J. Geogr. Sci. 2022, 32(3): 537-559
DOI: https://doi.org/10.1007/s11442-022-1960-2

Characteristics and progress of land use/cover change research during 1990–2018

HE Chunyang[1,2], ZHANG Jinxi[1,2], LIU Zhifeng[1,2], HUANG Qingxu[1,2]

1. Center for Human-Environment System Sustainability (CHESS), State Key Laboratory of Earth Surface Processes and Resource Ecology (ESPRE), Beijing Normal University, Beijing 100875, China;
2. School of Natural Resources, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China

Abstract: Land use/cover change (LUCC) is the foundation and frontier for integrating multiple land surface processes. This paper aims to systematically review LUCC research from 1990 to 2018. Based on qualitative and quantitative analyses, we delineated the history of LUCC research and summarized their characteristics and major progress at different stages. We also identified the main challenges and proposed future directions for LUCC research. We found that the number of publications on LUCC research and their total citations grew exponentially. The research foci shifted from the process of LUCC during 1990–2004 to the impact of LUCC during 2005–2013 and then to the sustainability of LUCC from 2014 onwards. Currently, LUCC research is facing theoretical, methodological and practical challenges ranging from integrating the framework of sustainability science, adopting emerging technologies to supporting territorial spatial planning. To move forward, LUCC research should be closely integrated with landscape sustainability science and geodesign and take the leading role in territorial spatial planning to achieve the related Sustainable Development Goals.

Keywords: land use/cover change; process; impact; sustainability; territorial spatial planning

1 Introduction

Land use refers to the development and utilization of land by humans, such as cultivated land, industrial land and commercial land (Meyer and Turner, 1994). Land cover refers to the surface elements covered by natural creations and artificial buildings, such as glaciers, bare rock and roads (Zuo, 1990). Land systems are composed of land use, land cover and ecosystems and are the basic component of the Earth surface system (GLP, 2005). Land use/cover change (LUCC) not only reproduces the spatiotemporal dynamic process of the Earth's surface but also objectively records the transformation of the Earth's surface by human activities. It is an effective way to reveal the interactive mechanism between human

Received: 2021-09-27 **Accepted:** 2021-11-26
Foundation: National Natural Science Foundation of China, No.41971270; Second Tibetan Plateau Scientific Expedition and Research Program, No.2019QZKK0405
Author: He Chunyang (1975–), Professor, specialized in integrated physical geography, land use/cover change and urban landscape sustainability. E-mail: hcy@bnu.edu.cn
This paper is initially published in *Acta Geographica Sinica* (Chinese edition), 2021, 76(11): 2730–2748.

activities and the natural environment and is the foundation and frontier of geography for conducting integrative research on Earth surface systems (GLP, 2005). LUCC research has progressed through nearly 30 years, dating back to the 1990s. Recently, with human society entering the Anthropocene, climate change, biodiversity loss and the nitrogen cycle have exceeded the safety thresholds of the Earth system, while land systems, as a basic part of the Earth's surface, have transitioned into potentially high-risk areas (Rockström *et al*., 2009; Steffen *et al*., 2015). Therefore, it is imperative to understand the characteristics, challenges and trends of LUCC research in a timely manner.

Recently, many scholars have reviewed the progress of LUCC research. Internationally, Lambin *et al*. (2001) presented a systematic review on the driving factors of LUCC. Foley *et al*. (2005) comprehensively reviewed the impacts of global LUCC on food production, freshwater resources, forest resources, regional climate and air quality, and infectious diseases. Verburg *et al*. (2015) noted that LUCC research has transitioned from the observation of change and understanding the drivers of these changes to using these understandings to design sustainable transformations. Long *et al*. (2018) developed a theoretical model of regional land use transitions and probed the mechanism of mutual feedbacks between land use transition and land management. Liu *et al*. (2018) described the strategic adjustment of land use policy under economic transformation. In China, Li (1996) introduced the basic contents, key problems and research methods of LUCC research from the perspective of global change research. Cai (2005) elaborated that LUCC research needs to seek new methods to integrate driving forces, scales, methods and theories. Tang *et al*. (2009) summarized the progress of LUCC models in theories, methods and applications. Liu *et al*. (2009) reviewed the progress of LUCC in spatiotemporal dynamics from the aspects of monitoring, driving mechanism analysis and ecological effect evaluation. Fu *et al*. (2014) summarized the backgrounds, concepts, methods and progress of land use change and ecosystem services. Fan (2018) explained the relationship between land resources and regional sustainable development based on the theory of regional systems of the human-land relationship. Fu *et al*. (2019) argued that systematically understanding land resources is not only a theoretical need for a comprehensive and in-depth understanding of the complex human-land system but also a practical demand for China's ecological civilization development. These reviews have promoted the continuous expansion and deepening of LUCC research. However, a systematic review based on the bibliometric method is relatively rare.

To this end, based on bibliometric analysis, this paper reviews the history of LUCC research since 1990. We summarize the characteristics and main research progress and identify the main challenges and development trends of LUCC research. This review can provide guidance for the further development of LUCC research.

2 History of LUCC research

LUCC research is closely related to the launches of international scientific programs since the 1990s, which has led to several key research directions. While the effectiveness of each program varies, we divide the history of LUCC research into three phases, namely, the process phase (1990–2004), the impact phase (2005–2013) and the sustainability phase (2014–present), depending on the major concerns of each program (Figure 1). During the process phase, the LUCC program, cosponsored by the International Geosphere-Biosphere Programme (IGBP) and the International Human Dimensions Programme on Global Environmental Change (IHDP) in 1995, played a leading role. The core of this program was to establish an LUCC model that could project future LUCC, evaluate its eco-environmental consequences and provide decision-making support by understanding the interactive mechanisms among LUCC, human driving forces, global changes, regional responses and environmental feedbacks (Li, 1996). Driven by this program, LUCC research emerged globally (Lambin *et al*., 1999).

During the impact phase, the Global Land Programme, cosponsored by the IGBP and IHDP in 2005, played a leading role. It clearly proposed the concept of land systems, which integrate land use, land cover and ecosystems. That is, the program emphasized a systematic approach to model and assess the eco-environmental impacts of global land system changes and recognize and understand the vulnerability and resilience of global land system changes. In 2007, Turner *et al*. (2007) further emphasized the significance of land change science for global environmental change and sustainability. In 2010, the first Global Land Programme Open Science Meeting was held in Arizona, USA, with the theme of "Land systems, global change and sustainability". In 2013, Verburg *et al*. (2013) proposed land system science. This progress has had positive roles in promoting LUCC research globally.

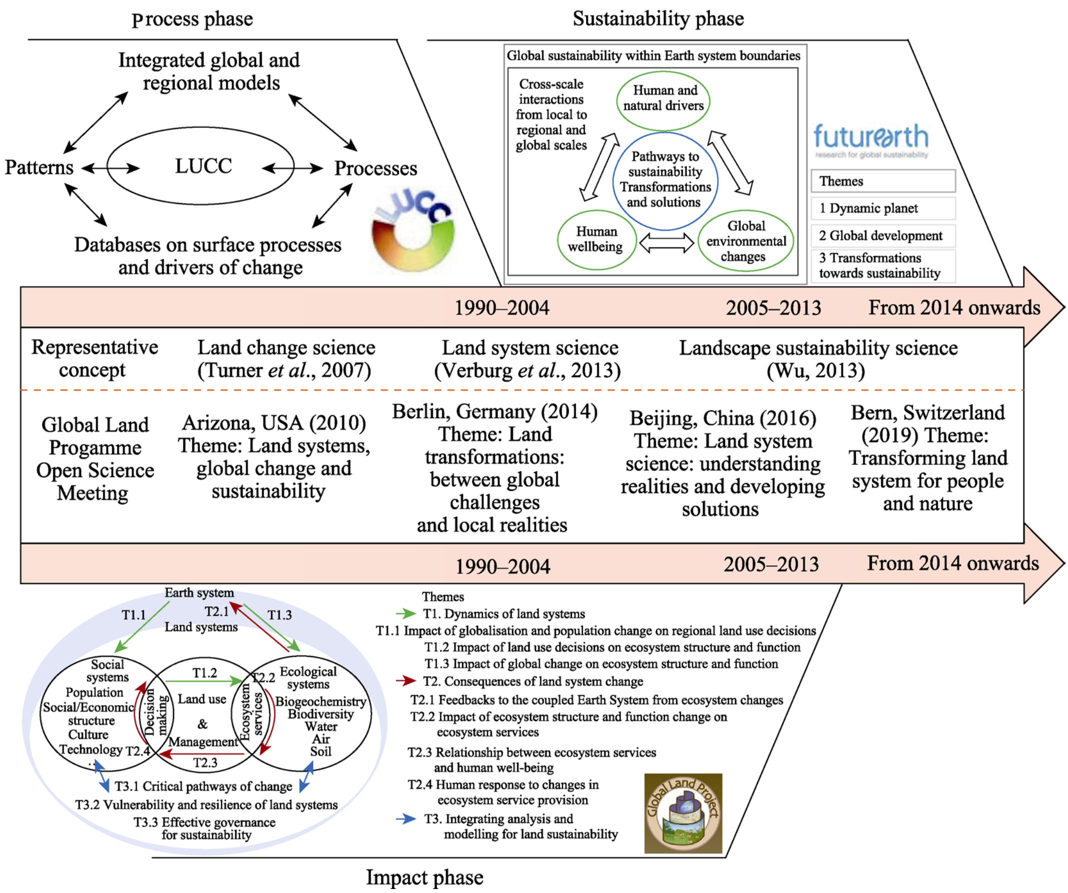

Figure 1 The history of LUCC research (based on Lambin *et al*. (1999), GLP (2005) and Future Earth (2013))

During the sustainability phase, the International Council for Science and International Social Science Council officially launched the Future Earth program in 2014. Driven by the program, LUCC research began to focus on the coupling of LUCC processes, ecosystem services and human well-being at different scales, with the goal of improving global sustainability (Future Earth, 2013). In 2013, Wu (2013) proposed the concept of landscape sustainability science, emphasizing an understanding of the interrelationships among landscape patterns, ecosystem services and human well-being at landscape or regional scales to improve global sustainability. Meanwhile, three Global Land Programme Open Science Meetings further pushed forward sustainability-oriented LUCC research. The themes for the three meetings in 2014, 2016, and 2019 were "Land transformations: between global challenges and local realities", "Land system science: understanding realities and developing solutions" and "Transforming land system for people and nature", respectively.

