283	1	1	SCI
142	Hydrological Processes	2.677	2	1	SCI
143	Hydrology and Earth System Sciences	3.535	2	1	SCI
144	Hydrology Research	1.555	2	1	SCI
145	IEEE Geoscience and Remote Sensing Letters	2.095	1	3	SCI
146	IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing	3.026	1	3	SCI
147	IEEE Transactions on Geoscience and Remote Sensing	3.514	1	3	SCI
148	Indoor Air	4.904	2	4	SCI
149	International Journal of Applied Earth Observation and Geoinformation	3.470	1	3	SCI
150	International Journal of Climatology	3.157	2	1	SCI
151	International Journal of Digital Earth	3.291	1	3	SCI
152	International Journal of Earth Sciences	2.093	1	1	SCI
153	International Journal of Environment and Pollution	0.433	2	4	SCI
154	International Journal of Environmental Health Research	1.573	2	4	SCI
155	International Journal of Environmental Research	1.100	2	4	SCI
156	International Journal of Environmental Research and Public Health	2.063	2	4	SCI
157	International Journal of Environmental Science and Technology	2.190	2	4	SCI
158	International Journal of Geographical Information Science	1.655	1	3	SCI/SSCI
159	International Journal of Health Geographics	2.447	2	3	SSCI
160	International Journal of Hygiene and Environmental Health	3.829	2	4	SCI
161	International Journal of Life Cycle Assessment	3.988	2	4	SCI
162	International Journal of Remote Sensing	1.652	1	3	SCI
163	International Journal of Sediment Research	1.306	2	1	SCI
164	International Journal of Tourism Research	1.314	2	2	SSCI
165	International Journal of Urban and Regional Research	1.672	1	2	SSCI
166	International Journal of Water Resources Development	1.094	2	1	SCI
167	International Regional Science Review	1.182	2	2	SSCI
168	ISPRS Journal of Photogrammetry and Remote Sensing	3.132	1	3	SCI
169	Journal of Applied Ecology	4.564	2	1	SCI
170	Journal of Applied Remote Sensing	1.183	1	3	SCI
171	Journal of Arid Environments	1.641	1	1	SCI
172	Journal of Arid Land	0.931	1	1	SCI
173	Journal of Biogeography	4.590	1	1	SCI
174	Journal of Cleaner Production	3.844	2	4	SCI
175	Journal of Climate	4.435	2	1	SCI
176	Journal of Coastal Research	0.980	2	1	SCI
177	Journal of Contaminant Hydrology	2.204	2	4	SCI
178	Journal of Development Studies	0.983	2	2	SSCI
179	Journal of Earth System Science	1.040	1	1	SCI
180	Journal of Ecology	5.521	2	1	SCI
181	Journal of Economic Geography	2.494	1	2	SSCI
182	Journal of Environmental Informatics	2.792	2	4	SCI
183	Journal of Environmental Management	2.723	1	4	SCI

(continued)

Code	Journal name	Impact factor	Type	Subdiscipline	Index type
184	Journal of Environmental Monitoring	2.179	1	4	SCI
185	Journal of Environmental Quality	2.652	2	4	SCI
186	Journal of Environmental Science and Health, Part A: Toxic/Hazardous Substances & Environmental Engineering	1.164	2	4	SCI
187	Journal of Environmental Science and Health, Part C: Environmental Carcinogenesis & Ecotoxicology Reviews	3.560	2	4	SCI
188	Journal of Environmental Sciences-China	2.002	1	4	SCI
189	Journal of Exposure Science and Environmental Epidemiology	3.185	2	4	SCI
190	Journal of Flood Risk Management	1.119	2	1	SCI
191	Journal of Geodesy	2.699	2	3	SCI
192	Journal of Geographical Sciences	1.344	1, 2	1, 2	SCI
193	Journal of Geographical Systems	1.500	1, 2	2, 3	SSCI
194	Journal of Geography	1.048	2	2	SSCI
195	Journal of Geography in Higher Education	0.488	2	2	SSCI
196	Journal of Glaciology	3.240	2	1	SCI
197	Journal of Hazardous Materials	4.529	2	4	SCI
198	Journal of Historical Geography	1.028	1	2	SSCI
199	Journal of Hydro-environment Research	2.474	2	4	SCI
200	Journal of Hydroinformatics	1.388	2	1	SCI
201	Journal of Hydrologic Engineering	1.583	2	1	SCI
202	Journal of Hydrology	3.053	2	1	SCI
203	Journal of Hydrometeorology	3.645	2	1	SCI
204	Journal of Integrative Environmental Sciences	0.644	2	4	SCI
205	Journal of Maps	1.193	2	3	SCI/SSCI
206	Journal of Mountain Science	0.963	1	1	SCI
207	Journal of Plant Ecology	2.646	2	1	SCI
208	Journal of Quaternary Science	3.357	1	1	SCI
209	Journal of Regional Science	2.042	2	2	SSCI
210	Journal of Rural Studies	2.444	1	2	SSCI
211	Journal of Sedimentary Research	1.786	2	1	SCI
212	Journal of Soils and Sediments	2.139	1, 2	1, 4	SCI
213	Journal of Spatial Science	0.588	1	3	SCI
214	Journal of Surveying Engineering-ASCE	1.000	2	3	SCI
215	Journal of Sustainable Tourism	1.959	2	2	SSCI
216	Journal of the American Water Resources Association	1.348	2	1	SCI
217	Journal of the Indian Society of Remote Sensing	0.764	2	3	SCI
218	Journal of Tourism and Cultural Change	0.361	2	2	SSCI
219	Journal of Transport Geography	2.650	1	2	SSCI
220	Journal of Tropical Ecology	0.904	2	1	SCI
221	Journal of Urban Economics	1.609	2	2	SSCI
222	Journal of Urban Planning and Development	0.809	2	2	SCI/SSCI
223	Journal of Urban Planning and Development-ASCE	0.809	2	2	SCI/SSCI
224	Journal of Vegetation Science	3.709	2	1	SCI
225	Land Degradation & Development	3.089	1	1	SCI
226	Land Economics	1.338	2	2	SSCI
227	Land Use Policy	2.631	1	1	SSCI
228	Landscape and Ecological Engineering	0.723	2	1	SCI
229	Landscape and Urban Planning	3.037	2, 2	1, 2	SCI/SSCI
230	Landscape Ecology	3.500	1	1	SCI
231	Landscape Research	1.077	2	2	SSCI

(continued)

Code	Journal name	Impact factor	Type	Subdiscipline	Index type
232	Limnology and Oceanography	3.794	2	1	SCI
233	Mountain Research and Development	1.021	1	1	SCI
234	Natural Hazards	1.719	1	1	SCI
235	Natural Resources Forum	1.146	2	1	SCI/SSCI
236	Networks & Spatial Economics	2.085	2	2	SCI
237	New Zealand Geographer	0.579	2	2	SSCI
238	Nordic Hydrology	1.555	2	1	SCI
239	Norsk Geografisk Tidsskrift-Norwegian Journal of Geography	0.418	2	2	SSCI
240	Ocean & Coastal Management	1.748	2	1	SCI
241	Palaeogeography Palaeoclimatology Palaeoecology	2.339	1	1	SCI
242	Papers in Regional Science	1.012	1	2	SSCI
243	Permafrost and Periglacial Processes	2.119	2	1	SCI
244	Photogrammetric Engineering and Remote Sensing	1.608	1	3	SCI
245	Photogrammetric Record	1.038	2	3	SCI
246	Photogrammetrie Fernerkundung Geoinformation	0.733	2	3	SCI
247	Physical Geography	0.839	1	1	SCI
248	Plant Ecology	1.463	2	1	SCI
249	Plant Ecology & Diversity	1.766	2	1	SCI
250	Plant Ecology and Evolution	0.986	2	1	SCI
251	Polish Journal of Ecology	0.567	2	1	SCI
252	Political Geography	2.676	1	2	SSCI
253	Population and Development Review	1.667	2	2	SSCI
254	Population and Environment	1.617	1	2	SSCI
255	Population Space and Place	1.781	1	2	SSCI
256	Process Safety and Environmental Protection	2.551	2	4	SCI
257	Professional Geographer	1.500	1	2	SSCI
258	Progress in Human Geography	5.010	1	2	SSCI
259	Progress in Physical Geography	2.612	1	1	SCI
260	Quaternary Geochronology	2.687	2	1	SCI
261	Quaternary International	2.062	1	1	SCI
262	Quaternary Research	2.544	1	1	SCI
263	Quaternary Science Reviews	4.572	1	1	SCI
264	Rangeland Ecology & Management	1.439	2	1	SCI
265	Regional Environmental Change	2.628	1, 2	1, 4	SCI/SSCI
266	Regional Science and Urban Economics	1.006	2	2	SSCI
267	Regional Studies	2.068	1	2	SSCI
268	Remote Sensing Letters	1.573	1	3	SCI
269	Remote Sensing of Environment	6.393	1, 1	3, 4	SCI
270	Remote Sensing	3.180	1	3	SCI
271	Restoration Ecology	1.838	2	1	SCI
272	Review of Palaeobotany and Palynology	1.940	2	1	SCI
273	River Research and Applications	2.025	2	1	SCI
274	Russian Meteorology and Hydrology	0.198	2	1	SCI
275	Scandinavian Journal of Hospitality and Tourism	0.432	2	2	SSCI
276	Science of the Total Environment	4.099	1	4	SCI
277	Sedimentology	2.948	2	1	SCI
278	Singapore Journal of Tropical Geography	0.640	2	2	SSCI
279	Social & Cultural Geography	1.315	1	2	SSCI
280	Soil & Sediment Contamination	1.039	2	4	SCI
281	South African Geographical Journal	0.462	2	2	SSCI

(continued)

Code	Journal name	Impact factor	Type	Subdiscipline	Index type
282	Space and Culture	0.615	1	2	SSCI
283	Spatial Cognition and Computation	0.857	2	3	SSCI
284	Stochastic Environmental Research and Risk Assessment	2.086	2	1	SCI
285	Theoretical and Applied Climatology	2.015	2	1	SCI
286	Third World Quarterly	0.981	2	2	SSCI
287	Tijdschrift voor economische en sociale geografie	1.096	1	2	SSCI
288	Tourism Geographies	1.695	1	2	SSCI
289	Transactions in GIS	1.398	1	3	SSCI
290	Transactions of the Institute of British Geographers	3.636	1	2	SSCI
291	Tree-Ring Research	1.250	1	1	SCI
292	Tropical Ecology	0.887	2	1	SCI
293	Urban Geography	1.355	1	2	SSCI
294	Urban Policy and Research	0.574	2	2	SSCI
295	Urban Studies	1.592	1	2	SSCI
296	Vegetation History and Archaeobotany	2.648	2	1	SCI
297	Waste Management & Research	1.297	2	4	SCI
298	Water Air and Soil Pollution	1.554	1	4	SCI
299	Water and Environment Journal	1.344	2	4	SCI
300	Water International	0.686	2	1	SCI
301	Water Resources	0.361	2	1	SCI
302	Water Resources Management	2.600	2	1	SCI
303	Water Resources Research	3.549	2	1	SCI
304	Wetlands	1.572	2	1	SCI
305	World Development	1.965	1	2	SSCI
306	World Economy	0.727	2	2	SSCI
307	Zeitschrift fur Geomorphologie	0.734	2	1	SCI

Note ① In the field "Type", the 307 mainstream journals are divided into two types. The 1 indicates the 118 comprehensive journals, and the 2 indicates professional journals. ② In the field "Subdiscipline", the 1 indicates Physical Geography; the 2 indicates Human Geography; the 3 indicates Geographical Information Science; and the 4 indicates Environmental Geography

Appendix B
Abbreviations of the Funding Agencies in Fig. 1.4

Code	Abbreviation	Name of agencies	Country
1	DFG	German Science Foundation	Germany
2	DOE	United States Department of Energy	USA
3	EPA/USEPA	United States Environmental Protection Agency	USA
4	ESRC	Economic and Social Research Council	UK
5	MOST	Ministry of Science and Technology of China	China
6	NASA	National Aeronautic and Space Administration	USA
7	NERC	Natural Environment Research Council	UK
8	NIH	National Institutes of Health	USA
9	NOAA	National Oceanic and Atmospheric Administration	USA
10	NSFC	National Natural Science Foundation of China	China
11	NSF	National Science Foundation	USA
12	USDA	United States Department of Agriculture	USA

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Appendix C
List of 29 CSCD and Chinese Core Journals

