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Nitrogen research at watershed scale: a bibliometric analysis during 1959–2011

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Abstract Because of enhanced anthropogenic nitrogen input, eutrophication, hypoxia, and acidification threaten the health of aquatic ecosystems. To better understand the current state of research and emerging trends in this area, a bibliometric approach was applied to quantitatively evaluate global nitrogen research at the watershed scale. Using 9,748 articles selected from among 10,163 returned by a search in the Science Citation Index Expanded (SCI-Expanded) database from 1900 to 2011, spatial and temporal characteristics of the articles, authors, institutions, countries, and keywords are presented, and focal research areas are derived. Compared with the annual increase in all articles in the SCI-Expanded (4.5 %), the studies on nitrogen in watersheds increased more quickly (11.2 %), indicating an increasing interest in this area. The relationship between authors and their output was evaluated by a two-step function, in which 6,074 authors (26.8 %) publishing on this topic were key scientists who contributed 56.4 % of the total articles. Based on the number of authors, first authors, international collaborators, and citations, four types of authors were analyzed using cluster methods. The influence of the authors, institutions and countries was also analyzed in terms of publication and citation, and a co-occurrence analysis was used to assess cooperation among countries and research hotpots. The keywords were compared among countries to assist our understanding of interests of research and modes. From the analysis of the primary subjects and the co-occurrence of keywords, studies involving nitrogen's environmental effects, the nitrogen process and models are increasing, which indicates that they are likely to become a primary research focus in the near future.

Keywords Nitrogen cycle · Nutrients · Bibliometric · Biogeochemistry · Review

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Introduction

Nitrogen is ubiquitous, and in living material, it provides the building blocks of important polymers such as proteins and nucleic acids (Canfield et al. 2010). For most ecosystems on earth, their structure, function and process are largely controlled by nitrogen (Vitousek et al. 1997; Vitousek and Howarth 1991). However, because the Haber–Bosch process for the manufacture of ammonia was invented, the human alteration of the nitrogen cycle has accelerated rapidly and has outstripped the natural process over multiple scales (Galloway et al. 2004; Swaney et al. 2012), leading to a variety of environmental issues such as climate change, acidification, eutrophication, hypoxia, biodiversity loss, and negative impacts on human health (Townsend et al. 2003; Vitousek et al. 1997). Human interference is estimated to have interfered with the nitrogen cycle to a degree that exceeds the earth's regulatory capacity by a factor of 3.5 (Rockstrom et al. 2009). Because of the well-documented increase in concentrations of atmospheric carbon dioxide and changes in land use/cover (Vitousek 1994), research on nitrogen cycling and management has developed as a critical topic. From local to global scales, the watershed is an important unit because of its relatively independent natural boundary. A number of nitrogen studies on water quality is carried out at the watershed scale (Kimura et al. 2012; Swaney et al. 2012; Zhang and Yang 2013). In this paper, a bibliometric analysis of nitrogen studies that are associated with water at the watershed scale is presented.

The purpose of this paper is to assess the state of research on nitrogen at the watershed scale, and a general profile of key authors, institutions, countries and hotpots was recognized by the bibliographic statistics. This study will serve as a reference to guide the study of nitrogen at the watershed scale.

Materials and methods

Data sources

Among available databases, the Science Citation Index Expanded (SCI-Expanded) database of the Web of Science is most often chosen for bibliometric research in natural sciences because of its comprehensiveness and high quality (Fu et al. 2013; Zhi and Ji 2012). According to the Journal Citation Report (JCR) of 2011, 8336 journals across 176 Web of Science subject categories were included in this database. As in other other studies, the SCI-Expanded databases of the Web of Science from Thomson Reuters were also used in this research. The research was conducted for the terms of nitrogen and watershed (or equivalent) within the publication years 1900 to 2011, with the specific search function "TS = nitrogen* AND TS = (basin* OR watershed* OR drainage* OR catchment*) AND PY = 1900–2011". The research period was chosen according to the earliest and most recent year covered in the databases. Altogether, 10163 publications from 1959 to 2011 met the selection criteria, and their titles, years of publication, authors, abstracts, keywords, institutions and countries were downloaded in Web of Science format for further analysis.