3 LUCC research progress

The numbers of Chinese and English papers on LUCC research and their total citations generally showed a rapid growth trend from 1990 to 2018 (Figure 2). Among them, Chinese papers declined in approximately 2010, which was related to an increasing number of Chinese scholars choosing to publish their papers in English journals. For English papers, the top 10 high-frequency words were land use, climate, land use change, impact, management, biodiversity, model, conservation, dynamics, and forest (Figure 3a). With regard to Chinese papers, the top 10 high-frequency words were land use, land use/cover change, land use change, spatiotemporal change, driving factors, remote sensing (RS), ecosystem services, landscape pattern, geographic information system (GIS), and cultivated land (Figure 3b).

3.1 The process phase between 1990 and 2004

Cluster analysis based on high-frequency words showed that English papers on LUCC research were divided into five categories in the process phase. The first category was the dynamic monitoring of land cover change by RS technology. The second category was the ef-

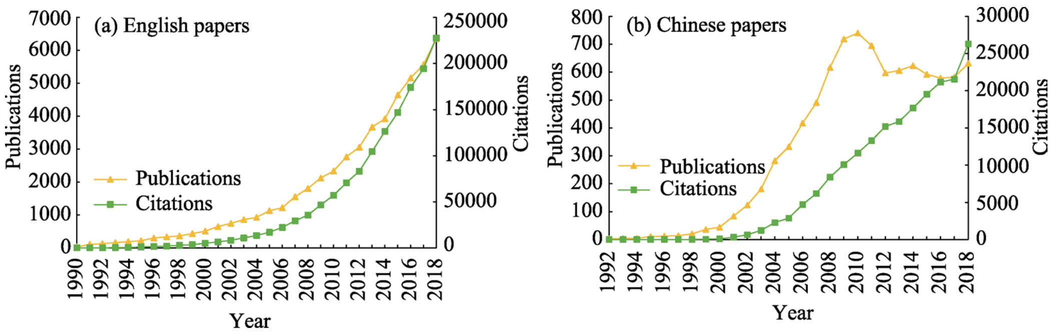

Figure 2 Publications on and citations of LUCC research

Note: On 29 July 2019, we searched the Web of Science Core Collection Database and China National Knowledge Infrastructure Core Database for English and Chinese papers on LUCC research from 1990 to 2018. The search strategy of English papers was TS = ('land use' OR 'land cover') AND TS = ('change' OR 'changes') OR TS = ('forest transition' OR 'agricultural land marginalization'), which yielded a total of 51,245 publications. The search strategy of Chinese papers was (SU= 'land use' OR SU= 'land cover') AND SU= 'change' OR (SU= 'forest transition' OR SU= 'agricultural land marginalization'), which included a total of 9042 publications.

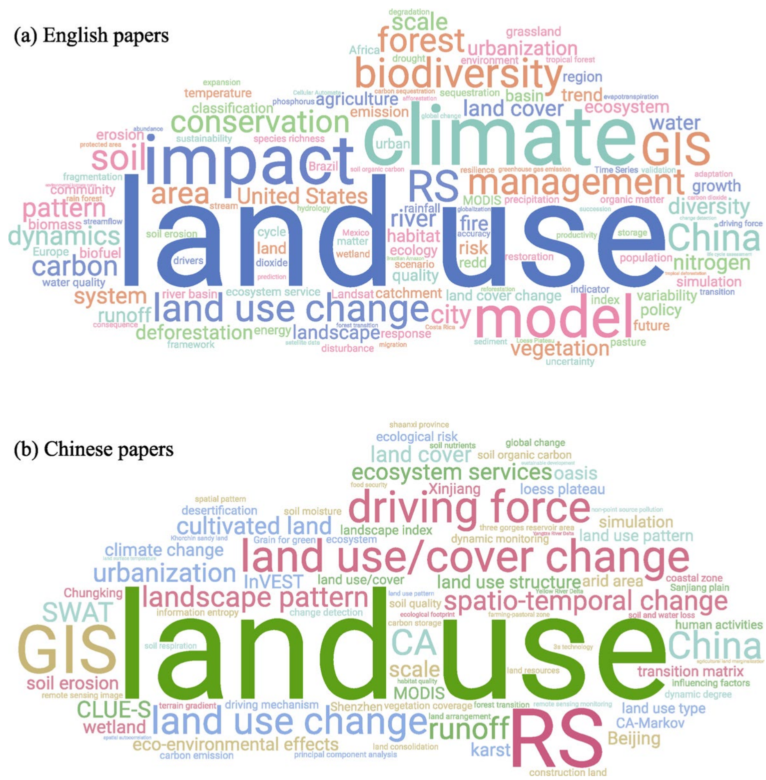

Figure 3 Word clouds generated from LUCC papers

Note: Based on the CiteSpace platform, we analyzed the word frequency of 51,245 English papers and 9042 Chinese papers and created word clouds through WordArt to visualize them. In each word cloud, the font size is proportional to the word frequency, and the colors are mainly used for distinguishing terms.

fect of LUCC on the nitrogen and phosphorus cycles. The third category was the impact of LUCC on soil carbon. The fourth category was the establishment of the LUCC model. The fifth category mainly involved the eco-environmental effects of LUCC, such as the effects of LUCC on water quality and soil erosion (Figure 4a). Chinese papers on LUCC research mainly focused on the dynamic monitoring of LUCC, spatiotemporal changes in LUCC and the driving forces, and the effects of LUCC on soil (erosion, nutrients, and moisture). In addition, cultivated land was the land use type of greatest concern in Chinese papers (Figure 4b). In terms of citations, the top five English papers covered topics such as LUCC drivers, biodiversity, climate and soil carbon and have been cited more than 1700 times. The top five Chinese papers were mainly about the LUCC mechanism, method, and small-scale application of LUCC on eco-environmental impacts and reviews, solicitating more than 1000 cites.

First, land cover data covering various global resolutions were established and improved on the basis of the development of RS technology, the classification system and the classification method. Representative global land cover data included UMD data from the University of Maryland (Hansen *et al*., 2000), International Geosphere-Biosphere Program Data and Information System Cover (IGBP DISCover) data from the United States Geological Survey (Loveland *et al*., 2000) , Global Land Cover 2000 (GLC2000) data from the European Commission's Joint Research Centre (Roy *et al*., 2003), Moderate Resolution Imaging Spectroradiometer (MODIS) data from Boston University (Friedl *et al*., 2002), and Glob-

Cover data and Climate Change Initiative Land Cover (CCI-LC) data from the European Space Agency (Bicheron *et al*., 2006; ESA, 2014).

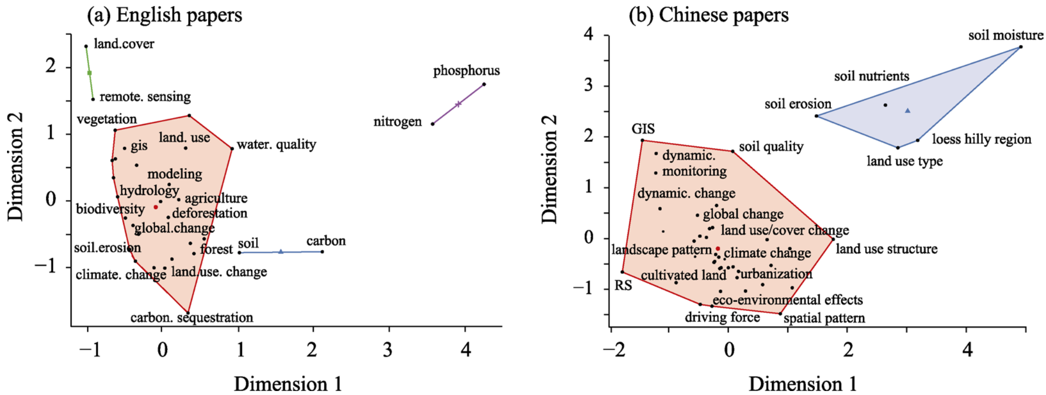

Figure 4 Multidimensional analysis of high-frequency words in English and Chinese papers during the process phase from 1990 to 2004

Note: We used the Bibliometrix and Biblioshiny packages in the R programming language for clustering high-frequency words with the clustering method of multiple corresponding analysis (MCA).

Second, the driving forces of LUCC were analyzed. The driving forces of LUCC include natural forces and socioeconomic forces. Natural forces mainly refer to climate, soil and hydrology (Bai and Zhao, 2001). Socioeconomic forces can be divided into direct and indirect driving forces. Direct socioeconomic forces refer to the demand for land products, investment in land, degree of urbanization, degree of land use intensification, land tenure, land use policy and attitude toward the protection of land resources. Indirect socioeconomic forces mainly include population change, technology development, economic growth, political and economic policies, degree of affluence and value orientation (Fischer *et al*., 1996). LUCC is the result of the joint efforts between natural and socioeconomic forces. Generally, socioeconomic forces are significant on a short time scale, while natural forces are mainly expressed in a cumulative way (Bai and Zhao, 2001).