Code	Journal name	Subdiscipline
1	Journal of Glaciology and Geocryology	1
2	Acta Geodaetica et Cartographica Sinica	3
3	Resources and Environment in the Yangtze Basin	1, 2
4	City Planning Review	2
5	Scientia Geographica Sinica	1, 2
6	Acta Geographica Sinica	1, 2
7	Geographical Research	1, 2
8	Journal of Geo-Information Science	3
9	Areal Research and Development	1, 2
10	Quaternary Sciences	1
11	Journal of Lake Sciences	1
12	Environmental Science	4
13	Acta Scientiae Circumstantiae	4
14	Economic Geography	2
15	Chinese Science Bulletin	1
16	Human Geography	2
17	Acta Ecologica Sinica	1
18	Advances in Water Science	1
19	Geomatics and Information Science of Wuhan University	3
20	Journal of Remote Sensing	3
21	Chinese Journal of Applied Ecology	1
22	China Environmental Science	4
23	Scientia Sinica Terrae	1
24	China Population Resources and Environment	1, 2
25	Journal of Desert Research	1
26	China Land Sciences	1, 2
27	Resources Science	1, 2
28	Journal of Natural Disasters	1
29	Journal of Natural Resources	1, 2

Note In the field “Subdiscipline”, the 1 indicates Physical Geography; the 2 indicates Human Geography; the 3 indicates Geographical Information Science; and the 4 indicates Environmental Geography

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Appendix D
List of Institutions in the Collaborative Networks of Chinese Authors in the SCI/SSCI and CSCD (& Chinese Core Journals) Indexed Articles

Abbreviation	Full name of institution	Name in ISI database
ANU	Anhui Normal University	Anhui Normal Univ
BNU	Beijing Normal University	Beijing Normal Univ
CAREERI	Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences	Chinese Acad Sci, Cold & Arid Reg Environm & Engn Res Inst
CASM	Chinese Academy of Surveying & Mapping	Chinese Acad Surveying & Mapping
CEA	China Earthquake Administration	China Earthquake Adm
CIB	Chengdu Institute of Biology, Chinese Academy of Sciences	Chinese Acad Sci, Chengdu Inst Biol
CLSPI	China Land Surveying and Planning Institute	China Land Surveying & Planning Inst
CRAES	Chinese Research Academy of Environmental Sciences	Chinese Res Inst Environm Sci
CSU	Central South University	South Central Univ
CUHK	Chinese University of Hong Kong	Chinese Univ Hong Kong
CUMTB	China University of Mining & Technology, Beijing	China Univ Min & Technol, Beijing
DLUT	Dalian University of Technology	Dalian Univ Technol
ECNU	East China Normal University	E China Normal Univ
ECUST	East China University of Science and Technology	E China Univ Sci & Technol
EGI	Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences	Chinese Acad Sci, Xinjiang Inst Ecol & Geog
FUDAN	Fudan University	Fudan Univ
FZU	Fuzhou University	Fuzhou Univ
GIG	Guangzhou Institute of Geochemistry, Chinese Academy of Sciences	Chinese Acad Sci, Guangzhou Inst Geochem
GUT	Guilin University of Technology	Guilin Univ Technol
GYIG	Institute of Geochemistry, Chinese Academy of Sciences	Chinese Acad Sci, Inst Geochem
HBNU	Hebei Normal University	Hebei Normal Univ
HENU	Henan University	Henan Univ
HHU	HoHai University	Hohai Univ
HKBU	Hong Kong Baptist University	Hong Kong Baptist Univ
HKU	The University of Hong Kong	Univ Hong Kong
HKUST	Hong Kong University of Science and Technology	Hong Kong Univ Sci & Technol
HRBUST	Harbin University of Science and Technology	Harbin Inst Technol
HUNU	Hunan University	Hunan Univ
IAE	Shenyang Institute of Applied Ecology, Chinese Academy of Sciences	Chinese Acad Sci, Inst Appl Ecol
IAP	Institute of Atmospheric Physics, Chinese Academy of Sciences	Chinese Acad Sci, Inst Atmospher Phys
IBCAS	Institute of Botany, Chinese Academy of Sciences	Chinese Acad Sci, Inst Bot

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Abbreviation	Full name of institution	Name in ISI database
IEUPLA	Information Engineering University, People's Liberation Army of China	PLA Informat Engn Univ
IFRIT	Research Institute of Forest Resource Information Techniques	Chinese Acad Forestry, Inst Forest Resource Informat Technol
IGSNRR	Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences	Chinese Acad Sci, Inst Geog Sci & Nat Resources Res
IHB	Institute of Hydrobiology, Chinese Academy of Sciences	Chinese Acad Sci, Inst Hydrobiol
IMHE	Institute of Mountain Hazards and Environment, Chinese Academy of Sciences	Chinese Acad Sci, Inst Mt Hazards & Environm
ISL	Qinghai Institute of Salt Lakes, Chinese Academy of Sciences	Chinese Acad Sci, Qinghai Inst Salt Lakes
ISSAS	Institute of Soil Science, Chinese Academy of Sciences	Chinese Acad Sci, Inst Soil Sci
ITP	Institute of Tibetan Plateau Research, Chinese Academy of Sciences	Chinese Acad Sci, Inst Tibetan Plateau Res
IUE	Institute of Urban Environment, Chinese Academy of Sciences	Chinese Acad Sci, Inst Urban Environm
IWHR	China Institute of Water Resources and Hydropower Research	China Inst Water Resources & Hydropower Res
KJZH	Air Force Command College, People's Liberation Army of China	Air Force Command Coll
LNNU	Liaoning Normal University	Liaoning Normal Univ
LZU	Lanzhou University	Lanzhou Univ
NANKAI	Nankai University	Nankai Univ
NCEPU	North China Electric Power University	North China Elect Power Univ
NEIGAE	Northeast Institute of Geography and Agricultural Ecology, Chinese Academy of Sciences	Chinese Acad Sci, Northeast Inst Geog & Agroecol
NENU	Northeast Normal University	Northeast Normal Univ
NGCC	National Geomatics Center of China	Natl Geometr Ctr China
NIGLAS	Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences	Chinese Acad Sci, Nanjing Inst Geog & Limnol
NJAU	Nanjing Agricultural University	Nanjing Agr Univ
NJNU	Nanjing Normal University	Nanjing Normal Univ
NJU	Nanjing University	Nanjing Univ
NWNU	Northwest Normal University	Northwest Normal Univ
PKU	Peking University	Peking Univ
POLYU	Hong Kong Polytechnic University	Hong Kong Polytech Univ
QDGEO	Qingdao Institute of Marine Geology	Qingdao Inst Marine Geol
RADI	Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences	Chinese Acad Sci, Inst Remote Sensing & Digital Earth
RCEES	Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences	Chinese Acad Sci, Ecoenvironm Sci Res Ctr
SCIB	South China Botanical Garden, Chinese Academy of Sciences	Chinese Acad Sci, South China Bot Garden
SCNU	South China Normal University	S China Normal Univ
SDU	Shandong Polytechnical University	Shandong Polytech Univ
SDUST	Shandong University of Science and Technology	Shandong Univ Sci & Technol
SHNU	Shanghai Normal University	Shanghai Normal Univ
SJTU	Shanghai Jiao Tong University	Shanghai Jiao Tong Univ
SNNU	Shaanxi Normal University	Shaanxi Normal Univ
STU	Shantou University	Shantou Univ
SWJTU	Southwest Jiaotong University	Southwest Jiaotong Univ
SYSU	Sun Yat-sen University	Sun Yat Sen Univ
SZU	Shenzhen University	Shenzhen Univ
TONGJI	Tongji University	Tongji Univ

(continued)

Abbreviation	Full name of institution	Name in ISI database
TSINGHUA	Tsinghua University	Tsinghua Univ
UESTC	University of Electronic Science and Technology of China	Univ Elect Sci & Technol China
UGEO	China University of Geosciences (Wuhan)	China Univ Geosci Wuhan
UIBE	University of International Business and Economics	Univ Int Business & Econ
WHU	Wuhan University	Wuhan Univ
XMU	Xiamen University	Xiamen Univ
YIC	Yantai Institute of Coastal Zone Research, Chinese Academy of Science	Chinese Acad Sci, Yantai Inst Coastal Zone Res
ZJU	Zhejiang University	Zhejiang Univ

Appendix E
Journals Retrieved with No Less than 15 SCI/SSCI-Indexed Articles in Chap. 8 "Global Change and Terrestrial Ecosystems"

Code	Journal name	Included in Appendix A	Number of articles
1	Agriculture Ecosystems & Environment	YES	956
2	Applied and Environmental Microbiology		519
3	Applied Ecology and Environmental Research	YES	116
4	Applied Soil Ecology	YES	315
5	Applied Vegetation Science		566
6	Biodiversity and Conservation	YES	1086
7	Biogeosciences	YES	920
8	Biological Invasions		528
9	Chinese Science Bulletin		460
10	Ecography	YES	536
11	Ecohydrology	YES	295
12	Ecological Applications	YES	973
13	Ecological Complexity	YES	104
14	Ecological Economics		431
15	Ecological Indicators	YES	453
16	Ecological Modelling	YES	1200
17	Ecological Monographs	YES	201
18	Ecological Research	YES	537
19	Ecology		1305
20	Ecology and Society	YES	299
21	Ecology Letters		497
22	Ecosphere		235
23	Ecosystems	YES	725
24	European Journal of Soil Biology		167
25	Folia Geobotanica	YES	196
26	Frontiers in Ecology and the Environment	YES	260
27	Frontiers of Earth Science		61
28	Geophysical Research Letters		1789
29	Global Biogeochemical Cycles	YES	702
30	Global Change Biology	YES	2375
31	Global Ecology and Biogeography	YES	595
32	Journal of Applied Ecology	YES	747
33	Journal of Arid Environments	YES	1282
34	Journal of Biogeography	YES	1451
35	Journal of Ecology	YES	925

(continued)

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Code	Journal name	Included in Appendix A	Number of articles
36	Journal of Geophysical Research-Atmospheres		1681
37	Journal of Geophysical Research-Biogeosciences		674
38	Journal of Geophysical Research-Earth Surface		218
39	Journal of Plant Ecology	YES	129
40	Journal of Plant Research		107
41	Journal of Soil and Water Conservation		130
42	Journal of Vegetation Science	YES	1127
43	Landscape and Urban Planning	YES	515
44	Landscape Ecology	YES	557
45	Microbial Ecology		178
46	Nature		739
47	Nature Climate Change		420
48	Nature Communications		110
49	Nature Geoscience		288
50	Oecologia		1277
51	Plant and Soil		1005
52	PLoS ONE		2932
53	Proceedings of the National Academy of Sciences of the United States of America		1400
54	Science		961
55	Science China-Earth Sciences		128
56	Scientific Reports		140
57	Soil Biology & Biochemistry		930
58	Wetlands	YES	631

Appendix F
Journals Retrieved with No Less than 15 SCI/SSCI-Indexed Articles in Chap. 9 "Terrestrial Water Cycle and Water Resources"

Code	Journal name	Included in Appendix A	Number of articles
1	Advances in Water Resources		392
2	Agricultural Water Management		541
3	Bulletin of the American Meteorological Society		48
4	Ecohydrology	YES	208
5	Ground Water		188
6	Hydrogeology Journal		275
7	Hydrological Processes	YES	2023
8	Hydrological Sciences Journal-Journal des Sciences Hydrologiques		658
9	Hydrology and Earth System Sciences	YES	1069
10	Hydrology Research	YES	158
11	International Journal of Climatology	YES	151
12	International Journal of Water Resources Development	YES	249
13	Irrigation Science		71
14	Journal of Hydro-Environment Research	YES	19
15	Journal of Hydroinformatics	YES	120
16	Journal of Hydrology	YES	2572
17	Journal of Hydrometeorology	YES	327
18	Journal of the American Water Resources Association	YES	608
19	Journal of Water Resources Planning and Management-ASCE		207
20	Nature		54
21	Nature Climate Change		24
22	Nature Geoscience		44
23	Science		62
24	Water International	YES	379
25	Water Policy		190
26	Water Resources Management	YES	874
27	Water Resources Research	YES	1738

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Appendix G
Journals Retrieved with No Less than 15 SCI/SSCI-Indexed Articles in Chap. 10 "Land Change"