Methods

The analysis was conducted using BibExcel 1.0.0.0, Histcite 12.03.17, Pajek 1.0.0.1, SPSS 18.0 and Office Excel 2010. Bibexcel is a free bibliometric toolbox developed by Olle

Persson (Persson et al. 2009), which is capable of most types of bibliometric analysis, e.g., citation analysis, co-occurrence analysis, and frequency analysis, and allows easy interaction with other software. Histcite, short for history of citations (Thomson Reuters, Philadelphia, PA, USA; http://www.hiscite.com), is good for uncovering relationships between publications and performing citation analysis, which is particularly useful for bibliometric analysis (Ashrafi et al. 2012; Bornmann and Marx 2012; Rajagopal et al. 2013). Histcite was used as a tool to assist making cooperation networks in this study. Further analysis such as cluster analysis and graph making were performed by SPSS 18.0 and Office Excel 2010.

Results and discussion

Document types and records

Using the selected search words, a total of 10,163 publications in 10 document types were found in the 53-year study period. Most (9,744) were articles, accounting for 86.6 % of the total documents. Proceedings papers (1,083; 9.6 %) and reviews (334; 3.0 %) were also common, with other seven categories that represented <1 % combined. This pattern of documents is similar to other bibliometric research using the Web of Science database (Fu et al. 2013; Li et al. 2011; Zhi and Ji 2012), which is why articles are usually chosen as the type for analysis (Ho et al. 2010). In this study, 9,744 articles were used for further analysis and 4 letters were also included because of their important role in research. The articles represented work by 22,665 authors, 1,064 journals and 129 countries or districts. Further analysis including annual outputs, citations, keywords, cooperation, etc. were based on the articles.

Characterization of publication output

Because abstracts are not available in the SCI-Expand before 1991, the publications collected before that year are very limited, and most researchers simply discard that period by using the research period starting from 1991 (Hu et al. 2010; Li et al. 2008, 2009; Suk et al. 2011; Wen et al. 2007; Zhang et al. 2010b). To fully understand the history of the discipline, all articles since 1900 were included in this study. However, there were no articles matching the search before 1959, and a total of only 126 publications from 1959 to 1990 were found, with fewer than 6 per year. We believe this value may be a significant underestimation because that lacked an abstract may have been missed. In the annual output analysis, data from 1959 to 1990 were presented by one aggregated value in the figure to avoid the over interpretation of unrealistic results given that the output in that period may be underestimated (Fig. 1). Between 1991 and 2011, there is a significant uptrend in the number of publications, increasing from 111 in 1991 to 842 in 2011, with annual increment of 38. The annual increase rate of 11.2 % was much higher than the average increase (3.9 %) for all records in the SCI-Expand database. Furthermore, the increase is also larger than the growth rate of publications in records resulting from a search of nitrogen alone (6.3 %) or watershed alone (4.5 %). Research on nitrogen at the watershed scale has clearly been a hot topic in natural sciences, and we expect more research output in this area in the foreseeable future. In addition, some interesting phenomena in the trend of growth rate could be observed. For the growth rate in publications of SCI-Expanded, the variability in the annual growth rate is relatively small, and it has