Third, a series of LUCC models were developed. The LUCC model is an important tool for understanding the LUCC process and its driving mechanism, projecting LUCC trends and supporting decision-making. During the process phase, LUCC models mainly consisted of nonspatial models, spatial models and comprehensive models (Figure 5). Nonspatial models quantify the rate and quantitative characteristics of LUCC, such as the Markov and system dynamics (SD) models (Muller and Middleton, 1994; Portela and Rademacher, 2001). Spatial models express the spatial patterns of LUCC (Tang *et al*., 2009). Some focus on the expression of human behavior in the 'human-environment' system, with different levels of land use agents as basic simulation units, such as in the agent-based model (ABM) (Parker *et al*., 2003; Valbuena *et al*., 2010). Others focus on reflecting the environmental suitability and constraints in the 'human-environment' system, with different resolutions of land units, such as the cellular automata (CA) model (Li and Ye, 2005). Comprehensive models combining spatial models and nonspatial models can be used to simulate multiscale LUCC. Such models usually first determine the overall demand for LUCC in a region at the macroscale and then gradually allocate the macroscale total demand to finer scale spatial units. Examples of these models include the Conversion of Land Use and Its Effects at Small Regional Extent (CLUE-S) model and the Land Use Scenarios Dynamics (LUSD) model (Verburg *et al*., 2002; He *et al*., 2005). In contrast, some comprehensive models, starting at the microscale, first simulate the selection behavior and specific land use decisions of decision-makers and then reflect the LUCC patterns at the macroscale through upscaling, such as in the SAMBA model (Boissau and Castella, 2003).

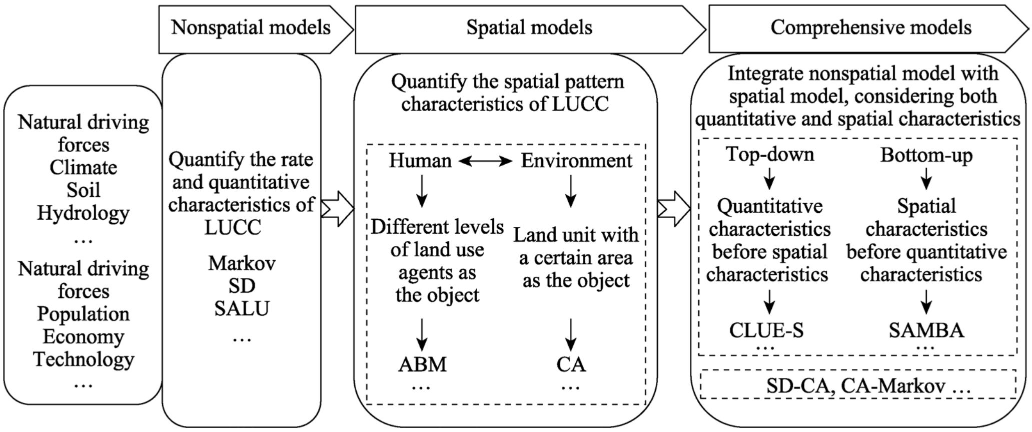

Figure 5 The history of LUCC models

3.2 The impact phase between 2005 and 2013

Cluster analysis based on high-frequency words showed that English papers on LUCC research could be divided into six categories at the impact phase. The first category was the impact of LUCC on climate. The second category involved the effect of LUCC on soil carbon and nitrogen. The third category was the impact of LUCC on biodiversity. The fourth category was the effect of LUCC on water quality. The fifth category mainly involved the impact of LUCC on ecosystem services. The sixth category was the dynamic monitoring of land cover change using RS and GIS (Figure 6a). Chinese papers on LUCC research mainly focused on the dynamic monitoring of LUCC, spatiotemporal changes in LUCC and the driving force analysis, LUCC simulation, and the impact of LUCC on soil, runoff and ecosystem service value (Figure 6b). For citations, the top five English papers were mainly related to the eco-environmental impacts of LUCC, with special attention given to the impact of LUCC on climate; together, these papers have accumulated more than 2400 citations. The top five Chinese papers were mainly about LUCC model simulation, LUCC mechanism and the impact of LUCC on soil quality, together accumulating more than 440 citations.

Specifically, major progress has been made in revealing the effects of LUCC on natural habitat and biodiversity. First, LUCC mainly affects the natural habitat through habitat loss, degradation and fragmentation (Fischer and Lindenmayer, 2007). Approximately 39% of terrestrial habitats have been converted to cultivated land or construction land, and 37% of terrestrial habitats have been degraded and fragmented (Ellis *et al*., 2010). Second, LUCC is the main driving factor of biodiversity loss as a result of negatively affecting natural habitats (Cardinale *et al*., 2012). Previous studies have shown that approximately 20~35% of mam-

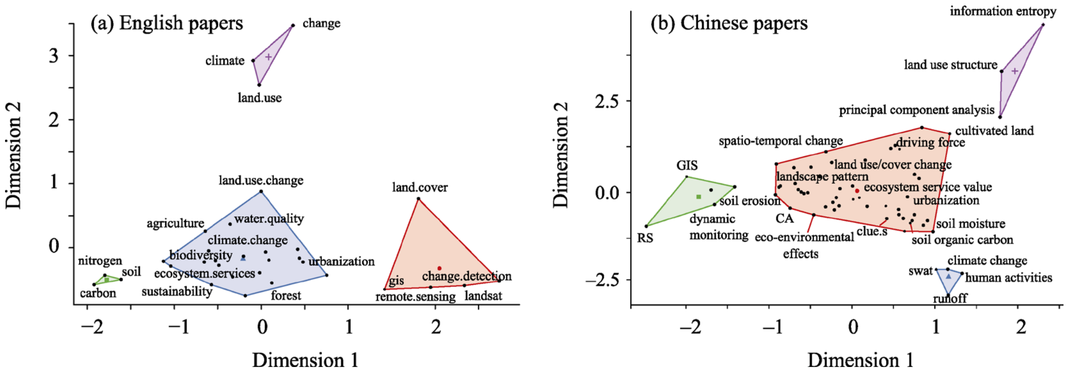

Figure 6 Multidimensional analysis of high-frequency words in English and Chinese papers during the impact phase from 2005 to 2013

mals, reptiles and amphibians worldwide are at risk of extinction as their natural habitats decline (Schipper *et al*., 2008; Böhm *et al*., 2013). Previous studies also showed that by 2070, suitable habitats of global species will be significantly reduced, and land use change will cause nearly 1700 species to be endangered (Powers and Jetz, 2019). For terrestrial ecosystems in particular, land use change may have the greatest impact on biodiversity, followed by climate change, nitrogen deposition, biological exchange and elevated carbon dioxide concentrations (Sala *et al*., 2000).

Another form of progress was evaluating the effects of LUCC on the atmosphere, mainly in terms of regional climate and air quality. LUCC can change the regional climate by affecting the net radiation or the distribution process of precipitation in soil moisture, evapotranspiration and runoff (Foley *et al*., 2005). For example, land cover change in tropical regions affects climate to a large extent by changing the water balance, while land cover change in temperate regions changes climate mainly by affecting surface radiation (Snyder *et al*., 2004). In some cases, the impact of LUCC on climate may even exceed the contribution of greenhouse gases, such as the impact of LUCC caused by urbanization on the regional climate (Dirmeyer *et al*., 2010). Kishtawal *et al*. (2010) analyzed the impact of urbanization on precipitation in India. He not only found that the more rapid urbanization was, the more obvious the trend of increasing frequency of heavy rainfall events was but also found that urban areas may have greater precipitation rates than nonurban areas. Kim *et al*. (2011) found that urbanization played a major role in warming from 1954 to 2008, which was greater than the greenhouse effect. Additionally, LUCC is closely related to air quality (Kume *et al*., 2010). LUCC can affect air quality by changing the amount and composition of gas emissions and by changing atmospheric conditions such as reaction rate, transmission and deposition (Foley *et al*., 2005).

A third form of progress was assessing the effects of LUCC on soil. LUCC can change the physical and chemical properties of the soil, as well as the composition of the soil ecosystem, thereby affecting soil quality and soil fertility and ultimately affecting land productivity (Geissen *et al*., 2009; Batlle-Aguilar *et al*., 2011). For example, the shift from forest to grassland and farmland leads to a decrease in aboveground biomass, thereby reducing soil carbon input. Meanwhile, farming can further reduce soil carbon (Houghton, 2012). In addition, land use change has an important impact on soil nutrients (such as nitrogen and phosphorus). For example, with the expansion of agricultural activities, the extent of utilization of agricultural land by humans has further intensified, and the use of chemical fertilizers and pesticides has increased rapidly. Consequently, the anthropogenic nutrient input to the soil ecosystem far exceeds the natural nutrient source, and eventually soil degradation may occur (Manson, 2005; Thampi *et al*., 2010). More importantly, land use change may lead to soil environmental problems such as soil erosion and soil desertification. For example, the natural forest and grassland on the Loess Plateau in China were almost destroyed after long-term human reclamation. According to the “Comprehensive Scientific Survey of Water and Soil Erosion and Ecological Safety in China”, the area of soil erosion on the Loess Plateau was 390,000 km^2, and the area of severe water erosion (i.e., the soil erosion modulus higher than 15,000 $t/(a \cdot km^2)$) was 36,700 km^2, accounting for 89% of the total area of severe water erosion in China (MWR, 2010). Furthermore, the observed data showed that 90% of the sediment discharge in the Yellow River came from the Loess Plateau in the 1970s (Yao *et al*., 2013).

The last form of progress was investigating the effects of LUCC on the water cycle and water resources. LUCC can directly affect the water cycle through vegetation canopy interception, root absorption and stomatal transpiration and indirectly affect the water cycle via the vertical and horizontal structures of plant communities embedded in evaporation, runoff, infiltration and groundwater recharge (Bradshaw *et al*., 2007). Studies have shown that deforestation reduces canopy interception, evaporation and infiltration but increases surface runoff and aggravates flood threats (Laurance, 2007). Studies have also shown that global land cover change has resulted in a decrease of approximately 5% in terrestrial evaporation and a 7.6% increase in runoff (Sterling *et al*., 2012). For water resources, LUCC mainly affects water quantity and quality. For example, the increase in impervious surfaces caused by urban expansion leads to a decrease in infiltration capacity and an increase in runoff (Hurkmans *et al*., 2009). Additionally, water demand closely related to land use has a direct impact on water resources, especially agricultural irrigation. Existing studies showed that the global water intake quantity was approximately 3900 km^3/a, and the expendable water (i.e., water no longer returned to the basin) was approximately 1800 to 2300 km^3/a, up to 85% of which was used for agriculture (Gleick, 2003). With a gradual increase in human demand for water, groundwater levels have dropped rapidly in many regions (Grafton, 2009; Yu *et al*., 2011). In addition, LUCC is an important cause of water quality change (Ouyang *et al*., 2006). In particular, unreasonable farmland use and management can lead to excessive nitrogen and phosphorus being washed into rivers through runoff, and eventually water quality deteriorates (Ongley *et al*., 2010).