Code	Journal name	Included in Appendix A	Number of articles
1	Acta Agriculturae Scandinavica Section B-Soil and Plant Science		31
2	Advanced Materials Research		32
3	Advances in Agronomy		36
4	Advances in Atmospheric Sciences		105
5	Advances in Meteorology	YES	54
6	Advances in Space Research		52
7	Advances in Water Resources		43
8	Aeolian Research	YES	15
9	Agricultural and Forest Meteorology	YES	144
10	Agricultural Systems		146
11	Agricultural Water Management		95
12	Agriculture Ecosystems & Environment	YES	590
13	Agroforestry Systems		70
14	Agronomy for Sustainable Development		49
15	Agronomy Journal		51
16	Ambio	YES	127
17	American Journal of Botany		20
18	Annals of Botany		37
19	Annals of Forest Science		30
20	Annals of Glaciology	YES	37
21	Annals of Regional Science	YES	23
22	Annals of the Association of American Geographers	YES	98
23	Annual Review of Environment and Resources	YES	38
24	Antarctic Science	YES	70
25	Applied and Environmental Microbiology		22
26	Applied Ecology and Environmental Research	YES	17
27	Applied Geochemistry		55
28	Applied Geography	YES	256
29	Applied Soil Ecology	YES	90
30	Aquatic Sciences		31
31	ARCTIC	YES	29
32	Arctic Antarctic and Alpine Research	YES	46
33	Area	YES	24
34	Arid Land Research and Management	YES	42

(continued)

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Code	Journal name	Included in Appendix A	Number of articles
35	Atmospheric Chemistry and Physics		138
36	Atmospheric Environment	YES	124
37	Atmospheric Research		35
38	Australian Geographer	YES	26
39	Australian Journal of Botany		36
40	Australian Journal of Earth Sciences		16
41	Australian Journal of Soil Research		76
42	Basic and Applied Ecology	YES	65
43	Biodiversity and Conservation	YES	214
44	Biogeochemistry	YES	133
45	Biogeosciences	YES	234
46	Biological Conservation	YES	401
47	Biological Invasions		36
48	Biology and Fertility of Soils		63
49	Bioresource Technology		25
50	Bioscience		75
51	Boreas	YES	26
52	Bulletin of the American Meteorological Society		36
53	Canadian Geographer-Geographe Canadien	YES	30
54	Canadian Journal Forest Research-Revue Canadienne de Recherche Forestiere		74
55	Canadian Journal of Soil Science		52
56	Catena	YES	311
57	Chemical Geology		26
58	Chemosphere	YES	42
59	Chinese Geographical Science	YES	123
60	Chinese Journal of Geophysics-Chinese Edition		32
61	Chinese Science Bulletin		117
62	Cities	YES	66
63	Climate Dynamics	YES	310
64	Climate of the Past	YES	81
65	Climate Research		102
66	Climatic Change	YES	396
67	Communications in Soil Science and Plant Analysis		70
68	Computers Environment and Urban Systems	YES	51
69	Computers & Geosciences	YES	29
70	Conservation Biology		205
71	Continental Shelf Research	YES	30
72	Disaster Advances	YES	20
73	Earth Interactions		89
74	Earth Surface Processes and Landforms	YES	105
75	Ecography	YES	75
76	Ecohydrology	YES	73
77	Ecological Applications	YES	351
78	Ecological Complexity	YES	32
79	Ecological Economics		188
80	Ecological Engineering	YES	121
81	Ecological Indicators	YES	233
82	Ecological Informatics	YES	29
83	Ecological Modelling	YES	292
84	Ecological Monographs	YES	23

(continued)

Code	Journal name	Included in Appendix A	Number of articles
85	Ecological Research	YES	63
86	Ecology		108
87	Ecology and Evolution		33
88	Ecology and Society	YES	205
89	Ecology Letters		51
90	Ecoscience	YES	22
91	Ecosystems	YES	181
92	Energy		17
93	Environment and Development Economics	YES	19
94	Environment and Planning A	YES	47
95	Environment and Urbanization	YES	34
96	Environment International	YES	21
97	Environmental Conservation	YES	78
98	Environmental Earth Sciences		189
99	Environmental Geology		101
100	Environmental Impact Assessment Review	YES	28
101	Environmental Management	YES	394
102	Environmental Modeling & Assessment	YES	32
103	Environmental Modelling & Software	YES	156
104	Environmental Pollution	YES	66
105	Environmental Research Letters	YES	212
106	Environmental Science and Engineering		35
107	Environmental Science and Pollution Research	YES	38
108	Environmental Science & Policy	YES	158
109	Environmental Science & Technology	YES	180
110	Erdkunde	YES	34
111	Estuarine Coastal and Shelf Science	YES	91
112	Eurasian Geography and Economics	YES	18
113	Eurasian Soil Science		44
114	European Journal of Agronomy		45
115	European Journal of Forest Research		35
116	European Journal of Soil Biology		30
117	European Journal of Soil Science		95
118	European Planning Studies	YES	31
119	FEMS Microbiology Ecology		18
120	Field Crops Research		36
121	Folia Geobotanica	YES	17
122	Food Policy		30
123	Forest Ecology and Management		607
124	Forest Policy and Economics		98
125	Forest Science		54
126	Forestry		20
127	Fresenius Environmental Bulletin	YES	77
128	Frontiers in Ecology and the Environment	YES	80
129	Frontiers of Earth Science		24
130	Functional Ecology		26
131	Geochemistry Geophysics Geosystems		20
132	Geochimica et Cosmochimica Acta		48
133	Geoderma		303
134	Geoforum	YES	86

(continued)

Code	Journal name	Included in Appendix A	Number of articles
135	Geografisk Tidsskrift-Danish Journal of Geography	YES	35
136	Geografiska Annaler Series A-Physical Geography	YES	25
137	Geographical Journal	YES	49
138	Geographical Research	YES	37
139	Geographical Review	YES	21
140	Geomorphologie-Relief Processus Environnement	YES	18
141	Geomorphology	YES	271
142	Geophysical Journal International		51
143	Geophysical Research Letters		453
144	Geophysics		17
145	GIScience & Remote Sensing	YES	44
146	Global and Planetary Change	YES	259
147	Global Biogeochemical Cycles	YES	184
148	Global Change Biology	YES	534
149	Global Change Biology Bioenergy		98
150	Global Ecology and Biogeography	YES	116
151	Global Environmental Change-Human and Policy Dimensions	YES	146
152	Grass and Forage Science		15
153	Ground Water		24
154	Habitat International	YES	63
155	Holocene	YES	182
156	Human and Ecological Risk Assessment		18
157	Hydrobiologia		157
158	Hydrogeology Journal		49
159	Hydrological Processes	YES	395
160	Hydrological Sciences Journal-Journal des Sciences Hydrologiques		93
161	Hydrology and Earth System Sciences	YES	275
162	Hydrology Research	YES	33
163	IAHS Publication		20
164	IEEE Geoscience and Remote Sensing Letters	YES	43
165	IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing	YES	64
166	IEEE Transactions on Geoscience and Remote Sensing	YES	186
167	International Journal of Applied Earth Observation and Geoinformation	YES	134
168	International Journal of Climatology	YES	168
169	International Journal of Digital Earth	YES	26
170	International Journal of Environmental Research	YES	30
171	International Journal of Environmental Research and Public Health	YES	35
172	International Journal of Geographical Information Science	YES	86
173	International Journal of Health Geographics	YES	16
174	International Journal of Life Cycle Assessment	YES	98
175	International Journal of Sustainable Development and World Ecology		85
176	International Journal of Urban and Regional Research	YES	21
177	International Journal of Water Resources Development	YES	18
178	ISPRS Journal of Photogrammetry and Remote Sensing	YES	54
179	Journal of Advances in Modeling Earth Systems		21
180	Journal of Agricultural Science		24
181	Journal of Applied Ecology	YES	221
182	Journal of Applied Remote Sensing	YES	71
183	Journal of Arid Environments	YES	279
184	Journal of Arid Land	YES	45

(continued)

Code	Journal name	Included in Appendix A	Number of articles
185	Journal of Asian Earth Sciences		31
186	Journal of Biogeography	YES	179
187	Journal of Cleaner Production	YES	77
188	Journal of Climate	YES	444
189	Journal of Coastal Research	YES	247
190	Journal of Earth System Science	YES	17
191	Journal of Ecology	YES	93
192	Journal of Environmental Biology		24
193	Journal of Environmental Economics and Management		18
194	Journal of Environmental Informatics	YES	15
195	Journal of Environmental Management	YES	324
196	Journal of Environmental Monitoring	YES	28
197	Journal of Environmental Planning and Management		47
198	Journal of Environmental Protection and Ecology		22
199	Journal of Environmental Quality	YES	168
200	Journal of Environmental Radioactivity		15
201	Journal of Environmental Science and Health Part A-Toxic/Hazardous Substances & Environmental Engineering	YES	15
202	Journal of Forest Research		19
203	Journal of Forestry Research		16
204	Journal of Geographical Sciences	YES	106
205	Journal of Geophysical Research-Atmospheres		568
206	Journal of Geophysical Research-Biogeosciences		171
207	Journal of Geophysical Research-Earth Surface		56
208	Journal of Geophysical Research-Oceans		58
209	Journal of Geophysical Research-Planets		42
210	Journal of Glaciology	YES	45
211	Journal of Great Lakes Research		42
212	Journal of Hazardous Materials	YES	20
213	Journal of Historical Geography	YES	18
214	Journal of Hydrologic Engineering	YES	61
215	Journal of Hydrology	YES	493
216	Journal of Hydrometeorology	YES	184
217	Journal of Maps	YES	24
218	Journal of Mountain Science	YES	55
219	Journal of Plant Ecology	YES	16
220	Journal of Plant Nutrition and Soil Science		26
221	Journal of Plant Nutrition and Soil Science-Zeitschrift für Pflanzenernährung und Bodenkunde		28
222	Journal of Quaternary Science	YES	69
223	Journal of Soil and Water Conservation		75
224	Journal of Soils and Sediments	YES	55
225	Journal of Sustainable Agriculture		31
226	Journal of the American Water Resources Association	YES	161
227	Journal of the Indian Society of Remote Sensing	YES	58
228	Journal of Transport Geography	YES	40
229	Journal of Tropical Ecology	YES	21
230	Journal of Urban Planning and Development-ASCE	YES	32
231	Journal of Vegetation Science	YES	90
232	Journal of Water Resources Planning and Management-ASCE		16
233	Land Degradation & Development	YES	241

(continued)

Code	Journal name	Included in Appendix A	Number of articles
234	Land Economics	YES	43
235	Land Use Policy	YES	454
236	Landscape and Ecological Engineering	YES	16
237	Landscape Ecology	YES	363
238	Landscape Research	YES	45
239	Lecture Notes in Computer Science		59
240	Limnology and Oceanography	YES	38
241	Marine Ecology Progress Series		52
242	Marine Pollution Bulletin		57
243	Methods in Ecology and Evolution		16
244	Microbial Ecology		27
245	Mitigation and Adaptation Strategies for Global Change		86
246	Molecular Ecology		54
247	Mountain Research and Development	YES	109
248	Natural Hazards	YES	116
249	Natural Hazards and Earth System Sciences		69
250	Natural Resources Forum	YES	16
251	Natural Resources Journal		21
252	Nature		115
253	Nature Climate Change		62
254	Nature Communications		18
255	Nature Geoscience		50
256	New Forests		22
257	New Phytologist		59
258	New Zealand Journal of Agricultural Research		29
259	Norsk Geografisk Tidsskrift-Norwegian Journal of Geography	YES	16
260	Nutrient Cycling in Agroecosystems		83
261	Ocean & Coastal Management	YES	65
262	Oecologia		74
263	Oikos		33
264	Organic Geochemistry		35
265	Paddy and Water Environment		27
266	Palaeogeography Palaeoclimatology Palaeoecology	YES	207
267	Pedobiologia		28
268	Pedosphere		67
269	Philosophical Transactions of the Royal Society B-Biological Sciences		114
270	Photogrammetric Engineering and Remote Sensing	YES	112
271	Physical Geography	YES	60
272	Physics and Chemistry of the Earth		112
273	Plant and Soil		176
274	Plant Ecology	YES	87
275	Plant Ecology & Diversity	YES	26
276	Plant Physiology		17
277	PLoS ONE		458
278	Polish Journal of Ecology	YES	41
279	Polish Journal of Environmental Studies		41
280	Population and Environment	YES	51
281	Proceedings of SPIE		114
282	Proceedings of the Society of Photo-Optical Instrumentation Engineers (SPIE)		136
283	Progress in Natural Science		16

(continued)