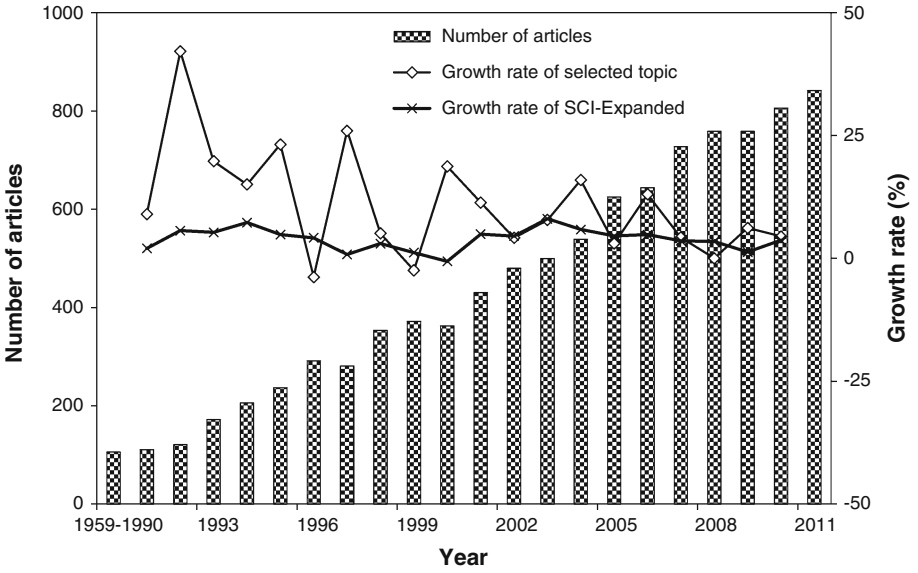

Fig. 1 Annual output and growth rate of publications between 1959 and 2011

slowed significantly, with the increase from 2001 to 2011 being only half of that of the previous decade. According to the general rules of literature growth, research in this area has passed its primary stage and is entering a relative stable and mature period overall.

Publications, citations and patterns of author

Author information includes their number of publications, citations, and cooperation status. In this study, different types of authors in the selected topic were assessed by their performance in publications and citations. In total, 22,665 authors contributed to the articles. There was a great variety among them in terms of output. On average, each author contributed to only 1.7 (with a standard variation of 2) records. Overall, 92.9 % of the authors contributed to fewer than 3 articles. There was an obvious threshold in the relationship between author number and article number (Fig. 2), at 56.1 % of publications. These points divided the authors into two groups: 26.4 % (5,968) of authors contributed to the majority of publications while the rest 73.6 % (16,658) contributed to less than half of the research output (43.9 %). Thus, the 26.4 % (5,968) could be considered key authors in this study and provide a base for further analysis.

Author performance was evaluated by publications and citations. Because authors can be co-authors, first authors or corresponding authors, author features should be analyzed using those variables. The same is true for citations, which can be assessed by Local Citation Score per Author (LCSA: the number of times that paper was cited within the group of papers divided by the publications of the author), an important metric for authors, and Global Citation Score per Author (GCSA: the number of times that paper was cited by any source divided by the publications of the author), which indicates the overall influence of the author in all related areas. The larger the difference between LCSA and GCSA, the broader the expertise of the author. The details of these two indexes are in the Histcite

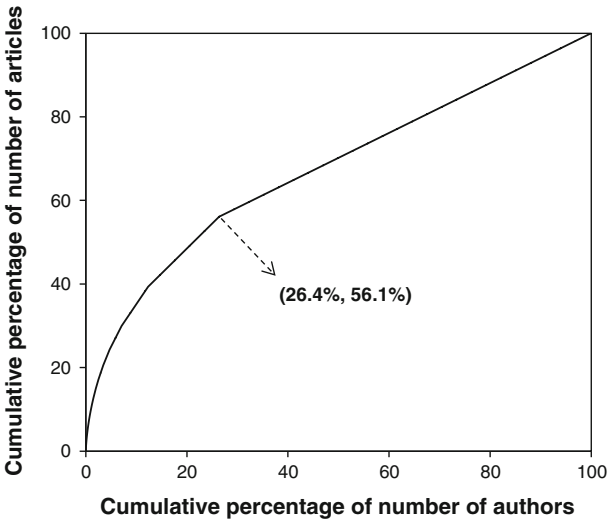

Fig. 2 Cumulative percentages of number of articles in terms of number of authors