3.3 The sustainability phase between 2014 and 2018

During the sustainability phase, the cluster analysis results of English papers on LUCC research were similar to those in the impact phase. The difference was that in the sustainability phase, the research on the relationship between LUCC and ecosystem services was more comprehensive and profound, and sustainable development received more attention. Research has attempted to achieve regional sustainability from the perspective of land use optimization and management (Figure 7a). In addition to continuing the research contents of the impact stage, Chinese papers on LUCC research focus on the impact of LUCC on runoff under different scenarios, the impact of urbanization on landscape, ecology and environment, and the impact of LUCC on ecosystem services (Figure 7b). In terms of citations, the top five English papers focused on the impact of LUCC on ecosystem services and biodiversity and the development of land cover products on a global scale. The citation frequency exceeded 590. The top five Chinese papers focused mainly on LUCC mechanism analysis and LUCC impact on ecosystem services, obtaining more than 180 citations. The major accomplishments during this phase are listed as below.

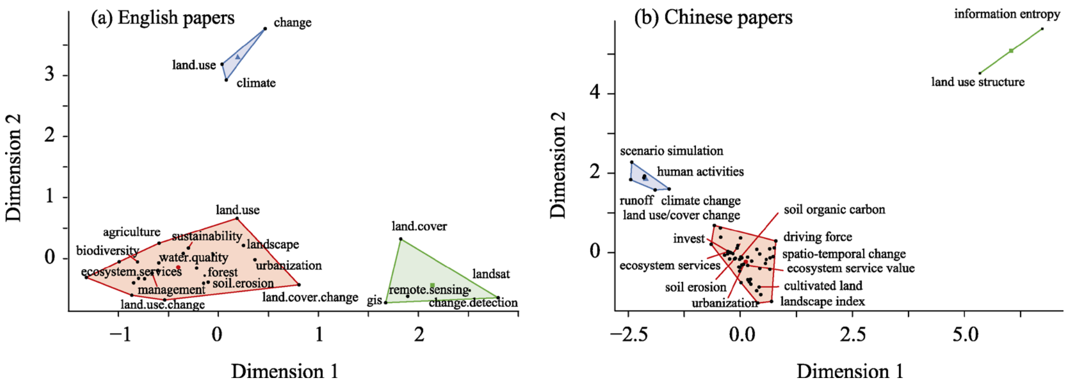

Figure 7 Multidimensional analysis of high-frequency words in English and Chinese papers during the sustainability phase from 2014 to 2018

Specifically, the LUCC process is embedded in human-earth system models. The human-earth system refers to the system formed by the interactions between human beings and nature, emphasizing the human-earth relationship and the integration of natural and anthropogenic elements. Human-earth system models can describe the feedback relationship between the human system and the earth system (Calvin *et al*., 2018). In general, the key elements for the human system entering the earth system are greenhouse gas emissions/concentrations, carbon dioxide emissions/concentrations, and LUCC. Conversely, the key elements for the earth system entering the human system are temperature, precipitation and ecosystem productivity (Reilly *et al*., 2013; Leng and Tang, 2014; Thornton *et al*., 2017; Yang *et al*., 2015). Human-earth system models link the human system with the earth system in a one-way or two-way coupled method. Currently, there are more human-earth system models using the one-way coupled method than the two-way coupled method. Representative human-earth system models using the one-way coupled method mainly include the CNRM-CM/IMAGE (Centre National de Recherches Météorologiques-Coupled Models/Integrated Model to Assess the Global Environment) and the GOLDMERGE (Complexity Ocean-Atmosphere-Sea Ice Model/Model for Evaluating the Regional and Global Effects) (Bahn *et al*., 2006; Voldoire *et al*., 2007). Typical human-earth system models using the two-way coupled method are primarily the iESM (integrated Earth System Model) and the MIT IGSM (MIT Integrated Global System Model) (Reilly *et al*., 2013; Collins *et al*., 2015). Taking the iESM as an example, it combines an integrated assessment model (i.e., Global Change Assessment Model, GCAM) with the Earth System Model (Community Earth System Model, CESM) to simulate the interaction between the human system and earth system through carbon dioxide emissions, LUCC and ecosystem productivity (Collins *et al*., 2015).

Calvin *et al*. (2019) analyzed the different feedback characteristics between the human system and earth system under the RCP (representative concentration pathways) 4.5 and RCP 8.5 scenarios based on iESM.

Second, the effects of LUCC on the ecosystem services were assessed. LUCC can change the ability to provide ecosystem services by directly or indirectly influencing ecosystem patterns and processes (Fu *et al*., 2014). According to the Millennium Ecosystem Assessment (MA), land cover change has been one of the two most important direct driving forces of terrestrial ecosystem service changes in the past 50 years (the other is the application of new technologies), particularly the transformation of natural ecosystems to agro-ecosystems (MA, 2005). The Global Assessment Report of Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) also notes that land use change is the most direct driving force affecting terrestrial and freshwater ecosystems at the global scale (IPBES, 2019). First, LUCC has an impact on provisioning services (such as food, freshwater and energy). Taking food production as an example, with the continuous growth of the global population, it is expected that by 2050, food demand will increase by 50 to 80% (Keating *et al*., 2014). Studies have shown that cultivated land has increased in recent decades, but per capita cultivated land has decreased from 0.34 ha per person in 1973 to 0.23 ha per person in 2008 (Grundy *et al*., 2016). Strategies to meet future food demand include improving the productivity of existing land and increasing the area of land for food production (Fischer *et al*., 2014; Springer and Duchin, 2014). However, land degradation continues, and land resources are scarce. The coordination among land use, food production and agriculture faces enormous challenges (Odegard and van der Voet, 2014; Grundy *et al*., 2016). Next, LUCC has an impact on regulating services (such as climate regulation, flood control and carbon sequestration). Taking climate regulation as an example, the Special Report of the Intergovernmental Panel on Climate Change (IPCC) elaborated the complex relationships between LUCC and climate change. The Special Report stated that under the RCP8.5 scenario, the biogeochemical effect generated by global land cover change will cause future climate warming, and the warming range will be between 0.04°C and 0.35°C. However, the impact of biophysical effects on the future global climate is not clear and could be perhaps warming or cooling (Boysen *et al*., 2014; Davies-Barnard *et al*., 2014; Simmons and Matthews, 2016; IPCC, 2019). Most studies also found that forests contributed the most to climate regulation services, followed by other natural ecosystems and agro-ecosystems (Vauhkonen and Packalen, 2018; Edwards *et al*., 2019). Last, LUCC has an impact on cultural services in two potential ways. One is a direct impact. For example, road building increases accessibility to natural or cultural landscapes and has a positive effect on the enjoyment of cultural services by consumers. The other is an indirect impact. For example, LUCC has an impact on the atmospheric environment and then on the occurrence environment of natural or cultural landscapes (Li, 2014). In addition, LUCC can affect the relationships among multiple ecosystem services (Fu *et al*., 2014). In arid and semiarid areas, for example, a trade-off between agricultural production and regulating services (such as carbon sequestration and soil conservation) remains (Kragt and Robertson, 2014; Wang *et al*., 2015).

Third, research on the impact of LUCC on human well-being emerged. There are many definitions of human well-being, among which the concepts proposed in the MA are widely used in research on ecosystem services and human well-being. In the MA report, human well-being consists of five elements, namely, the basic materials for a good life, health, good social relations, security and freedom of choice and action (MA, 2005). LUCC can alter the ability to deliver ecosystem services, thereby affecting human well-being (Fu *et al*., 2014). Currently, quantitative research on the relationships among LUCC, ecosystem services and human well-being is still in its infancy (Wang *et al*., 2017). Xu *et al*. (2016) analyzed the impact of land use intensity on ecosystem services (food production, soil conservation and climate regulation) and human well-being (especially in living standards and food security) and found that land use intensity was closely related to ecosystem services and human well-being.

Fourth, research on land use optimization and management toward sustainability gradually began to thrive. Sustainable development is necessary, not optional (Wu, 2013). The ultimate goal of sustainable development is to improve human well-being, that is, to meet the material and spiritual needs of contemporary and future generations (Wu *et al*., 2014). Ecosystem services are generally regarded as an important bridge between natural capital and human well-being (Leviston *et al*., 2018). They provide an operational framework for sustainable development research (Wu *et al*., 2014). Keeping ecosystem services as the core is the main approach for sustainability-oriented land use optimization and management research. For example, Wu *et al*. (2018) conducted a land use optimization study based on ecosystem service assessment in the Yanhe River basin of the Loess Plateau and proposed a suitable land use optimization scheme. This scheme can ensure the improvement of ecosystem service supplies while also meeting the needs of social and economic activities to a certain extent. Zhang *et al*. (2019) simulated the dynamic changes in the urban landscape in the Beijing-Tianjin-Hebei urban agglomeration under different ecosystem services protection scenarios from 2013 to 2040 and then sought the best landscape planning scheme with the goal of maintaining and protecting key ecosystem services.