Code	Journal name	Included in Appendix A	Number of articles
284	Progress in Physical Geography	YES	68
285	Quaternary International	YES	170
286	Quaternary Research	YES	67
287	Quaternary Science Reviews	YES	235
288	Rangeland Ecology & Management	YES	71
289	Regional Environmental Change	YES	186
290	Regional Science and Urban Economics	YES	19
291	Remote Sensing Letters	YES	19
292	Remote Sensing of Environment	YES	526
293	Renewable Energy		21
294	Renewable & Sustainable Energy Reviews		60
295	Resources Conservation and Recycling		24
296	Restoration Ecology	YES	79
297	Revista Brasileira de Ciencia do Solo		56
298	Risk Analysis		17
299	River Research and Applications	YES	64
300	Scandinavian Journal of Forest Research		15
301	Science		94
302	Science China-Earth Sciences		36
303	Science in China Series C-Life Sciences		18
304	Science in China Series D-Earth Sciences		55
305	Science of the Total Environment	YES	330
306	Scientific Reports		22
307	Sedimentary Geology		31
308	Sedimentology	YES	19
309	Sensors		49
310	Singapore Journal of Tropical Geography	YES	29
311	Soil Biology & Biochemistry		206
312	Soil Research		40
313	Soil Science		60
314	Soil Science and Plant Nutrition		59
315	Soil Science Society of America Journal		161
316	Soil & Tillage Research		163
317	Soil Use and Management		127
318	Spectroscopy and Spectral Analysis		20
319	Stochastic Environmental Research and Risk Assessment	YES	38
320	Tectonophysics		24
321	Terrestrial Atmospheric and Oceanic Sciences		17
322	Theoretical and Applied Climatology	YES	105
323	Tijdschrift voor Economische en Sociale Geografie	YES	17
324	Transportation Research Part A-Policy and Practice		30
325	Transportation Research Part D-Transport and Environment		18
326	Trends in Ecology & Evolution		37
327	Urban Geography	YES	25
328	Urban Studies	YES	77
329	Vadose Zone Journal		41
330	Water Air and Soil Pollution	YES	89
331	Water International	YES	31
332	Water Policy		16
333	Water Research		38

(continued)

Code	Journal name	Included in Appendix A	Number of articles
334	Water Resources Management	YES	104
335	Water Resources Research	YES	275
336	Water Science and Technology		92
337	Weed Research		15
338	Wetlands	YES	71
339	World Development	YES	56
340	Zeitschrift für Geomorphologie	YES	35

Appendix H
Journals Retrieved with No Less than 15 SCI/SSCI-Indexed Articles in Chap. 11 "Global Cryosphere Evolution and Land Surface Processes on the Tibetan Plateau"

Code	Journal name	Included in Appendix A	Number of articles
1	Advances in Atmospheric Sciences		258
2	Advances in Water Resources		37
3	Agricultural and Forest Meteorology	YES	68
4	Ambio	YES	138
5	Annals of Glaciology	YES	1052
6	Antarctic Science	YES	735
7	Applied Soil Ecology	YES	30
8	Aquatic Geochemistry		22
9	Aquatic Sciences		34
10	Archives of Environmental Contamination and Toxicology	YES	18
11	ARCTIC	YES	432
12	Arctic Antarctic and Alpine Research	YES	544
13	Atmospheric Chemistry and Physics		762
14	Atmospheric Environment	YES	376
15	Atmospheric Research		88
16	Atmospheric Science Letters		32
17	Australian Journal of Earth Sciences		36
18	Austrian Journal of Earth Sciences		24
19	Biodiversity and Conservation	YES	25
20	Biogeochemistry	YES	106
21	Biogeosciences	YES	350
22	Biological Conservation	YES	64
23	Boreas	YES	388
24	Bulletin of the American Meteorological Society		122
25	Canadian Journal of Soil Science		21
26	Catena	YES	68
27	Chemical Geology		217
28	Chinese Geographical Science	YES	37
29	Chinese Journal of Geophysics-Chinese Edition		144
30	Chinese Journal of Oceanology and Limnology	YES	25
31	Chinese Science Bulletin		449
32	Climate Dynamics	YES	700
33	Climate of the Past	YES	389

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Code	Journal name	Included in Appendix A	Number of articles
34	Climate Research		103
35	Climatic Change	YES	298
36	Cold Regions Science and Technology	YES	540
37	Dendrochronologia		23
38	Earth Interactions		27
39	Earth Surface Processes and Landforms	YES	174
40	Ecography	YES	67
41	Ecohydrology	YES	19
42	Ecological Applications	YES	82
43	Ecological Research	YES	39
44	Ecology and Evolution		50
45	Ecology and Society	YES	18
46	Ecosystems	YES	99
47	Environment International	YES	44
48	Environmental Chemistry		42
49	Environmental Earth Sciences		103
50	Environmental Geology		46
51	Environmental Management	YES	23
52	Environmental Pollution	YES	149
53	Environmental Research	YES	16
54	Environmental Research Letters	YES	234
55	Environmental Science and Pollution Research	YES	38
56	Environmental Science & Technology	YES	495
57	Environmental Toxicology and Chemistry	YES	95
58	Eurasian Soil Science		62
59	European Journal of Soil Science		19
60	Frontiers in Ecology and the Environment	YES	28
61	Frontiers of Earth Science		15
62	Geochemical Journal		34
63	Geochemistry Geophysics Geosystems		286
64	Geochemistry International		53
65	Geochimica et Cosmochimica Acta		573
66	Geographie Physique et Quaternaire		15
67	Geomicrobiology Journal		39
68	Geomorphologie-Relief Processus Environnement	YES	20
69	Geomorphology	YES	475
70	Geophysical Journal International		212
71	Geophysical Research Letters		2544
72	Geophysics		33
73	Geosciences Journal		31
74	Global and Planetary Change	YES	595
75	Global Biogeochemical Cycles	YES	349
76	Global Change Biology	YES	381
77	Global Ecology and Biogeography	YES	48
78	Global Environmental Change-Human and Policy Dimensions	YES	26
79	Holocene	YES	393
80	Hydrogeology Journal		34
81	Hydrological Processes	YES	453
82	Hydrological Sciences Journal-Journal des Sciences Hydrologiques		63
83	Hydrology and Earth System Sciences	YES	145
84	Hydrology Research	YES	38

(continued)

Code	Journal name	Included in Appendix A	Number of articles
85	IAHS Publication		16
86	IEEE Geoscience and Remote Sensing Letters	YES	70
87	IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing	YES	35
88	IEEE Transactions on Geoscience and Remote Sensing	YES	355
89	International Journal of Applied Earth Observation and Geoinformation	YES	38
90	International Journal of Climatology	YES	378
91	International Journal of Earth Sciences	YES	84
92	Journal of Applied Remote Sensing	YES	40
93	Journal of Arid Environments	YES	28
94	Journal of Arid Land	YES	25
95	Journal of Asian Earth Sciences		205
96	Journal of Biogeography	YES	160
97	Journal of Climate	YES	1342
98	Journal of Coastal Research	YES	53
99	Journal of Earth System Science	YES	43
100	Journal of Environmental Monitoring	YES	72
101	Journal of Geographical Sciences	YES	79
102	Journal of Geophysical Research-Atmospheres		2217
103	Journal of Geophysical Research-Biogeosciences		231
104	Journal of Geophysical Research-Earth Surface		377
105	Journal of Geophysical Research-Oceans		1325
106	Journal of Glaciology	YES	1029
107	Journal of Hydrology	YES	225
108	Journal of Hydrometeorology	YES	149
109	Journal of Mountain Science	YES	80
110	Journal of Quaternary Science	YES	481
111	Journal of the American Water Resources Association	YES	21
112	Journal of the Indian Society of Remote Sensing	YES	19
113	Limnology and Oceanography	YES	254
114	Marine Environmental Research		51
115	Marine Pollution Bulletin		213
116	Mountain Research and Development	YES	50
117	Nature		497
118	Nature Climate Change		77
119	Nature Communications		42
120	Nature Geoscience		283
121	New Phytologist		94
122	Nordic Hydrology	YES	57
123	Organic Geochemistry		90
124	Palaeogeography Palaeoclimatology Palaeoecology	YES	805
125	Permafrost and Periglacial Processes	YES	414
126	Physical Geography	YES	59
127	Physics and Chemistry of the Earth		35
128	PLoS ONE		540
129	Progress in Natural Science		31
130	Progress in Physical Geography	YES	87
131	Quaternary Geochronology	YES	83
132	Quaternary International	YES	518
133	Quaternary Research	YES	455
134	Quaternary Science Reviews	YES	1557

(continued)

Code	Journal name	Included in Appendix A	Number of articles
135	Regional Environmental Change	YES	30
136	Remote Sensing of Environment	YES	362
137	Russian Meteorology and Hydrology	YES	75
138	Science		514
139	Science China-Earth Sciences		118
140	Science in China Series D-Earth Sciences		245
141	Science of the Total Environment	YES	346
142	Terrestrial Atmospheric and Oceanic Sciences		32
143	Theoretical and Applied Climatology	YES	188
144	Water Resources	YES	36
145	Water Resources Management	YES	18
146	Water Resources Research	YES	150
147	Wetlands	YES	19
148	Zeitschrift für Geomorphologie	YES	91

Appendix I
Journals Retrieved with No Less than 15 SCI/SSCI-Indexed Articles in Chap. 12 "Economic Globalization and Local Responses"

Code	Journal name	Included in Appendix A	Number of articles
1	Annals of Regional Science	YES	60
2	Annals of the Association of American Geographers	YES	111
3	Annals of Tourism Research	YES	30
4	Antipode	YES	87
5	Applied Geography	YES	29
6	Area	YES	50
7	Cambridge Journal of Regions Economy and Society	YES	33
8	Canadian Geographer-Geographe Canadien	YES	39
9	China Quarterly		38
10	China & World Economy		59
11	Chinese Geographical Science	YES	20
12	Cities	YES	98
13	Economic Geography	YES	116
14	Environment and Planning A	YES	204
15	Environment and Planning C-Government and Policy	YES	61
16	Environment and Planning D-Society & Space	YES	50
17	Eurasian Geography and Economics	YES	78
18	European Planning Studies	YES	154
19	Gender Place and Culture	YES	23
20	Geoforum	YES	152
21	Geographical Journal	YES	29
22	Geographical Review	YES	18
23	Geography	YES	20
24	Geopolitics	YES	18
25	Global Environmental Change-Human and Policy Dimensions	YES	74
26	Global Networks-A Journal of Transnational Affairs	YES	119
27	Growth and Change	YES	54
28	Habitat International	YES	45
29	International Journal of Urban and Regional Research	YES	194
30	Journal of Development Studies	YES	95
31	Journal of Economic Geography	YES	107
32	Journal of Regional Science	YES	54
33	Journal of Rural Studies	YES	56
34	Journal of the Asia Pacific Economy		41

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Code	Journal name	Included in Appendix A	Number of articles
35	Journal of Transport Geography	YES	21
36	Journal of Urban Economics	YES	23
37	Pacific Economic Review		43
38	Papers in Regional Science	YES	45
39	Political Geography	YES	104
40	Population and Development Review	YES	46
41	Population Space and Place	YES	53
42	Proceedings of the National Academy of Sciences of the United States of America		41
43	Professional Geographer	YES	82
44	Progress in Human Geography	YES	153
45	Regional Science and Urban Economics	YES	50
46	Regional Studies	YES	184
47	Third World Quarterly	YES	101
48	Transactions of the Institute of British Geographers	YES	73
49	Urban Geography	YES	96
50	Urban Studies	YES	172
51	World Development	YES	268
52	World Economy	YES	272

Appendix J
Journals Retrieved with No Less than 15 SCI/SSCI-Indexed Articles in Chap. 13 "Regional Sustainable Development"

Code	Journal name	Included in Appendix A	Number of articles
1	Agricultural Water Management		21
2	Annals of the Association of American Geographers	YES	26
3	Annual Review of Environment and Resources	YES	18
4	Applied Geography	YES	50
5	Asia Pacific Viewpoint		16
6	Australian Geographer	YES	23
7	Canadian Geographer-Geographe Canadien	YES	17
8	Cities	YES	43
9	Energy		158
10	Energy Conversion and Management		52
11	Environment and Development Economics	YES	48
12	Environment and Planning A	YES	40
13	Environment and Planning B-Planning & Design	YES	21
14	Environment and Planning C-Government and Policy	YES	48
15	Environmental Management	YES	201
16	Environmental Science & Policy	YES	87
17	European Planning Studies	YES	43
18	Food Policy		17
19	Forest Ecology and Management		66
20	Forest Policy and Economics		79
21	Geoforum	YES	77
22	Geographical Journal	YES	40
23	Geographical Research	YES	16
24	Geography	YES	32
25	Global Environmental Change-Human and Policy Dimensions	YES	75
26	Habitat International	YES	52
27	International Development Planning Review		16
28	International Journal of Sustainable Development and World Ecology		279
29	International Journal of Water Resources Development	YES	27
30	Journal of Cleaner Production	YES	461
31	Journal of Environmental Management	YES	247
32	Journal of Environmental Planning and Management		64
33	Journal of Geographical Sciences	YES	40
34	Journal of Geography in Higher Education	YES	23