Table 1 Top 20 authors with most publications and citations from 1959 to 2011

No.	Co-author		First-author		GCSA		LCSA	
1	Driscoll CT	51	Kopacek J	18	White RE	124.7	King KW	49.1
2	Groffman PM	49	Bakhsh A	16	Schwarz GE	121.4	Lewis WM	47.8
3	Kanwar RS	48	Schilling KE	16	Hirt U	111.7	White RE	40.4
4	Billen G	45	Owens LB	15	Grimvall A	106.9	Durand P	39.8
5	Valiela I	45	Groffman PM	14	King KW	103.8	Howarth RW	38.4
6	Wright RF	43	Mcdowell RW	13	Durand P	103.6	Schwarz GE	36.7
7	Whitehead PG	38	Neal C	13	Lewis WM	102.2	Grimvall A	36.5
8	Mitchell MJ	38	Wright RF	13	Henriksen A	102.2	Williams JR	35.5
9	Skaggs RW	38	Billen G	12	Williams JR	87.8	Hirt U	35.0
10	Mcdowell WH	37	James JJ	12	Smith KA	87.5	Henriksen A	32.5
11	Garnier J	35	Wade AJ	12	Clair TA	83.1	Aherne J	32.0
12	Dillon PJ	35	Whitehead PG	12	Howarth RW	83.0	Day JW	29.7
13	Neal C	33	Williams MW	12	Lajtha K	79.4	Kroeger KD	27.0
14	Wade AJ	31	Arheimer B	11	Haggard BE	77.2	Lajtha K	26.1
15	David MB	30	Kronvang B	11	Seitzinger SP	76.7	Moss B	26.0
16	Likens GE	29	Paerl HW	11	Grizzetti B	73.1	Ulen B	25.3
17	Arheimer B	28	Ulen B	11	Meyers PA	71.6	Ma L	24.3
18	Kronvang B	28	Sharpley AN	10	Edwards WM	70.0	Evans CD	23.9
19	Jaynes DB	28	Stottlemyer R	10	Aherne J	69.9	Gassman PW	23.3
20	Butterfield D	28	Sullivan TJ	10	Evans CD	69.8	Schilling KE	23.2

manual. To eliminate the correlation between them, a Pearson Correlation test was applied, which showed that the correlation coefficient between first author and corresponding author reached 0.925 ($P < 0.0001$). Therefore, the corresponding author designation was omitted from analysis, and the remaining four indices are listed in Table 1. Table 1 shows

the differences in the ranks of authors under different index systems. When co-authors are used, Driscoll CT (51 records), Groffman PM (49 records) and Kanwar RS (48 records) were listed as the authors with the most publications. Using first authors, none of them was among the top three. The difference between co-authors and first author can be explained in part by the fact that the co-author often represents a team leader, while the first author is the main paper writer. Driscoll CT, for example, was No 1 in publications but failed to reach the top 20 in the first-author list, which indicates that he took a leading role in his research team. The GCSA is an index for assessing the impact of authors in all related areas. The results of the GCSA differed from the first two indexes, and none of the top 20 GCSA authors could be found in either the top co-author list or the first-author list. The reason for this difference is very complex, and may reflect the author's number of publications, study interests, or analysis error. Because the GCSA is strongly correlated with LCSA ($r = 0.487$, $P < 0.0001$) and they share more than half the authors in common in the top 20 list, we conclude that the authors identified by the GCSA and LCSA are the most influential in spite of the fact that average publication total in the top 20 GCSA records is only 11.5 per capita. The ratio of LCSA to GCSA is close to 3 for the top 30 authors, illustrating that 1/3 of the total citations are by other nitrogen studies at the watershed scale.

For authors of at least 10 articles (274 in total), a trend analysis according to Daniel's method was used to test the change in author rank in terms of their cumulative publications. If the rank of an author decreases over time, we assumed their influence on the study area is declining as well. The results show that at a 0.01 α significance level, 39.1 % (107 authors) of the total 274 authors present an upward trend in author rank (namely, the Daniel test value is positive) while 13.1 % (36 authors) present an downward trend, and the rest 47.8 % (131) have no obvious change. These results indicate that a group of 36 people is becoming more and more important in this study area, and the top ten are shown in Fig. 3. Billen G, Gamier J, and Groffman PM have outstanding performance, with more than 10 publications each of the past 3 years. A moderately negative relationship was found between number of articles and Daniel test value (Fig. 4), but the pattern was not easy to interpret.