4 Research gaps and challenges

4.1 Research gaps

LUCC research still has some gaps in the theory, data, methods, content and application. Regarding the theory of LUCC research, it needs multidisciplinary theoretical support. Sustainable development is the ultimate goal of LUCC research. To achieve this goal, the target of LUCC research shows a trend of systematization, such as the regional system, land surface system and land system. Once the research target is a system, scientific problems must be comprehensive and complex, involving multiple disciplines. Therefore, approaches to improve the LUCC research system based on a multidisciplinary theoretical framework should be considered (Wu, 2012). LUCC research data also need to be improved. At present, a single land cover data product can no longer meet the increasing demands of LUCC research. Data fusion can not only meet the demands but also improve the data accuracy to a certain extent. Thus, a major gap is how to use the existing land cover data and related auxiliary information to obtain continuous and accurate fusion results through effective data fusion methods (Bai and Feng, 2018). Regarding the methods of LUCC research, a major gap is how to scientifically validate the LUCC model to ensure its reliability (Wu *et al*., 2007). In addition, the coupling degree between the LUCC model and ecological process model needs to be improved. The model is an effective method used to reveal the influence of LUCC on many natural factors, such as soil, climate, hydrology and biogeochemical cycling. However, most of the existing models are loosely coupled, and it is difficult to dynamically express the relationship between LUCC and ecological processes (Robinson *et al*., 2018). Consequently, it is urgent to establish a tightly coupled model integrating LUCC and ecological processes. For the content of LUCC research, research on the relationship between ecosystem services and human well-being is a major gap. The relationship between ecosystem services and human well-being is the focus of sustainability-oriented LUCC research, but the complexity of the relationship makes it a difficult field (Agarwala *et al*., 2014). Regarding the application of LUCC research, applying LUCC findings in regional decision-making management is still a major obstacle. Currently, the watershed is considered to be an ideal regional unit. Although we have accumulated enormous findings on LUCC and its impacts at the watershed scale, such knowledge is rarely applied to sustainable watershed management. Furthermore, the application of LUCC research findings in territorial spatial planning needs to be improved.

4.2 Main challenges

With the rapid development of sustainability science globally and the deepening of the ecological civilization in China, we are facing great challenges in the theory, methods and application of LUCC research. The theory of LUCC research is facing the challenge of how to respond to the Sustainable Development Goals (SDGs) under the framework of sustainability science. Sustainability science is the science of studying the dynamic relationship between nature and society, aiming to provide a theoretical basis for sustainable development (Kates *et al*., 2001; Wu *et al*., 2014). Among the 17 SDGs, many goals (such as zero hunger, good health and well-being, clean water and sanitation, sustainable cities and communities, climate action and life on land) are closely linked to LUCC (UN, 2015; Gao and Bryan, 2017). Therefore, LUCC research in the new era is facing the challenge of how to move the research object to the all-element cross-scale land system and extend the research content to land optimization and management toward sustainability with the guidance of SDGs under the framework of sustainability science.

Meanwhile, emerging technologies, including big data, cloud computing and artificial intelligence, are booming and deeply integrated in LUCC research. Big data usually refers to data that cannot be obtained, managed and processed by ordinary equipment within an acceptable time range for users. It has four basic characteristics, namely, large volume, multiple types, authenticity and rapid change (Mayer-Svhönberger and CuKier, 2013; Guo *et al*., 2014). Big data provide new opportunities for understanding the relationship between the LUCC process and sustainable development (Runting *et al*., 2020). The rapid development of artificial intelligence technology and distributed computation as well as storage platforms provide important pillars for analyzing and mining information provided by big data (Bergen *et al*., 2019). For artificial intelligence, representative machine learning algorithms mainly include artificial neural networks, Bayesian networks and deep learning. For distributed computation, cloud computing is representative. With the support of new technologies, the virtual geographical environment is thriving (Lv, 2011; Lin *et al*., 2013). These new data and technologies can bring opportunities and challenges for us to more deeply understand the interaction mechanisms among the LUCC process, impact and sustainability and are beneficial for all-element cross-scale land system simulation and emulation. Therefore, LUCC research in the new era is facing the challenge of how to effectively integrate these emerging data and technologies to develop a new methodology.

In addition, territorial spatial planning proposed in China aims to realize the effective protection, orderly development, efficient utilization and high-quality construction of territory space. It is the guideline of national and local spatial development and the blueprint of sustainable development in China. Scientific territorial spatial planning can help us coordinate the management of mountains, rivers, forests, farmlands, lakes and grasslands and promote the development of China's Ecological Civilization and the realization of the Beautiful China initiative (Chen *et al*., 2019; Fan, 2019; Wu *et al*., 2019). In July 2019, the Ministry of Natural Resources in China issued the "Notification on 'One Map' construction and status assessment of territorial spatial planning", which clearly found that under the support of the national land space basic information platform, the "One Map" construction and the status assessment of territorial spatial development and protection in cities and counties were comprehensively conducted. In January 2020, the Ministry of Natural Resources in China issued the "territorial spatial planning guidelines" (Trial), which established a series of basic principles and requirements for territorial spatial planning, such as "prioritizing ecological conservation and boosting green development", "people-centered high-quality development" and "coordinated urban and rural development". These policies push China's territorial spatial planning into a new stage. Due to the close connection between territorial spatial planning and LUCC research, LUCC research in the new era is facing the challenge of how to integrate a sustainability science framework and emerging technologies to implement territorial spatial planning (Zhen *et al*., 2019).

5 Future perspectives

The theory of LUCC research needs to be closely integrated with landscape sustainability science. Landscape sustainability science is a science that focuses on landscape and regional scales and uses spatially explicit methods to study the relationships among landscape patterns, ecosystem services, and human well-being. The ultimate goal of science is to seek a landscape and regional spatial pattern that can promote long-term maintenance and positive feedback between ecosystem services and human well-being to achieve sustainable development (Wu, 2013; Wu *et al*., 2014). In other words, landscape sustainability science provides an important theoretical basis and operational practice platform for LUCC research toward sustainability at landscape and regional scales (Wu, 2019). Specifically, the final target of landscape sustainability science is to coordinate the human-earth relationship to improve regional sustainability. The basic idea is to adjust the land use type, scale, mode and intensity during the LUCC process at the landscape and regional scales. On the one hand, it can improve the supply capacity of natural resources and ecosystem services to promote human well-being. On the other hand, it can reduce disaster exposure and vulnerability to decrease disaster risks (Figure 8). In the future, LUCC research needs to actively develop the multiscale integration of the "ecosystem-landscape-region". The basic goal is to maintain and improve landscape and regional sustainability, and the research core is the relationship among ecosystem services, human well-being and disaster risks under different land use patterns. The main methods are spatial display model simulation and scenario analysis (Wu *et al*., 2014; Fu *et al*., 2019).

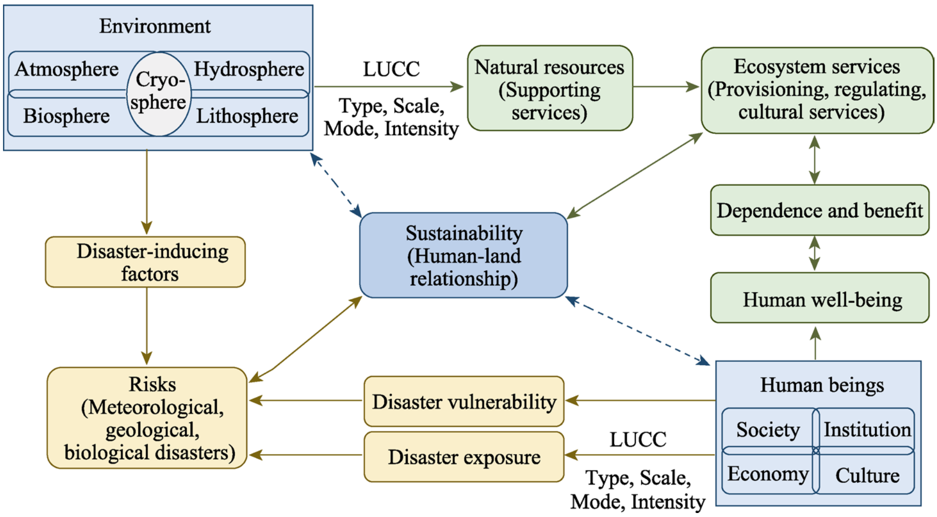

Figure 8 LUCC and landscape sustainability

The LUCC research method needs to be closely integrated with geodesign under the support of emerging technologies represented by big data, cloud computing and artificial intelligence. Geodesign, with the goal of regional sustainable development, emphasizes a design concept and method that closely combines planning and design activities with real-time dynamic environmental impact simulation under the close cooperation of geographers, technical experts, designers and stakeholders (Steinitz, 2012; Ma, 2013; Wu, 2019). Moreover, geodesign is based on landscape sustainability science and supported by spatial information technology. The geodesign framework mainly includes five components, namely, the study area, the decision maker or stakeholders, the geodesign team, the geodesign process and the geodesign scheme. Among them, the geodesign process is the core component. It mainly answers six questions, and each question can be answered by a corresponding model. For example, is the study area functioning properly? The answer to this question can be solved by an evaluation model. Throughout the geodesign process, a three iterations operational mode is adopted. The first iteration is a top-down process understanding the geographic study area and the scope of the study (asking questions). The second iteration is a bottom-up process defining the methods of the study (determining methods). The third iteration is a top-down process conducting the study until the conclusion is given (answering questions) (Figure 9). Based on the geodesign framework, LUCC research can effectively combine emerging technologies (such as big data, artificial intelligence, cloud computing, blockchain and virtual reality) and integrate six models (representation, process, evaluation, change, impact and decision models) to produce spatial, quantitative and humanized design schemes (Huang *et al*., 2019). In 2010, the Environmental Systems Research Institute (ESRI), regarded as the world's largest GIS technology supplier, hosted the first GeoDesign Summit in southern California, USA. Since then, the GeoDesign Summit has been held annually. At each GeoDesign Summit, ESRI not only shares the latest GIS-related technologies but also exhibits geodesign cases from around the world using emerging technologies. The summit provides a platform for the technological innovation of LUCC research. Therefore, the close combination of LUCC research and geodesign is not only beneficial to the improvement of LUCC research methods but also provides a practical framework for LUCC research.