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Code	Journal name	Included in Appendix A	Number of articles
35	Journal of Rural Studies	YES	23
36	Journal of the American Water Resources Association	YES	30
37	Journal of Urban Planning and Development-ASCE	YES	17
38	Land Use Policy	YES	108
39	Landscape and Urban Planning	YES	96
40	Natural Resources Forum	YES	189
41	Political Geography	YES	20
42	Professional Geographer	YES	16
43	Progress in Human Geography	YES	15
44	Regional Studies	YES	29
45	Renewable Energy		83
46	Renewable & Sustainable Energy Reviews		349
47	Resources Conservation and Recycling		122
48	Singapore Journal of Tropical Geography	YES	22
49	Third World Quarterly	YES	20
50	Urban Studies	YES	26
51	Water Policy		27
52	Water Resources Management	YES	79
53	Water Resources Research	YES	25
54	World Development	YES	82

Appendix K
Journals Retrieved with No Less than 15 SCI/SSCI-Indexed Articles in Chap. 14 "Remote Sensing Modelling and Parameter Inversion"

Code	Journal name	Included in Appendix A	Number of articles
1	Canadian Journal of Remote Sensing	YES	92
2	IEEE Geoscience and Remote Sensing Letters	YES	114
3	IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing	YES	97
4	IEEE Transactions on Geoscience and Remote Sensing	YES	560
5	International Journal of Applied Earth Observation and Geoinformation	YES	80
6	International Journal of Remote Sensing	YES	500
7	ISPRS Journal of Photogrammetry and Remote Sensing	YES	32
8	Journal of Applied Remote Sensing	YES	71
9	Photogrammetric Engineering and Remote Sensing	YES	38
10	Remote Sensing	YES	158
11	Remote Sensing Letters	YES	24
12	Remote Sensing of Environment	YES	828
13	Sensors		73

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Appendix L
Journals Retrieved with No Less than 15 SCI/SSCI-Indexed Articles in Chap. 15 "Spatial Analysis and Simulation"

Code	Journal name	Included in Appendix A	Number of articles
1	Applied Geography	YES	258
2	Cartography and Geographic Information Science	YES	83
3	Chinese Geographical Science	YES	201
4	Computers Environment and Urban Systems	YES	207
5	Computers & Geosciences	YES	1006
6	Earth Science Informatics	YES	68
7	Environment and Planning B-Planning & Design	YES	316
8	Geographical Analysis	YES	181
9	Geoinformatica	YES	189
10	Geospatial Health	YES	118
11	GIScience & Remote Sensing	YES	29
12	International Journal of Applied Earth Observation and Geoinformation	YES	59
13	International Journal of Digital Earth	YES	78
14	International Journal of Geographical Information Science	YES	609
15	International Journal of Health Geographics	YES	199
16	Journal of Geographical Systems	YES	107
17	Journal of Spatial Science	YES	56
18	Journal of Transport Geography	YES	364
19	Landscape and Urban Planning	YES	486
20	Mathematical Geosciences		141
21	Transactions in GIS	YES	165

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Appendix M
Journals Retrieved with No Less than 15 SCI/SSCI-Indexed Articles in Chap. 16 "Tempo-Spatial Processes and Modelling of Environmental Pollutants"

Code	Journal name	Included in Appendix A	Number of articles
1	Acta Agriculturae Scandinavica Section B-Soil and Plant Science		16
2	Advanced Materials Research		45
3	Advances in Environmental Research		17
4	Advances in Space Research		36
5	Agricultural Water Management		69
6	Agriculture Ecosystems & Environment	YES	127
7	Agrochimica		18
8	Agronomy for Sustainable Development		58
9	Ambio	YES	94
10	Applied and Environmental Microbiology		290
11	Applied Catalysis B-Environmental		115
12	Applied Clay Science		47
13	Applied Geochemistry		90
14	Applied Microbiology and Biotechnology		180
15	Applied Radiation and Isotopes		16
16	Applied Soil Ecology	YES	73
17	Aquatic Toxicology	YES	306
18	Archives of Environmental Contamination and Toxicology	YES	411
19	Archives of Environmental Protection	YES	27
20	Atmospheric Chemistry and Physics		2027
21	Atmospheric Environment	YES	2605
22	Atmospheric Research		375
23	Australian Journal of Soil Research		44
24	Biodegradation		97
25	Biogeochemistry	YES	77
26	Biogeosciences	YES	72
27	Biological Trace Element Research		59
28	Biology and Fertility of Soils		41
29	Biomedical and Environmental Sciences		15
30	Bioresource Technology		260
31	Bulletin of Environmental Contamination and Toxicology		323
32	Bulletin of the American Meteorological Society		32
33	Canadian Journal of Soil Science		20
34	Carbon		27

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Code	Journal name	Included in Appendix A	Number of articles
35	Catena	YES	27
36	Chemical Geology		37
37	Chemosphere	YES	1990
38	Chinese Geographical Science	YES	16
39	Chinese Journal of Analytical Chemistry		46
40	Chinese Science Bulletin		100
41	Climate Dynamics	YES	50
42	Climatic Change	YES	25
43	Colloids and Surfaces A-Physicochemical and Engineering Aspects		87
44	Colloids and Surfaces B-Biointerfaces		34
45	Communications in Soil Science and Plant Analysis		94
46	Compost Science & Utilization		17
47	Crop Protection		75
48	Ecological Modelling	YES	147
49	Ecotoxicology	YES	332
50	Ecotoxicology and Environmental Safety	YES	575
51	Environment International	YES	293
52	Environmental Chemistry		80
53	Environmental Chemistry Letters		63
54	Environmental Earth Sciences		200
55	Environmental Engineering and Management Journal		58
56	Environmental Engineering Science		93
57	Environmental Geochemistry and Health	YES	105
58	Environmental Geology		101
59	Environmental Health	YES	70
60	Environmental Health Perspectives	YES	410
61	Environmental Management	YES	53
62	Environmental Microbiology		67
63	Environmental Microbiology Reports		16
64	Environmental Modeling & Assessment	YES	24
65	Environmental Modelling & Software	YES	56
66	Environmental Monitoring and Assessment	YES	743
67	Environmental Pollution	YES	1001
68	Environmental Research	YES	142
69	Environmental Research Letters	YES	52
70	Environmental Science and Pollution Research	YES	671
71	Environmental Science-Processes & Impacts	YES	77
72	Environmental Science & Technology	YES	2029
73	Environmental Technology		162
74	Environmental Toxicology	YES	169
75	Environmental Toxicology and Chemistry	YES	916
76	Environmental Toxicology and Pharmacology		117
77	Eurasian Soil Science		35
78	European Journal of Soil Biology		44
79	European Journal of Soil Science		42
80	FEMS Microbiology Ecology		79
81	FEMS Microbiology Letters		98
82	Fresenius Environmental Bulletin	YES	429
83	Frontiers in Microbiology		45
84	Frontiers of Environmental Science & Engineering	YES	27
85	Frontiers of Environmental Science & Engineering in China		16

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Code	Journal name	Included in Appendix A	Number of articles
86	Geochemical Journal		22
87	Geochemistry Geophysics Geosystems		17
88	Geochimica et Cosmochimica Acta		98
89	Geoderma		122
90	Geomicrobiology Journal		19
91	Geophysical Research Letters		474
92	Global and Planetary Change	YES	16
93	Global Biogeochemical Cycles	YES	72
94	Global Change Biology	YES	48
95	Human and Ecological Risk Assessment		107
96	Indoor and Built Environment		17
97	International Journal of Environment and Pollution	YES	70
98	International Journal of Environmental Analytical Chemistry		173
99	International Journal of Environmental Health Research	YES	23
100	International Journal of Environmental Research	YES	58
101	International Journal of Environmental Research and Public Health	YES	66
102	International Journal of Environmental Science and Technology	YES	81
103	International Journal of Life Cycle Assessment	YES	137
104	International Journal of Phytoremediation		126
105	ISME Journal		21
106	Journal of Agricultural and Food Chemistry		460
107	Journal of Applied Microbiology		160
108	Journal of Bacteriology		169
109	Journal of Cleaner Production	YES	78
110	Journal of Climate	YES	110
111	Journal of Colloid and Interface Science		150
112	Journal of Contaminant Hydrology	YES	65
113	Journal of Earth System Science	YES	26
114	Journal of Economic Entomology		110
115	Journal of Environmental Biology		139
116	Journal of Environmental Management	YES	182
117	Journal of Environmental Monitoring	YES	361
118	Journal of Environmental Protection and Ecology		50
119	Journal of Environmental Quality	YES	442
120	Journal of Environmental Radioactivity		56
121	Journal of Environmental Science and Health Part A-Toxic/Hazardous Substances & Environmental Engineering	YES	266
122	Journal of Environmental Science and Health Part B-Pesticides Food Contaminants and Agricultural Wastes		292
123	Journal of Environmental Science and Health Part C-Environmental Carcinogenesis & Ecotoxicology Reviews	YES	16
124	Journal of Environmental Sciences-China	YES	327
125	Journal of Exposure Science and Environmental Epidemiology	YES	38
126	Journal of Geophysical Research-Atmospheres		2322
127	Journal of Geophysical Research-Biogeosciences		19
128	Journal of Geophysical Research-Oceans		17
129	Journal of Geophysical Research-Planets		25
130	Journal of Hazardous Materials	YES	952
131	Journal of Plant Nutrition and Soil Science		20
132	Journal of Plant Nutrition and Soil Science-Zeitschrift für Pflanzenernährung und Bodenkunde		33
133	Journal of Soil and Water Conservation		34

(continued)

Code	Journal name	Included in Appendix A	Number of articles
134	Journal of Soils and Sediments	YES	199
135	Journal of the Science of Food and Agriculture		69
136	Lecture Notes in Computer Science		15
137	Limnologica		40
138	Limnology		17
139	Marine Environmental Research		150
140	Marine Pollution Bulletin		655
141	Microbial Ecology		63
142	Microbiological Research		25
143	Mycorrhiza		24
144	Nanoscale		17
145	Nature		72
146	Nature Geoscience		24
147	New Phytologist		56
148	Nutrient Cycling in Agroecosystems		25
149	Ocean & Coastal Management	YES	23
150	Optical Engineering		21
151	Organic Geochemistry		44
152	Pedobiologia		17
153	Pedosphere		63
154	Pesticide Biochemistry and Physiology		119
155	Photochemical & Photobiological Sciences		15
156	Photochemistry and Photobiology		24
157	Physics and Chemistry of the Earth		27
158	Plant and Soil		134
159	Plant Cell and Environment		29
160	Plant Physiology and Biochemistry		36
161	PLoS ONE		883
162	Polish Journal of Environmental Studies		148
163	Proceedings of the National Academy of Sciences of the United States of America		284
164	Proceedings of the Society of Photo-Optical Instrumentation Engineers (SPIE)		34
165	Process Biochemistry		37
166	Process Safety and Environmental Protection	YES	15
167	Regional Environmental Change	YES	16
168	Remote Sensing of Environment	YES	81
169	Revista Brasileira de Ciencia do Solo		43
170	Risk Analysis		32
171	Russian Meteorology and Hydrology	YES	16
172	Science		68
173	Science China-Earth Sciences		23
174	Science in China Series D-Earth Sciences		27
175	Science of the Total Environment	YES	1441
176	Scientific Reports		28
177	Soil Biology & Biochemistry		125
178	Soil Science		43
179	Soil Science and Plant Nutrition		20
180	Soil Science Society of America Journal		63
181	Soil & Sediment Contamination	YES	125
182	Soil & Tillage Research		20
183	Soil Use and Management		33

(continued)