Institutional publication performance

The contribution of different institutions was estimated by the affiliation of at least one author of the published article. There are a total of 5,022 institutions represented in the set of articles. Top 30 with the most publications was graphed in Fig. 5, representing 3,470 records accounting for 35.6 % of the total publications. United States Department of Agriculture, Agricultural Research Service (USDA ARS), United States Geology Survey (US Geol Survey) and Chinese Academy Science (Chinese Acad Sci) were foremost among them, each with publications exceeding 200. However, the Chinese Acad Sci was composed of 116 branches distributed throughout China. Thus, we cannot conclude that Chinese Acad Sci is a very important institution simply from this figure, which is consistent with its low rank according to LCSA (1.1) and GCSA (9.2) among the top 30 institutions. In contrast, Inst Ecosyst Studies (Cary Institute of Ecosystem Studies) enjoyed the highest GCSA (70.4) and LCSA (22.6) values with a rank of 26 in number of publications. Overall, government institutions such as USDA ARS, US Geol Survey, Chinese Acad Sci, United States Forest Service (US Forest Serv) and US EPA had a relatively large number of publications that could be explained by their massive resources, while universities and labs often had more citations in the GCSA and LCSA. Large publications had

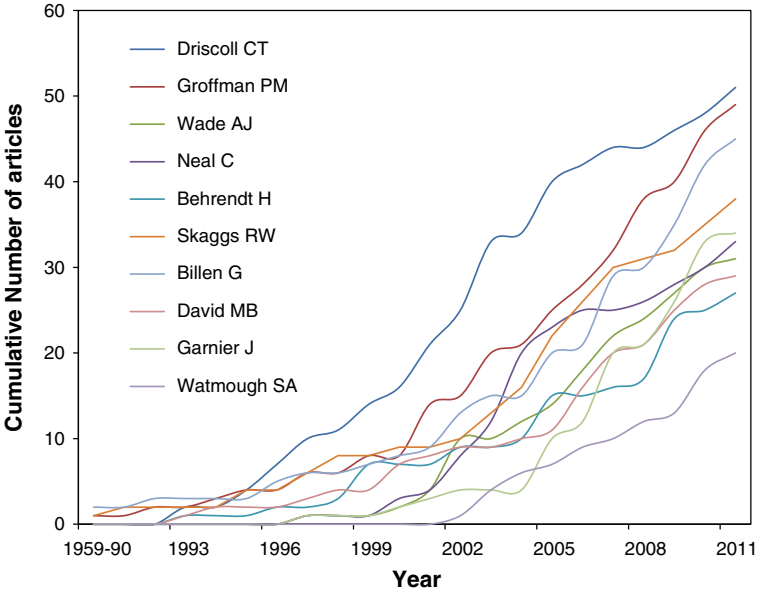

Fig. 3 Top 10 authors showing the increase in authors' rank of cumulative outputs

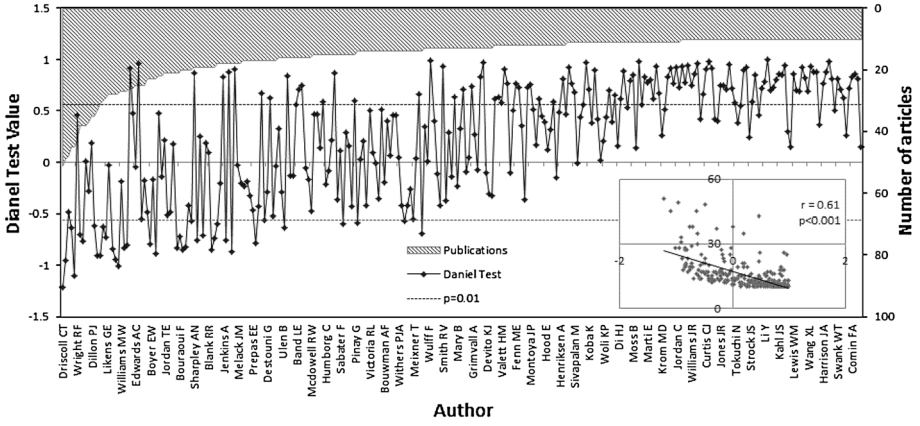

Fig. 4 Trend test of author's rank in cumulative outputs and their correlation from 1959 to 2011