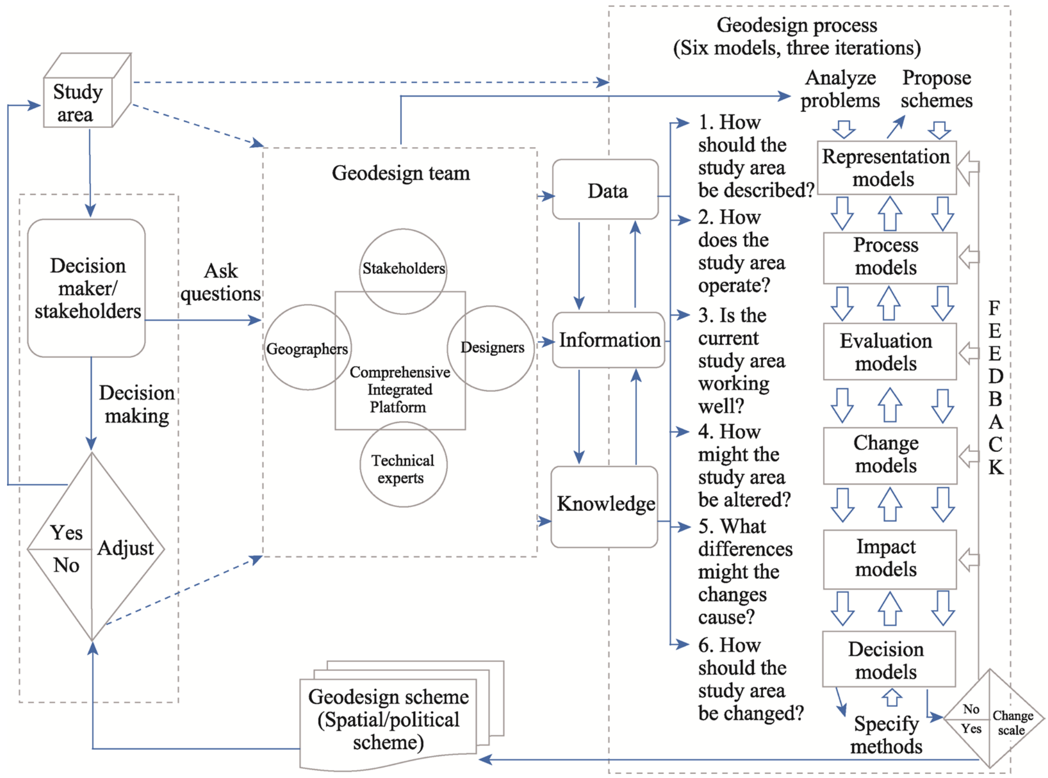

Figure 9 LUCC and geodesign (adapted from Steinitz (2012) and Zhang *et al*. (2016))

In the practice of LUCC research, it is necessary to actively serve the main battlefield of territorial spatial planning. Territorial spatial planning is a key way to not only promote urban-rural integration and rural revitalization but also achieve the Beautiful China initiative and implement the SDGs (Liu, 2018; Fang *et al*., 2019). LUCC research is able to converge with territorial spatial planning in the optimization and management of land use spatial patterns to provide theoretical and methodological support for territorial spatial planning (Figure 10). In terms of theoretical support, LUCC research focuses on the dynamic relationships among patterns, ecosystem services and human well-being. The multiscale coupling of the pattern and process explores the LUCC process mechanism. The mapping and simulating of ecosystem services realize the regional integration on the basis of clarifying the LUCC process mechanism. Revealing the complex relationship between ecosystem services and human well-being helps LUCC research move toward sustainability. That is, an in-depth integration of the LUCC process mechanism, regional integration and sustainability-oriented research can provide effective theoretical support for territorial spatial planning. In terms of methodological support, combined with RS technology, model simulation and scenario analysis, LUCC research has formed a complete technical route covering the LUCC database, LUCC model, coupled model of LUCC and ecological process, ecosystem services evaluation model and human-earth system model. In the future, with the close combination of LUCC research and territorial spatial planning, LUCC research will be substantially improved.

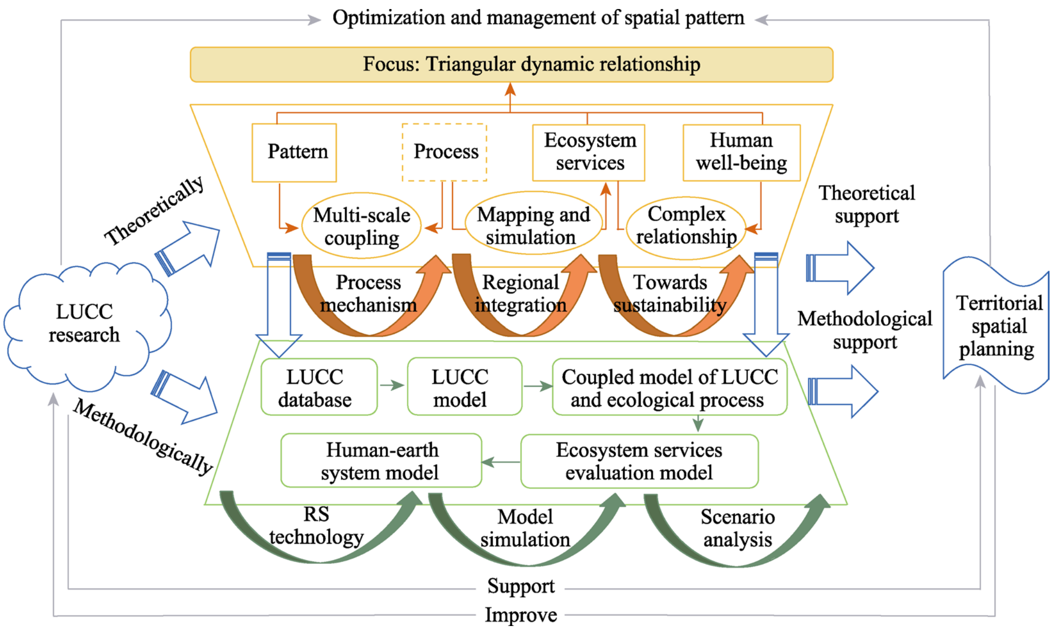

Figure 10 LUCC and territorial spatial planning

6 Conclusions

The numbers of publications on LUCC research and their total citations grew exponentially from 1990 to 2018. The research foci shifted from the process of LUCC during 1990–2004 to the impact of LUCC during 2005–2013 and then to the sustainability of LUCC from 2014 onwards. In the process phase, the main progress of LUCC research included the establishment of the LUCC database, the analysis of the driving force, and the development of the LUCC model. In the impact phase, the main progress was reflected in the evaluation of the effects of LUCC on natural habitats and biodiversity, regional climate and air quality, soil physical and chemical properties, and hydrological processes. In the sustainability phase, the main progress was shown in four aspects, i.e., embedding the LUCC process into a human-earth system model, revealing the impact of LUCC on ecosystem services, investigating the impact of LUCC on human well-being, and land use optimization and management toward sustainability.

With the rapid development of sustainability science globally and the deepening of ecological civilization in China, we are still facing theoretical, methodological and practical challenges in LUCC research. Theoretically, LUCC research is facing the challenge of how to serve the SDGs within the framework of sustainability science. Methodologically, LUCC research is facing the challenge of how to integrate emerging technologies such as big data, cloud computing, artificial intelligence and virtual reality to develop a new methodology. Practically, LUCC research is facing the challenge of how to integrate a sustainability science framework and emerging technologies to implement territorial spatial planning.

To this end, LUCC research should be closely integrated with landscape sustainability science. The core of LUCC research in the future should be focused on the relationships among ecosystem services, human well-being and disaster risk under different land use patterns. Meanwhile, LUCC research should be closely combined with geodesign to promote the deep integration of emerging technologies. In addition, LUCC research should theoretically and methodologically support territorial spatial planning and actively serve the main battlefield of the Beautiful China initiative and the achievement of SDGs.

Acknowledgements

We would like to express our gratitude to Professor Peijun Shi and Professor Jianguo Wu for their inspiration and guidance in the writing process. We also thank the anonymous reviewers and editors for their insightful and critical comments, which have improved the quality of the manuscript.

References

Agarwala M, Atkinson G, Fry B P *et al.*, 2014. Assessing the relationship between human well-being and ecosystem services: A review of frameworks. *Conservation & Society*, 12(4): 437–449.

Bahn O, Drouet L, Edwards N *et al.*, 2006. The coupling of optimal economic growth and climate dynamics. *Climatic Change*, 79(1): 103–119.

Bai W Q, Zhao S D, 2001. An analysis on driving forces system of land use changes. *Resources Science*, 23(3): 39–41. (in Chinese)

Bai Y, Feng M, 2018. Data fusion and accuracy evaluation of multi-source global land cover datasets. *Acta Geographica Sinica*, 73(11): 2223–2235. (in Chinese)

Batlle-Aguilar J, Brovelli A, Porporato A *et al.*, 2011. Modelling soil carbon and nitrogen cycles during land use change: A review. *Agronomy for Sustainable Development*, 31(2): 251–274.

Bergen K J, Johnson P A, de Hoop M V *et al.*, 2019. Machine learning for data-driven discovery in solid Earth geoscience. *Science*, 363(6433): 1299–1299.

Bicheron P, Leroy M, Brockmann C *et al.*, 2006. GlobCover: A 300 m Global Land Cover Product for 2005 Using ENVISAT MERIS Time Series. Valencia: Publishing Services, University of Valencia.

Böhm M, Collen B, Baillie J E M *et al.*, 2013. The conservation status of the world's reptiles. *Biological Conservation*, 157: 372–385.

Boissau S, Castella J C, 2003. Constructing a common representation of local institutions and land use systems through simulation-gaming and multiagent modeling in rural areas of northern Vietnam: The SAMBA-Week methodology. *Simulation and Gaming*, 34(3): 342–357.

Boysen L R, Brovkin V, Arora V K *et al.*, 2014. Global and regional effects of land-use change on climate in 21st century simulations with interactive carbon cycle. *Earth System Dynamics*, 5(2): 309–319.

Bradshaw C J A, Sodhi N S, Peh K S H *et al.*, 2007. Global evidence that deforestation amplifies flood risk and severity in the developing world. *Global Change Biology*, 13(11): 2379–2395.