Code	Journal name	Included in Appendix A	Number of articles
184	Talanta		217
185	Terrestrial Atmospheric and Oceanic Sciences		15
186	Theoretical and Applied Climatology	YES	22
187	Toxicological Sciences		163
188	Toxicology		151
189	Toxicology Letters		131
190	Vadose Zone Journal		19
191	Waste Management		99
192	Waste Management & Research	YES	31
193	Water Air and Soil Pollution	YES	592
194	Water and Environment Journal	YES	15
195	Water Research		481
196	Water Resources Research	YES	24

Appendix N
Journals Retrieved with No Less than 15 SCI/SSCI-Indexed Articles in Chap. 17 "Geomorphology"

Code	Journal name	Included in Appendix A	Number of articles
1	Aeolian Research	YES	180
2	Annals of Glaciology	YES	613
3	Arctic Antarctic and Alpine Research	YES	515
4	Boreas	YES	572
5	Catena	YES	1367
6	Climate of the Past	YES	382
7	Cold Regions Science and Technology	YES	465
8	Cryosphere	YES	356
9	Earth Surface Processes and Landforms	YES	1852
10	Geomorphologie-Relief Processus Environnement	YES	199
11	Geomorphology	YES	3703
12	Holocene	YES	1223
13	International Journal of Sediment Research	YES	306
14	Journal of Arid Land	YES	162
15	Journal of Asian Earth Sciences		1849
16	Journal of Cold Regions Engineering		65
17	Journal of Glaciology	YES	870
18	Journal of Great Lakes Research		700
19	Journal of Hydraulic Engineering		127
20	Journal of Hydraulic Research		483
21	Journal of Mountain Science	YES	349
22	Journal of Paleolimnology		1128
23	Journal of Quaternary Science	YES	904
24	Journal of Sedimentary Research	YES	1076
25	Journal of Soil and Water Conservation		414
26	Journal of Soils and Sediments	YES	593
27	Landslides		475
28	Limnology and Oceanography	YES	1414
29	Natural Hazards	YES	1144
30	Palaeogeography Palaeoclimatology Palaeoecology	YES	3584
31	Permafrost and Periglacial Processes	YES	459
32	Quaternary Geochronology	YES	444
33	Quaternary International	YES	2736
34	Quaternary Research	YES	1158
35	Quaternary Science Reviews	YES	2523

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Code	Journal name	Included in Appendix A	Number of articles
36	Science China-Earth Sciences		526
37	Sedimentary Geology		2025
38	Terra Nova		566
39	Zeitschrift für Geomorphologie	YES	585

Appendix O
Journals Retrieved with No Less than 15 SCI/SSCI-Indexed Articles in Chap. 18 "Ecohydrology"

Code	Journal name	Included in Appendix A	Number of articles
1	Acta Physiologiae Plantarum		21
2	Advances in Water Resources		41
3	Agricultural and Forest Meteorology	YES	192
4	Agricultural Water Management		228
5	Agriculture Ecosystems & Environment	YES	26
6	Agroforestry Systems		18
7	Agronomy Journal		50
8	American Journal of Botany		18
9	Annals of Applied Biology		21
10	Annals of Botany		28
11	Annals of Forest Science		16
12	Biogeosciences	YES	15
13	Crop Science		33
14	Ecohydrology	YES	141
15	Ecological Applications	YES	19
16	Ecological Engineering	YES	22
17	Ecological Modelling	YES	49
18	Ecology		16
19	Ecosystems	YES	29
20	European Journal of Agronomy		33
21	Field Crops Research		61
22	Forest Ecology and Management		81
23	Functional Ecology		19
24	Functional Plant Biology		46
25	Geophysical Research Letters		25
26	Global Change Biology	YES	88
27	Hydrobiologia		15
28	Hydrological Processes	YES	166
29	Hydrological Sciences Journal-Journal des Sciences Hydrologiques		31
30	Hydrology and Earth System Sciences	YES	81
31	International Journal of Plant Sciences		15
32	International Journal of Remote Sensing	YES	37
33	Irrigation Science		44
34	Journal of Arid Environments	YES	52

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Code	Journal name	Included in Appendix A	Number of articles
35	Journal of Climate	YES	21
36	Journal of Ecology	YES	17
37	Journal of Experimental Botany		53
38	Journal of Geophysical Research-Atmospheres		52
39	Journal of Geophysical Research-Biogeosciences		49
40	Journal of Hydrologic Engineering	YES	18
41	Journal of Hydrology	YES	174
42	Journal of Hydrometeorology	YES	52
43	Journal of the American Water Resources Association	YES	22
44	New Phytologist		46
45	Oecologia		63
46	Pakistan Journal of Botany		17
47	Photosynthetica		48
48	Physics and Chemistry of the Earth		20
49	Physiologia Plantarum		23
50	Plant and Soil		108
51	Plant Cell and Environment		40
52	Plant Ecology	YES	19
53	PLoS ONE		35
54	Proceedings of the National Academy of Sciences of the United States of America		17
55	Remote Sensing	YES	19
56	Remote Sensing of Environment	YES	50
57	Scientia Horticulturae		45
58	Soil Science Society of America Journal		21
59	Tree Physiology		105
60	Trees-Structure and Function		46
61	Vadose Zone Journal		46
62	Water Resources Research	YES	135

Appendix P
Journals Retrieved with No Less than 15 SCI/SSCI-Indexed Articles in Chap. 19 “Ecosystem Services”

Code	Journal name	Included in Appendix A	Number of articles
1	Agricultural Systems		18
2	Agriculture Ecosystems & Environment	YES	145
3	Agroforestry Systems		33
4	Agronomy for Sustainable Development		15
5	Ambio	YES	66
6	Annals of the New York Academy of Sciences		28
7	Annual Review of Environment and Resources	YES	24
8	Applied Soil Ecology	YES	27
9	Aquatic Conservation-Marine and Freshwater Ecosystems		19
10	Basic and Applied Ecology	YES	31
11	Biodiversity and Conservation	YES	80
12	Biological Conservation	YES	131
13	Biological Control		32
14	Biological Invasions		16
15	Bioscience		66
16	Biotropica		18
17	Climatic Change	YES	16
18	Conservation Biology		76
19	Conservation Letters		45
20	Current Opinion in Environmental Sustainability		68
21	Diversity and Distributions		19
22	Ecological Applications	YES	111
23	Ecological Complexity	YES	35
24	Ecological Economics		303
25	Ecological Engineering	YES	79
26	Ecological Indicators	YES	144
27	Ecological Modelling	YES	52
28	Ecological Research	YES	19
29	Ecology		39
30	Ecology and Society	YES	192
31	Ecology Letters		49
32	Ecosphere		36
33	Ecosystems	YES	48
34	Environmental Conservation	YES	46
35	Environmental Entomology		15

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Code	Journal name	Included in Appendix A	Number of articles
36	Environmental Management	YES	86
37	Environmental Modelling & Software	YES	31
38	Environmental Monitoring and Assessment	YES	26
39	Environmental Pollution	YES	19
40	Environmental Research Letters	YES	29
41	Environmental Science & Policy	YES	71
42	Environmental Science & Technology	YES	34
43	Estuarine Coastal and Shelf Science	YES	36
44	Forest Ecology and Management		96
45	Forest Policy and Economics		44
46	Forests		26
47	Freshwater Biology		22
48	Frontiers in Ecology and the Environment	YES	79
49	Global Change Biology	YES	62
50	Global Change Biology Bioenergy		17
51	Global Environmental Change-Human and Policy Dimensions	YES	62
52	Hydrobiologia		23
53	Hydrological Sciences Journal-Journal des Sciences Hydrologiques		22
54	Hydrology and Earth System Sciences	YES	16
55	International Journal of Agricultural Sustainability		16
56	International Journal of Sustainable Development and World Ecology		32
57	Journal of Applied Ecology	YES	125
58	Journal of Arid Environments	YES	16
59	Journal of Coastal Research	YES	23
60	Journal of Ecology	YES	32
61	Journal of Environmental Management	YES	121
62	Journal of Hydrology	YES	19
63	Journal of Insect Conservation		17
64	Journal of Soil and Water Conservation		16
65	Landscape and Urban Planning	YES	122
66	Landscape Ecology	YES	82
67	Marine Ecology Progress Series		45
68	Marine Pollution Bulletin		17
69	Nature		28
70	Nature Climate Change		16
71	Ocean & Coastal Management	YES	46
72	Oecologia		30
73	Oikos		18
74	Oryx		18
75	Philosophical Transactions of the Royal Society B-Biological Sciences		40
76	PLoS ONE		201
77	Proceedings of the National Academy of Sciences of the United States of America		123
78	Proceedings of the Royal Society B-Biological Sciences		36
79	Rangeland Ecology & Management	YES	20
80	Regional Environmental Change	YES	41
81	Remote Sensing	YES	15
82	Remote Sensing of Environment	YES	24
83	Renewable Agriculture and Food Systems		15
84	Restoration Ecology	YES	51
85	River Research and Applications	YES	16
86	Science		30

(continued)

Code	Journal name	Included in Appendix A	Number of articles
87	Science of the Total Environment	YES	63
88	Soil Biology & Biochemistry		24
89	Soil Science Society of America Journal		17
90	South African Journal of Science		16
91	Sustainability		36
92	Trends in Ecology & Evolution		27
93	Urban Ecosystems		28
94	Urban Forestry & Urban Greening		30
95	Water Resources Research	YES	15
96	Wetlands	YES	42
97	Wetlands Ecology and Management		23

Appendix Q
Journals Retrieved with No Less than 15 SCI/SSCI-Indexed Articles in Chap. 20 "The Urbanization Process and Mechanism"

Code	Journal name	Included in Appendix A	Number of articles
1	Annals of Regional Science	YES	296
2	Annals of the Association of American Geographers	YES	87
3	Applied Geography	YES	87
4	Cities	YES	73
5	Computers Environment and Urban Systems	YES	57
6	Environment and Planning A	YES	47
7	Environment and Urbanization	YES	44
8	Eurasian Geography and Economics	YES	39
9	Eure-Revista Latinoamericana De Estudios Urbano Regionales		38
10	European Planning Studies	YES	34
11	Geoforum	YES	31
12	Global Environmental Change-Human and Policy Dimensions	YES	30
13	Habitat International	YES	29
14	International Journal of Urban and Regional Research	YES	28
15	Journal of Regional Science	YES	26
16	Journal of Urban Economics	YES	24
17	Journal of Urban History		22
18	Landscape and Urban Planning	YES	22
19	Professional Geographer	YES	21
20	Regional Studies	YES	20
21	Scripta Nova-Revista Electronica de Geografia y Ciencias Sociales		20
22	Tijdschrift voor Economische en Sociale Geografie	YES	19
23	Urban Forestry & Urban Greening		19
24	Urban Geography	YES	19
25	Urban Studies	YES	18
26	World Development	YES	17

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Appendix R
Journals Retrieved with No Less than 15 SCI/SSCI-Indexed Articles in Chap. 21 "Medical and Health Geography"

Code	Journal name	Included in Appendix A	Number of articles
1	Advanced Materials Research		20
2	Advances in Space Research		23
3	Aerosol and Air Quality Research		50
4	Agricultural and Forest Meteorology	YES	16
5	Agriculture Ecosystems & Environment	YES	33
6	Agronomy for Sustainable Development		29
7	Ambio	YES	31
8	American Journal of Epidemiology		219
9	American Journal of Preventive Medicine		112
10	American Journal of Public Health		181
11	American Journal of Tropical Medicine and Hygiene		239
12	Annals of Applied Biology		18
13	Annals of the Association of American Geographers	YES	74
14	Antipode	YES	27
15	Applied and Environmental Microbiology		162
16	Applied Geochemistry		81
17	Applied Geography	YES	98
18	Applied Microbiology and Biotechnology		22
19	Applied Radiation and Isotopes		24
20	Aquatic Toxicology	YES	265
21	Archives of Environmental Contamination and Toxicology	YES	19
22	Archives of Environmental & Occupational Health		145
23	Area	YES	42
24	Atmospheric Chemistry and Physics		58
25	Atmospheric Environment	YES	613
26	Atmospheric Research		21
27	Biodiversity and Conservation	YES	16
28	Biological Conservation	YES	30
29	Biological Invasions		19
30	Biological Trace Element Research		135
31	Biomedical and Environmental Sciences		28
32	BMC Health Services Research		164
33	BMC Public Health		398
34	Building and Environment		59