Cai Y L, 2001. A study on land use/cover change: The need for a new integrated approach. *Geographical Research*, 20(6): 645–652. (in Chinese)

Calvin K, Bond-Lamberty B, 2018. Integrated human-earth system modeling-state of the science and future directions. *Environmental Research Letters*, 13(6): 063006. DOI: 10.1088/1748-9326/aac642.

Calvin K, Bond-Lamberty B, Jones A *et al.*, 2019. Characteristics of human-climate feedbacks differ at different radiative forcing levels. *Global and Planetary Change*, 180: 126–135.

Cardinale B J, Duffy J E, Gonzalez A *et al*., 2012. Biodiversity loss and its impact on humanity. *Nature*, 486: 59–67.

Chen M X, Liang L W, Wang Z B *et al*., 2019. Geographical thinking on the relationship between beautiful China and land spatial planning. *Acta Geographica Sinica*, 74(12): 2467–2481. (in Chinese)

Collins W D, Craig A P, Truesdale J E *et al*., 2015. The integrated Earth system model version 1: Formulation and functionality. *Geoscientific Model Development*, 8(7): 2203–2219.

Davies-Barnard T, Valdes P J, Singarayer J S *et al*., 2014. Full effects of land use change in the representative concentration pathways. *Environmental Research Letters*, 2014, 9: 114014. DOI: 10.1088/1748-9326/9/11/114014.

Dirmeyer P A, Niyogi D, de Noblet-Ducoudre N *et al*., 2010. Impacts of land use change on climate. *International Journal of Climatology*, 30: 1905–1907.

Edwards D P, Socolar J B, Mills S C *et al*., 2019. Conservation of tropical forests in the Anthropocene. *Current Biology*, 29(19): R1008–R1020.

Ellis E C, Klein Goldewijk K, Siebert S *et al*., 2010. Anthropogenic transformation of the biomes, 1700 to 2000. *Global Ecology and Biogeography*, 19(5): 589–606.

ESA, 2014. CCI-LC Product User Guide v2.4.

Fan J, 2018. "Territorial System of Human-environment Interaction": A theoretical cornerstone for comprehensive research on formation and evolution of the geographical pattern. *Acta Geographica Sinica*, 73(4): 597–607. (in Chinese)

Fan J, 2019. Spatial organization pathway for territorial function-structure: Discussion on implementation of major function zoning strategy in territorial spatial planning. *Geographical Research*, 38(10): 2373–2387. (in Chinese)

Fang C L, Wang Z B, Liu H M, 2019. Exploration on the theoretical basis and evaluation plan of Beautiful China construction. *Acta Geographica Sinica*, 74(4): 619–632. (in Chinese)

Fischer G, Ermoliev Y, Keyzer M A *et al*., 1996. Simulating the socio-economic and biogeophysical driving forces of land-use and land-cover change: The IIASA land-use change model. WP-96-010. Laxenburg: IIASA.

Fischer J, Lindenmayer D B, 2007. Landscape modification and habitat fragmentation: A synthesis. *Global Ecology and Biogeography*, 16(3): 265–280.

Fischer R A, Byerlee D, Edmeades G O, 2014. Crop yields and global food security: Will yield increase continue to feed the world? ACIAR Monograph No.158. Australian Centre for International Agricultural Research, Canberra.

Foley J A, DeFries R, Asner G P *et al*., 2005. Global consequences of land use. *Science*, 309(5734): 570–574.

Friedl M A, McIver D K, 2002. Global land cover mapping from MODIS: Algorithms and early results. *Remote Sensing of Environment*, 83(1): 287–302.

Fu B J, Liu Y X, 2019. The theories and methods for systematically understanding land resource. *Chinese Science Bulletin*, 64(21): 2172–2179. (in Chinese)

Fu B J, Zhang L W, 2014. Land-use change and ecosystem services: Concepts, methods and progress. *Progress in Geography*, 33(4): 441–446. (in Chinese)

Future Earth, 2013. Future Earth Initial Design: Report of the Transition Team. Paris, FRA: International Council for Science (ICSU).

Gao L, Bryan B A, 2017. Finding pathways to national-scale land-sector sustainability. *Nature*, 544: 217–222.

Geissen V, Sánchez-Hernández R, Kampichler C *et al*., 2009. Effects of land-use change on some properties of tropical soils: An example from Southeast Mexico. *Geoderma*, 151(3): 87–97.

Gleick P H, 2003. Water use. *Annual Review of Environment and Resources*, 28: 275–314.

Global Land Project (GLP), 2005. Science Plan and Implementation Strategy. IGBP Report No.53/IHDP Report No.19. IGBP Secretariat, Stockholm.

Grafton R Q, 2009. Addressing China's water scarcity: Recommendations for selected water resource management issues. *Asian-Pacific Economic Literature*, 23(2): 124–125.

Grundy M J, Bryan B A, Nolan M *et al*., 2016. Scenarios for Australian agricultural production and land use to 2050. *Agricultural Systems*, 142: 70–83.

Guo H D, Wang L Z, Chen F *et al*., 2014. Scientific big data and digital Earth. *Chinese Science Bulletin*, 59(12): 1047–1054. (in Chinese)

Hansen M, DeFries R, Townshend J R *et al*., 2000. Global land cover classification at 1 km spatial resolution using a classification tree approach. *International Journal of Remote Sensing*, 21(6/7): 1331–1364.

He C Y, Shi P J, Chen J *et al*., 2005. Land use scenario model study based on system dynamics model and cellular automata model. *Science in China*: *Series D*, 35(5): 464–473. (in Chinese)

Houghton R A, 2012. Carbon emissions and the drivers of deforestation and forest degradation in the tropics. *Current Opinion in Environmental Sustainability*, 4(6): 597–603.

Huang L, Xiang W N, Wu J G *et al*., 2019. Integrating geodesign with landscape sustainability science. *Sustainability*, 11: 833–849.

Hurkmans R T W L, Terink W, Uijlenhoet R *et al*., 2009. Effects of land use changes on streamflow generation in the Rhine basin. *Water Resources Research*, 45: W06405. DOI: 10.1029/2008WR007574.

Intergovernmental Panel on Climate Change (IPCC), 2019. Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. [2019-09-16]. https://www.ipcc.ch/srccl/chapter/summaryfor-policymakers.

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), 2019. The global assessment report on biodiversity and ecosystem services: Summary for policymakers. Bonn: IPBES Secretariat, [2019-11-22]. https://ipbes.net/system/tdf/inline/files/ipbes_global_assessment_report_summary_for_ policymakers.pdf?file=1&type=node&id=36213.

Kates R W, Clark W C, Corell R *et al*., 2001. Environment and development. Sustainability science. *Science*, 292(5517): 641–642.

Keating B A, Herrero M, Carberry P S *et al*., 2014. Food wedges: Framing the global food demand and supply challenge towards 2050. *Global Food Security*, 3(3/4): 125–132.

Kim M, Kim S, 2011. Quantitative estimates of warming by urbanization in South Korea over the past 55 years (1954–2008). *Atmospheric Environment*, 45(32): 5778–5783.

Kishtawal C M, Niyogi D, Tewari M *et al*., 2010. Urbanization signature in the observed heavy rainfall climatology over India. *International Journal of Climatology*, 30(13): 1908–1916.

Kragt M E, Robertson M J, 2014. Quantifying ecosystem services trade-offs from agricultural practices. *Ecological Economics*, 102(2): 147–157.

Kume A, Charles K, Berehane Y *et al*., 2010. Magnitude and variation of traffic air pollution as measured by CO in the city of Addis Ababa, Ethiopia. *Ethiopian Journal of Health Development*, 24(3): 156–166.

Lambin E F, Baulies X, Bockstael N *et al*., 1999. Land-Use and Land-Cover Change: Implementation Strategy. IGBP Report No.48 and IHDP Report No.10. Stockhdm, Sweden and Bonn, Germany.

Lambin E F, Turner II B L, Geist H J *et al*., 2001. The causes of land-use and land-cover change: Moving beyond the myths. *Global Environmental Change*, 11: 261–269.

Laurance W F, 2007. Forests and floods. *Nature*, 449(7161): 409–410.

Leng G Y, Tang Q H, 2014. Modeling the impacts of future climate change on irrigation over China: Sensitivity to adjusted projections. *Journal of Hydrometeorology*, 15(5): 2085–2103.

Leviston Z, Walker I, Green M *et al*., 2018. Linkages between ecosystem services and human wellbeing: A Nexus Webs approach. *Ecological Indicators*, 93: 658–668.

Li S C, 2014. The Geography of Ecosystem Services. Beijing: Science Press. (in Chinese)

Li X B, 1996. A review of the international researches on land use/land cover change. *Acta Geographica Sinica*, 51(6): 553–558. (in Chinese)

Li X, Ye J A, 2005. Cellular automata for simulating complex land use systems using neural networks. *Geographical Research*, 24(1): 19–27. (in Chinese)

Lin H, Hu M Y, Chen M, 2013. Research progress and prospect of virtual geographic environments (VGEs). *Journal of Geomatics Science and Technology*, 30(4): 361–368. (in Chinese)

Liu J Y, Deng X Z, 2009. Progress of the research methodologies on the temporal and spatial process of LUCC. *Chinese Science Bulletin*, 54(21): 3251–3258. (in Chinese)

Liu Y S, 2018. Research on the urban-rural integration and rural revitalization in the new era in China. *Acta Geographica Sinica*, 73(4): 637–650. (in Chinese)

Liu Y S, Li J T, Yang Y Y, 2018. Strategic adjustment of land use policy under the economic transformation. *Land Use Policy*, 74: 5–14.

Long H L, Qu Y, 2018. Land use transitions and land management: A mutual feedback perspective. *Land Use Policy*, 74: 111–120.

Loveland T R, Reed B C, Brown J F *et al*., 2000. Development of a global land cover characteristics database and IGBP DISCover from 1 km AVHRR data. *International Journal of Remote Sensing*, 21(6/7): 1303–1330.