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Code	Journal name	Included in Appendix A	Number of articles
35	Bulletin of Environmental Contamination and Toxicology		96
36	Bulletin of the World Health Organization		90
37	Canadian Geographer-Geographe Canadien	YES	36
38	Canadian Journal Forest Research-Revue Canadienne de Recherche Forestiere		23
39	Canadian Journal of Public Health-Revue Canadienne de Sante Publique		93
40	Chemical Geology		16
41	Chemosphere	YES	525
42	Chinese Science Bulletin		33
43	Climatic Change	YES	28
44	Communications in Soil Science and Plant Analysis		20
45	Computers Environment and Urban Systems	YES	19
46	Conservation Biology		31
47	Crop Protection		50
48	Crop Science		26
49	Ecography	YES	24
50	EcoHealth		71
51	Ecological Applications	YES	51
52	Ecological Economics		19
53	Ecological Indicators	YES	48
54	Ecological Modelling	YES	60
55	Ecology		36
56	Ecology Letters		18
57	Ecotoxicology	YES	144
58	Ecotoxicology and Environmental Safety	YES	214
59	Environment and Planning A	YES	85
60	Environment International	YES	307
61	Environmental and Experimental Botany		24
62	Environmental Chemistry		15
63	Environmental Chemistry Letters		18
64	Environmental Earth Sciences		90
65	Environmental Engineering and Management Journal		45
66	Environmental Engineering Science		17
67	Environmental Geochemistry and Health	YES	161
68	Environmental Geology		49
69	Environmental Health	YES	152
70	Environmental Management	YES	50
71	Environmental Microbiology		36
72	Environmental Modelling & Software	YES	29
73	Environmental Pollution	YES	313
74	Environmental Research	YES	298
75	Environmental Research Letters	YES	17
76	Environmental Science and Pollution Research	YES	635
77	Environmental Science-Processes & Impacts	YES	273
78	Environmental Science & Technology	YES	27
79	Environmental Technology		25
80	Environmental Toxicology	YES	69
81	Environmental Toxicology and Chemistry	YES	314
82	Environmental Toxicology and Pharmacology		58
83	Environmetrics		52
84	Epidemiology		153
85	Estuarine Coastal and Shelf Science	YES	46

(continued)

Code	Journal name	Included in Appendix A	Number of articles
86	FEMS Microbiology Ecology		16
87	FEMS Microbiology Letters		22
88	Forest Ecology and Management		67
89	Fresenius Environmental Bulletin	YES	93
90	Frontiers in Microbiology		27
91	Gender Place and Culture	YES	23
92	Geoderma		23
93	Geoforum	YES	60
94	Geographical Analysis	YES	16
95	Geographical Journal	YES	17
96	Geomorphology	YES	20
97	Geospatial Health	YES	157
98	Global Change Biology	YES	53
99	Global Ecology and Biogeography	YES	17
100	Global Environmental Change-Human and Policy Dimensions	YES	22
101	Health & Place		419
102	Human and Ecological Risk Assessment		111
103	Hydrobiologia		48
104	IEEE Transactions on Geoscience and Remote Sensing	YES	15
105	Indoor Air	YES	50
106	Indoor and Built Environment		43
107	International Archives of Occupational and Environmental Health		57
108	International Journal of Applied Earth Observation and Geoinformation	YES	22
109	International Journal of Environment and Pollution	YES	21
110	International Journal of Environmental Analytical Chemistry		21
111	International Journal of Environmental Health Research	YES	60
112	International Journal of Environmental Research and Public Health	YES	211
113	International Journal of Environmental Science and Technology	YES	29
114	International Journal of Epidemiology		93
115	International Journal of Geographical Information Science	YES	33
116	International Journal of Health Geographics	YES	334
117	International Journal of Hygiene and Environmental Health	YES	127
118	International Journal of Life Cycle Assessment	YES	26
119	ISME Journal		25
120	JAMA-Journal of the American Medical Association		99
121	Journal of Agricultural and Food Chemistry		95
122	Journal of Applied Ecology	YES	42
123	Journal of Applied Microbiology		59
124	Journal of Arid Environments	YES	18
125	Journal of Asian Earth Sciences		17
126	Journal of Bacteriology		32
127	Journal of Biogeography	YES	37
128	Journal of Cleaner Production	YES	21
129	Journal of Coastal Research	YES	27
130	Journal of Colloid and Interface Science		15
131	Journal of Ecology	YES	55
132	Journal of Economic Entomology		15
133	Journal of Environmental Biology		35
134	Journal of Environmental Management	YES	76
135	Journal of Environmental Monitoring	YES	150
136	Journal of Environmental Protection and Ecology		40

(continued)

Code	Journal name	Included in Appendix A	Number of articles
137	Journal of Environmental Quality	YES	55
138	Journal of Environmental Radioactivity		46
139	Journal of Environmental Science and Health Part A-Toxic/Hazardous Substances & Environmental Engineering	YES	105
140	Journal of Environmental Science and Health Part B-Pesticides Food Contaminants and Agricultural Wastes		39
141	Journal of Environmental Science and Health Part C-Environmental Carcinogenesis & Ecotoxicology Reviews	YES	22
142	Journal of Exposure Science and Environmental Epidemiology	YES	119
143	Journal of Geography in Higher Education	YES	16
144	Journal of Geophysical Research-Atmospheres		36
145	Journal of Great Lakes Research		17
146	Journal of Hazardous Materials	YES	214
147	Journal of Historical Geography	YES	25
148	Journal of Hydrology	YES	24
149	Journal of Soils and Sediments	YES	46
150	Journal of the Air & Waste Management Association		136
151	Journal of the American Water Resources Association	YES	23
152	Journal of the Science of Food and Agriculture		20
153	Journal of Transport Geography	YES	21
154	Journal of Urban Health-Bulletin of the New York Academy of Medicine		88
155	Journal of Water and Health		28
156	Lancet		112
157	Land Use Policy	YES	17
158	Landscape Ecology	YES	15
159	Lecture Notes in Computer Science		89
160	Malaria Journal		278
161	Marine Ecology Progress Series		90
162	Marine Environmental Research		62
163	Marine Pollution Bulletin		172
164	Medical Care		103
165	Microbial Ecology		31
166	Molecular Ecology		96
167	Natural Hazards	YES	39
168	Nature		44
169	Nature Communications		19
170	New Phytologist		20
171	New Zealand Geographer	YES	16
172	Occupational and Environmental Medicine		96
173	Ocean & Coastal Management	YES	23
174	Oecologia		33
175	Oikos		19
176	Philosophical Transactions of the Royal Society B-Biological Sciences		31
177	Photochemical & Photobiological Sciences		19
178	Photochemistry and Photobiology		27
179	Photogrammetric Engineering and Remote Sensing	YES	21
180	Physics and Chemistry of the Earth		19
181	Plant and Soil		23
182	Plant Disease		110
183	PLoS Neglected Tropical Diseases		251
184	PLoS ONE		1298

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Code	Journal name	Included in Appendix A	Number of articles
185	Polish Journal of Environmental Studies		41
186	Population and Environment	YES	19
187	Population Space and Place	YES	27
188	Proceedings of SPIE		18
189	Proceedings of the Society of Photo-Optical Instrumentation Engineers (Spie)		17
190	Progress in Human Geography	YES	52
191	Remote Sensing of Environment	YES	62
192	Renewable & Sustainable Energy Reviews		18
193	Risk Analysis		105
194	Rural and Remote Health		94
195	Science		29
196	Science of the Total Environment	YES	861
197	Scientific Reports		32
198	Sensors		15
199	Social & Cultural Geography	YES	41
200	Social Science & Medicine		472
201	Soil Biology & Biochemistry		21
202	Soil & Sediment Contamination	YES	20
203	Spectroscopy and Spectral Analysis		37
204	Stochastic Environmental Research and Risk Assessment	YES	39
205	Talanta		28
206	Toxicological Sciences		114
207	Toxicology		86
208	Toxicology and Applied Pharmacology		130
209	Toxicology Letters		115
210	Transactions of the Institute of British Geographers	YES	34
211	Transportation Research Part D-Transport and Environment		18
212	Urban Geography	YES	21
213	Urban Studies	YES	16
214	Waste Management		30
215	Water Air and Soil Pollution	YES	123
216	Water Research		91
217	Water Science and Technology		56
218	Zootaxa		18

Appendix S
Journals Retrieved with No Less than 15 SCI/SSCI-Indexed Articles in Chap. 22 "International Rivers and Transboundary Environment and Resources"

Code	Journal name	Included in Appendix A	Number of articles
1	Agricultural Water Management		33
2	Biodiversity and Conservation	YES	15
3	Canadian Water Resources Journal	YES	15
4	Chinese Science Bulletin		45
5	Climatic Change	YES	36
6	Conservation Biology		30
7	Earth Surface Processes and Landforms	YES	59
8	Ecohydrology	YES	28
9	Ecological Applications	YES	52
10	Ecology		17
11	Ecology and Society	YES	19
12	Environment International	YES	19
13	Environmental Earth Sciences		59
14	Environmental Geology		39
15	Global and Planetary Change	YES	45
16	Global Environmental Change-Human and Policy Dimensions	YES	15
17	Hydrobiologia		153
18	Hydrogeology Journal		24
19	Hydrological Processes	YES	205
20	Hydrological Sciences Journal-Journal des Sciences Hydrologiques		66
21	Hydrology and Earth System Sciences	YES	117
22	International Journal of Climatology	YES	31
23	International Journal of Water Resources Development	YES	46
24	Journal of Arid Environments	YES	53
25	Journal of Arid Land	YES	17
26	Journal of Biogeography	YES	27
27	Journal of Climate	YES	39
28	Journal of Environmental Management	YES	34
29	Journal of Environmental Monitoring	YES	19
30	Journal of Environmental Protection and Ecology		24
31	Journal of Environmental Quality	YES	17
32	Journal of Environmental Radioactivity		28
33	Journal of Freshwater Ecology		20
34	Journal of Geographical Sciences	YES	27

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Code	Journal name	Included in Appendix A	Number of articles
35	Journal of Geophysical Research-Atmospheres		48
36	Journal of Geophysical Research-Earth Surface		30
37	Journal of Great Lakes Research		76
38	Journal of Hydrologic Engineering	YES	38
39	Journal of Hydrology	YES	179
40	Journal of Hydrometeorology	YES	56
41	Journal of the American Water Resources Association	YES	71
42	Journal of Water Resources Planning and Management-ASCE		39
43	Natural Hazards	YES	40
44	Natural Resources Journal		28
45	Nature		18
46	PLoS ONE		84
47	Polish Journal of Environmental Studies		39
48	Regional Environmental Change	YES	34
49	River Research and Applications	YES	104
50	Russian Meteorology and Hydrology	YES	19
51	Science		31
52	Science in China Series D-Earth Sciences		26
53	Sedimentology	YES	33
54	Water Air and Soil Pollution	YES	39
55	Water International	YES	100
56	Water Policy		44
57	Water Research		38
58	Water Resources	YES	49
59	Water Resources Management	YES	85
60	Water Resources Research	YES	182
61	Water Science and Technology		49
62	Wetlands	YES	26

Appendix T
Journals Retrieved with No Less than 15 SCI/SSCI-Indexed Articles in Chap. 23 "Records of Environmental Changes in Physical Geography"

Code	Journal name	Included in Appendix A	Number of articles
1	Acta Geographica Slovenica-Geografski Zbornik	YES	15
2	Advances in Atmospheric Sciences		95
3	Aeolian Research	YES	151
4	Agriculture Ecosystems & Environment	YES	383
5	Ambio	YES	358
6	Annals of Glaciology	YES	631
7	Antarctic Science	YES	388
8	Aquatic Sciences		385
9	ARCTIC	YES	183
10	Arctic Antarctic and Alpine Research	YES	498
11	Atmospheric Environment	YES	2430
12	Biogeochemistry	YES	858
13	Biogeosciences	YES	1011
14	Boreas	YES	644
15	Catena	YES	1052
16	Chemical Geology		2956
17	Chinese Geographical Science	YES	122
18	Chinese Science Bulletin		1915
19	Climate of the Past	YES	664
20	Cold Regions Science and Technology	YES	202
21	Cryosphere	YES	362
22	Earth Surface Processes and Landforms	YES	1463
23	Environmental Earth Sciences		1385
24	Erde	YES	25
25	Erdkunde	YES	60
26	Frontiers of Earth Science		80
27	Geoderma		860
28	Geografia Fisica eDinamicaQuaternaria		105
29	Geografiska Annaler Series A-Physical Geography	YES	349
30	Geomorphologie-Relief Processus Environnement	YES	143
31	Geomorphology	YES	2859
32	Geophysical Research Letters		3257

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Code	Journal name	Included in Appendix A	Number of articles
33	GIScience & Remote Sensing	YES	23
34	Global and Planetary Change	YES	1114
35	Global Biogeochemical Cycles	YES	719
36	Global Ecology and Biogeography	YES	214
37	Holocene	YES	1571
38	IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing	YES	109
39	International Journal of Digital Earth	YES	20
40	International Journal of Earth Sciences	YES	1097
41	International Journal of Geographical Information Science	YES	46
42	International Journal of Sediment Research	YES	277
43	ISPRS Journal of Photogrammetry and Remote Sensing	YES	168
44	Journal of Arid Land	YES	66
45	Journal of Asian Earth Sciences		1901
46	Journal of Biogeography	YES	919
47	Journal of Coastal Research	YES	2235
48	Journal of Cold Regions Engineering		24
49	Journal of Geographical Sciences	YES	175
50	Journal of Glaciology	YES	967
51	Journal of Great Lakes Research		1325
52	Journal of Hydraulic Engineering		80
53	Journal of Hydraulic Research		334
54	Journal of Hydrology	YES	1833
55	Journal of Maps	YES	156
56	Journal of Paleolimnology		1208
57	Journal of Quaternary Science	YES	1105
58	Journal of Sedimentary Research	YES	1106
59	Journal of Soil and Water Conservation		293
60	Journal of Soils and Sediments	YES	583
61	Land Degradation & Development	YES	174
62	Landscape and Urban Planning	YES	102
63	Landscape Ecology	YES	184
64	Landslides		151
65	Limnology and Oceanography	YES	1593
66	Mountain Research and Development	YES	93
67	Natural Hazards	YES	449
68	Palaeogeography Palaeoclimatology Palaeoecology	YES	4299
69	Pedosphere		181
70	Permafrost and Periglacial Processes	YES	257
71	Photogrammetric Engineering and Remote Sensing	YES	107
72	Photogrammetric Record	YES	55
73	Physical Geography	YES	185
74	Progress in Physical Geography	YES	241
75	Quaternary Geochronology	YES	545
76	Quaternary International	YES	3405
77	Quaternary Research	YES	1391

(continued)

Code	Journal name	Included in Appendix A	Number of articles
78	Quaternary Science Reviews	YES	3147
79	Revista de Geografia Norte Grande		18
80	River Research and Applications	YES	365
81	Science China-Earth Sciences		490
82	Sedimentary Geology		2043
83	Soil & Sediment Contamination	YES	292
84	Soil & Tillage Research		184
85	Talanta		969
86	Terra Nova		568
87	Zeitschrift für Geomorphologie	YES	468

Appendix U
Journals Retrieved with No Less than 15 SCI/SSCI-Indexed Articles in Chap. 24 "Detection and Attribution of Changes in Land Surface Sensitive Components"

Code	Journal name	Included in Appendix A	Number of articles
1	Advances in Agronomy		26
2	Advances in Atmospheric Sciences		66
3	Advances in Water Resources		26
4	Agricultural and Forest Meteorology	YES	137
5	Agricultural Systems		59
6	Agricultural Water Management		117
7	Agriculture Ecosystems & Environment	YES	190
8	Agroforestry Systems		20
9	Agronomy for Sustainable Development		44
10	Agronomy Journal		47
11	Ambio	YES	69
12	Annals of Botany		41
13	Annals of Forest Science		24
14	Annual Review of Environment and Resources	YES	33
15	Antarctic Science	YES	18
16	ARCTIC	YES	20
17	Arctic Antarctic and Alpine Research	YES	38
18	Atmospheric Environment	YES	90
19	Atmospheric Research		25
20	Basic and Applied Ecology	YES	26
21	Biodiversity and Conservation	YES	60
22	Biogeosciences	YES	149
23	Biological Conservation	YES	130
24	Biological Invasions		44
25	Bioscience		46
26	Bulletin of the American Meteorological Society		28
27	Catena	YES	88
28	Chemosphere	YES	18
29	Chinese Geographical Science	YES	24
30	Chinese Science Bulletin		55
31	Climate Dynamics	YES	142
32	Climate of the Past	YES	42
33	Climate Research		111
34	Climatic Change	YES	294

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Code	Journal name	Included in Appendix A	Number of articles
35	Cold Regions Science and Technology	YES	15
36	Conservation Biology		74
37	Crop Science		17
38	Earth Interactions		36
39	Ecography	YES	55
40	Ecohydrology	YES	50
41	Ecological Applications	YES	162
42	Ecological Economics		52
43	Ecological Engineering	YES	56
44	Ecological Indicators	YES	75
45	Ecological Monographs	YES	39
46	Ecological Research	YES	47
47	Ecology		149
48	Ecology and Evolution		35
49	Ecology and Society	YES	76
50	Ecology Letters		65
51	Ecosystems	YES	110
52	Environment International	YES	18
53	Environmental and Experimental Botany		15
54	Environmental Conservation	YES	27
55	Environmental Earth Sciences		87
56	Environmental Management	YES	94
57	Environmental Modelling & Software	YES	45
58	Environmental Monitoring and Assessment	YES	86
59	Environmental Research Letters	YES	129
60	Environmental Science & Policy	YES	59
61	Environmental Science & Technology	YES	101
62	Estuarine Coastal and Shelf Science	YES	80
63	European Journal of Agronomy		52
64	European Journal of Forest Research		38
65	Field Crops Research		55
66	Forest Ecology and Management		393
67	Forest Policy and Economics		16
68	Forest Science		17
69	Frontiers in Ecology and the Environment	YES	48
70	Frontiers of Earth Science		15
71	Functional Ecology		22
72	Geoderma		98
73	Geomorphology	YES	176
74	Geophysical Research Letters		261
75	Global and Planetary Change	YES	140
76	Global Biogeochemical Cycles	YES	89
77	Global Change Biology	YES	447
78	Global Ecology and Biogeography	YES	108
79	Global Environmental Change-Human and Policy Dimensions	YES	92
80	Human and Ecological Risk Assessment		15
81	Hydrobiologia		118
82	Hydrogeology Journal		25
83	Hydrological Processes	YES	221
84	Hydrological Sciences Journal-Journal des Sciences Hydrologiques		68
85	Hydrology and Earth System Sciences	YES	137

(continued)

Code	Journal name	Included in Appendix A	Number of articles
86	Hydrology Research	YES	20
87	International Journal of Climatology	YES	107
88	International Journal of Remote Sensing	YES	99
89	International Journal of Water Resources Development	YES	17
90	Journal of Agricultural Science		19
91	Journal of Applied Ecology	YES	143
92	Journal of Applied Remote Sensing	YES	24
93	Journal of Arid Environments	YES	132
94	Journal of Arid Land	YES	20
95	Journal of Biogeography	YES	143
96	Journal of Climate	YES	239
97	Journal of Ecology	YES	89
98	Journal of Environmental Management	YES	97
99	Journal of Geographical Sciences	YES	33
100	Journal of Geophysical Research-Atmospheres		376
101	Journal of Geophysical Research-Biogeosciences		95
102	Journal of Geophysical Research-Earth Surface		35
103	Journal of Geophysical Research-Oceans		38
104	Journal of Geophysical Research-Planets		25
105	Journal of Great Lakes Research		25
106	Journal of Hydrologic Engineering	YES	43
107	Journal of Hydrology	YES	292
108	Journal of Hydrometeorology	YES	129
109	Journal of Mountain Science	YES	15
110	Journal of Soil and Water Conservation		16
111	Journal of the American Water Resources Association	YES	71
112	Journal of Vegetation Science	YES	79
113	Journal of Water and Climate Change		23
114	Land Degradation & Development	YES	50
115	Land Use Policy	YES	36
116	Landscape Ecology	YES	71
117	Limnology and Oceanography	YES	37
118	Mitigation and Adaptation Strategies for Global Change		38
119	Mountain Research and Development	YES	26
120	Natural Hazards	YES	85
121	Natural Hazards and Earth System Sciences		45
122	Nature		83
123	Nature Climate Change		53
124	Nature Geoscience		38
125	New Phytologist		53
126	Oecologia		94
127	Palaeogeography Palaeoclimatology Palaeoecology	YES	147
128	Permafrost and Periglacial Processes	YES	16
129	Philosophical Transactions of the Royal Society B-Biological Sciences		93
130	Physical Geography	YES	25
131	Plant Ecology	YES	52
132	Plant Ecology & Diversity	YES	20
133	PLoS ONE		384
134	Proceedings of the National Academy of Sciences of the United States of America		230
135	Rangeland Ecology & Management	YES	24
136	Regional Environmental Change	YES	93

(continued)

Code	Journal name	Included in Appendix A	Number of articles
137	Remote Sensing of Environment	YES	170
138	Restoration Ecology	YES	28
139	Science		66
140	Science China-Earth Sciences		21
141	Science in China Series D-Earth Sciences		23
142	Science of the Total Environment	YES	149
143	Stochastic Environmental Research and Risk Assessment	YES	20
144	Theoretical and Applied Climatology	YES	81
145	Trends in Ecology & Evolution		44
146	Water International	YES	20
147	Water Research		23
148	Water Resources Management	YES	95
149	Water Resources Research	YES	183
150	Water Science and Technology		64
151	Wetlands	YES	42

Appendix V
Journals Retrieved with No Less than 15 SCI/SSCI-Indexed Articles in Chap. 25 "Uncertainty of Spatial Information and Spatial Analysis"

Code	Journal name	Included in Appendix A	Number of articles
1	Applied Geography	YES	142
2	Canadian Journal of Remote Sensing	YES	364
3	Cartographic Journal	YES	25
4	Cartography and Geographic Information Science	YES	23
5	Chinese Geographical Science	YES	73
6	Computers Environment and Urban Systems	YES	372
7	Computers & Geosciences	YES	90
8	Earth Science Informatics	YES	16
9	Earth Surface Processes and Landforms	YES	190
10	Ecological Modelling	YES	479
11	Environment and Planning B-Planning & Design	YES	52
12	Environmental Modelling & Software	YES	227
13	Environmental Monitoring and Assessment	YES	451
14	Geographical Analysis	YES	79
15	Geospatial Health	YES	46
16	GIScience & Remote Sensing	YES	130
17	GPS Solutions	YES	30
18	IEEE Geoscience and Remote Sensing Letters	YES	506
19	IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing	YES	388
20	IEEE Sensors Journal		134
21	IEEE Transactions on Aerospace and Electronic Systems		99
22	IEEE Transactions on Geoscience and Remote Sensing	YES	1887
23	IEEE Transactions on Image Processing		1009
24	International Journal of Applied Earth Observation and Geoinformation	YES	370
25	International Journal of Digital Earth	YES	72
26	International Journal of Geographical Information Science	YES	342
27	International Journal of Health Geographics	YES	105
28	International Journal of Infrared and Millimeter Waves		17
29	International Journal of Remote Sensing	YES	2058
30	ISPRS Journal of Photogrammetry and Remote Sensing	YES	519
31	Journal of Applied Remote Sensing	YES	374
32	Journal of Geodesy	YES	114
33	Journal of Geographical Sciences	YES	50
34	Journal of Geographical Systems	YES	53
35	Journal of Geophysical Research-Earth Surface		85

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Code	Journal name	Included in Appendix A	Number of articles
36	Journal of Geophysical Research-Planets		107
37	Journal of Glaciology	YES	112
38	Journal of Infrared and Millimeter Waves		138
39	Journal of Maps	YES	34
40	Journal of Spatial Science	YES	56
41	Journal of Surveying Engineering-ASCE	YES	69
42	Journal of the Indian Society of Remote Sensing	YES	145
43	Landscape and Urban Planning	YES	122
44	Marine Geodesy		46
45	Mathematical Geosciences		78
46	Natural Hazards	YES	178
47	Natural Hazards and Earth System Sciences		184
48	Pattern Recognition Letters		469
49	Photogrammetric Engineering and Remote Sensing	YES	675
50	Photogrammetric Record	YES	147
51	Photogrammetrie Fernerkundung Geoinformation	YES	90
52	Proceedings of SPIE		33
53	Proceedings of the Society of Photo-Optical Instrumentation Engineers (Spie)		42
54	Remote Sensing	YES	597
55	Remote Sensing Letters	YES	113
56	Remote Sensing of Environment	YES	1951
57	Science China-Earth Sciences		76
58	Science China-Information Sciences		68
59	Sensor Letters		73
60	Sensors		445
61	Spatial Cognition and Computation	YES	17
62	Spectroscopy and Spectral Analysis		327
63	Transactions in GIS	YES	65