Lv G N, 2011. Geographic analysis-oriented virtual geographic environment: Framework, structure and functions. *Scientia Sinica* (*Terrae*), 41(4): 549–561. (in Chinese)

Ma J W, 2013. An introduction to geodesign: Concept, framework and practice. *Landscape Architecture*, (1): 26–32. (in Chinese)

MA (Millennium Ecosystem Assessment), 2005. Ecosystems and Human Well-being. Washington, DC: Island Press.

Manson S M, 2005. Agent-based modeling and genetic programming for modeling land change in the Southern Yucatán Peninsular region of Mexico. *Agriculture Ecoystems & Environment*, 111(1–4): 47–62.

Mayer-Svhönberger V, CuKier K, 2013. Big Data: A Revolution That Will Transform How We Live, Work and Think. New York: Houghton Mifflin Harcourt Publishing Company.

Meyer W B, Turner Ⅱ B L, 1994. Changes in Land Use and Land Cover: A Global Perspective. Cambridge: Cambridge University Press.

Muller M R, Middleton J, 1994. A Markov model of land-use change dynamics in the Niagara Region, Ontario, Canada. *Landscape Ecology*, 9(2): 151–157.

Odegard I Y R, van der Voet E, 2014. The future of food-scenarios and the effect on natural resource use in agriculture in 2050. *Ecological Economics*, 97: 51–59.

Ongley E D, Zhang X L, Yu T, 2010. Current status of agricultural and rural non-point source pollution assessment in China. *Environmental Pollution*, 158(5): 1159–1168.

Ouyang Y, Nkedi-Kizza P, Wu Q T *et al*., 2006. Assessment of seasonal variations in surface water quality. *Water Research*, 40(20): 3800–3810.

Parker D C, Manson S M, Janssen M A *et al*., 2003. Multi-agent systems for the simulation of land-use and land-cover change: A review. *Annals of the Association of American Geographers*, 93: 314–337.

Portela R, Rademacher I, 2001. A dynamic model of patterns of deforestation and their effect on the ability of the Brazilian Amazonia to provide ecosystem services. *Ecological Modelling*, 143(1): 115–146.

Powers R P, Jetz W, 2019. Global habitat loss and extinction risk of terrestrial vertebrates under future land-use-change scenarios. *Nature Climate Change*, 9(4): 323–329.

Reilly J, Paltsev S, Strzepek K *et al*., 2013. Valuing climate impacts in integrated assessment models: The MIT IGSM. *Climatic Change*, 117(3): 561–573.

Robinson D T, Di Vittorio A, Alexander P *et al*., 2018. Modelling feedbacks between human and natural processes in the land system. *Earth System Dynamics*, 9(2): 895–914.

Rockström J, Steffen W, Noone K *et al*., 2009. A safe operating space for humanity. *Nature*, 461: 472–475.

Roy P S, Agrawal S, Joshi P *et al*., 2003. The Land Cover Map for Southern Asia for the Year 2000. GLC2000 database, European Commision Joint Research Centre.

Runting R K, Phinn S, Xie Z *et al*., 2020. Opportunities for big data in conservation and sustainability. *Nature Communications*, 11(1): 1–4.

Sala O E, Chapin III F S, Armesto J J *et al*., 2000. Global biodiversity scenarios for the year 2100. *Science*, 287(5459): 1770–1774.

Schipper J, Chanson J S, Chiozza F *et al*., 2008. The status of the world's land and marine mammals: Diversity, threat, and knowledge. *Science*, 322(5899): 225–230.

Simmons C T, Matthews H D, 2016. Assessing the implications of human land-use change for the transient climate response to cumulative carbon emissions. *Environmental Research Letters*, 11(3): 035001. DOI: 10.1088/1748-9326/11/3/035001.

Snyder P K, Delire C, Foley J A, 2004. Evaluating the influence of different vegetation biomes on the global climate. *Climate Dynamics*, 23: 279–302.

Song H L, Zhang X N, Chen Y J, 2014. Land cover mapping using multi-sources data based on Dempster-Shafer theory. *Transactions of the Chinese Society of Agricultural Engineering*, 30(14): 132–139. (in Chinese)

Springer N P, Duchin F, 2014. Feeding nine billion people sustainably: Conserving land and water through shifting diets and changes in technologies. *Environmental Science & Technology*, 48(8): 4444–4451.

Steffen W, Richardson K, Rockström J *et al*., 2015. Planetary boundaries: Guiding human development on a changing planet. *Science*, 347: 736–747.

Steinitz C, 2012. A Framework for Geodesign. California: Esri Press.

Sterling S M, Ducharne A, Polcher J, 2013. The impact of global land-cover change on the terrestrial water cycle. *Nature Climate Change*, 3(4): 385–390.

Tang H J, Wu W B, Yang P *et al*., 2009. Recent progresses of land use and land cover change (LUCC) models. *Acta Geographica Sinica*, 64(4): 456–468. (in Chinese)

Thampi S G, Raneesh K Y, Surya T V, 2010. Influence of scale on SWAT model calibration for streamflow in a river basin in the humid tropics. *Water Resources Management*, 24: 4567–4578.

Ministry of Water Resources of the People's Republic of China (MWR), Chinese Academy of Sciences, Chinese Academy of Engineering, 2010. Water Loss and Soil Erosion and Ecological Security of China: The Loess Plateau. Beijing: Science Press, 28–59. (in Chinese)

Thornton P E, Calvin K, Jones A D *et al*., 2017. Biospheric feedback effects in a synchronously coupled model of human and Earth systems. *Nature Climatic Change*, 7: 496–500.

Turner II B L, Lambin E F, Reenberg A, 2007. The emergence of land change science for global environmental change and sustainability. *Proceedings of the National Academy of Sciences*, 104(52): 20666–20671.

United Nations (UN), 2015. Transforming Our World: The 2030 Agenda for Sustainable Development. Seventieth Session of the United Nations General Assembly Resolution A/RES/70/1. UN, New York.

Valbuena D, Verburg P H, Bregt A K *et al*., 2010. An agent-based approach to model land-use change at a regional scale. *Landscape Ecology*, 25(2): 185–199.

Vauhkonen J, Packalen T, 2018. Uncertainties related to climate change and forest management with implications on climate regulation in Finland. *Ecosystem Services*, 33: 213–224.

Verburg P H, Crossman N, Ellis E C *et al*., 2015. Land system science and sustainable development of the earth system: A global land project perspective. *Anthropocene*, 12: 29–41.

Verburg P H, Erb K, Mertz O *et al*., 2013. Land system science: Between global challenges and local realities. *Current Opinion in Environmental Sustainability*, 5(5): 433–437.

Verburg P H, Soepboer W, Veldkamp A *et al*., 2002. Modeling the spatial dynamics of regional land use: The CLUE-S model. *Environmental Management*, 30(3): 391–405.

Voldoire A, Eickhout B, Schaeffer M *et al*., 2007. Climate simulation of the twenty-first century with interactive land-use changes. *Climate Dynamics*, 29(2): 177–193.

Wang X C, Dong X B, Liu H M *et al*., 2017. Linking land use change, ecosystem services and human well-being: A case study of the Manas River Basin of Xinjiang, China. *Ecosystem Services*, 27: 113–123.

Wang Z M, Mao D H, Li L *et al*., 2015. Quantifying changes in multiple ecosystem services during 1992–2012 in the Sanjiang Plain of China. *Science of the Total Environment*, 514: 119–130.

Wu C F, Ye Y M, Wu Y Z *et al*., 2019. Spatial Planning of National Territory. Beijing: Geological Publishing House. (in Chinese)

Wu J G, 2012. A landscape approach for sustainability science//Weinstein M, Turner R. Sustainability Science. New York: Springer, 59–77.

Wu J G, 2013. Landscape sustainability science: Ecosystem services and human well-being in changing landscapes. *Landscape Ecology*, 28: 999–1023.

Wu J G, 2019. Linking landscape, land system and design approaches to achieve sustainability. *Journal of Land Use Science*, 14(2): 173–189.

Wu J G, Guo X C, Yang J *et al*., 2014. What is sustainability science? *Chinese Journal of Applied Ecology*, 25(1): 1–11. (in Chinese)

Wu W B, Yang P, Shibasaki R *et al*., 2007. Agent-based model for land use/cover change: A review. *Scientia Geographica Sinica*, 27(4): 573–578. (in Chinese)

Wu X T, Wang S, Fu B J *et al*., 2018. Land use optimization based on ecosystem service assessment: A case study in the Yanhe watershed. *Land Use Policy*, 72: 303–312.

Xu Y, Tang H P, Wang B J *et al*., 2016. Effects of land-use intensity on ecosystem services and human well-being: A case study in Huailai County, China. *Environmental Earth Sciences*, 75: 416–426.

Yang S L, Dong W J, Chou J M *et al*., 2015. A brief introduction to BNU-HESM1.0 and its earth surface temperature simulations. *Advances in Atmospheric Sciences*, 32: 1683–1688.

Yao W Y, Ran D C, Chen J N, 2013. Recent changes in runoff and sediment regimes and future projections in the Yellow River Basin. *Advances in Water Science*, 24(5): 607–616. (in Chinese)

Yu C Q, Gong P, Yin Y Y, 2011. China's water crisis needs more than words. *Nature*, 470(7334): 307.

Zhang D, Huang Q X, He C Y *et al*., 2019. Planning urban landscape to maintain key ecosystem services in a rapidly urbanizing area: A scenario analysis in the Beijing-Tianjin-Hebei urban agglomeration, China. *Ecological Indicators*, 96: 559–571.

Zhang Y, Jin X F, Zhang Z L *et al*., 2016. Geodesign Theory, Technology and Practice. Beijing: Science Press. (in Chinese)

Zhen F, Zhang S Q, Qin X *et al*., 2019. From informational empowerment to comprehensive empowerment: Exploring the ideas of smart territorial spatial planning. *Journal of Natural Resources*, 34(10): 2060–2072. (in Chinese)

Zuo D K, 1990. A Dictionary of Modern Geography. Beijing: The Commercial Press. (in Chinese)