more interest in the applied areas of agriculture, water resources and engineering, and institutions of higher education favored geology, marine, fresh water ecology and meteorology, which are more theoretical fields.

National publication performance

The contribution of publications provided by different countries or territories was estimated using the same method as the institution statistic. There are a total of 129 countries/territories represented in the 9748 articles. There was a strong, nonlinear relationship

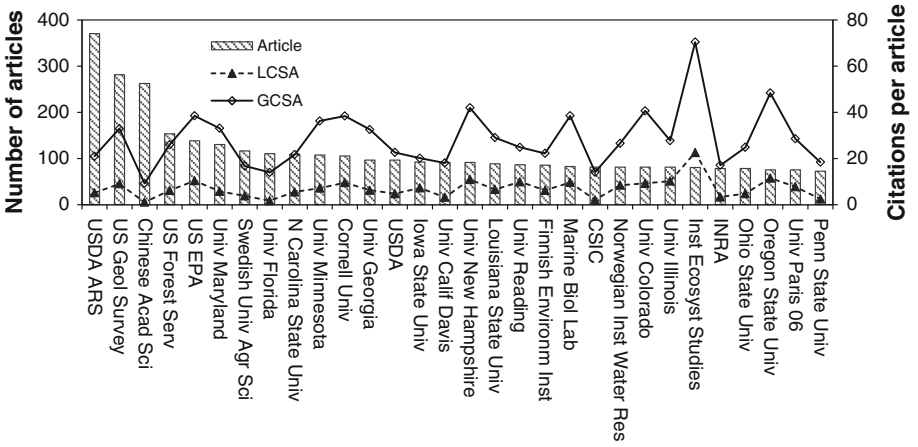

Fig. 5 Number of publications and citations in the top 30 institutions from 1959 to 2011

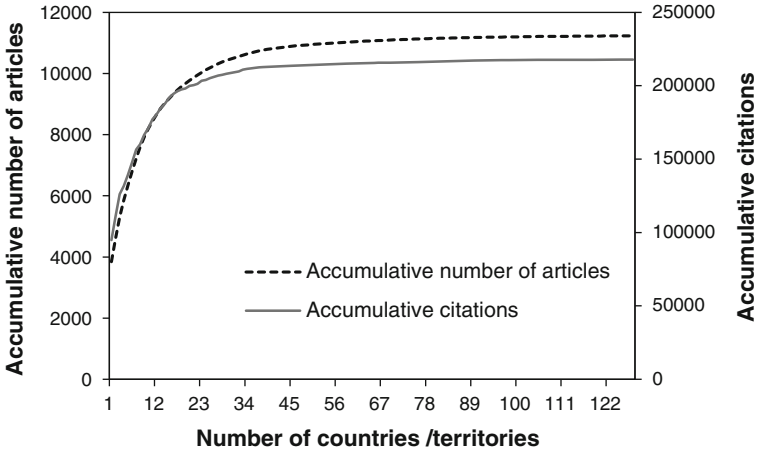

Fig. 6 Accumulative number of publications and citations from 129 countries/territories

between the number of countries/territories and the number of publications or citations, indicating an uneven distribution of articles and impacts at spatial scales (Fig. 6). The USA, UK, Canada and 17 other countries/territories contributed 87 % of the total publications and 92 % of the total citations. All of the top 20 countries had developed economies with three exceptions. China, Brazil and India belong to the BRICs and illustrate the significant influence of economy on research. The close relationship between research output and economy has also been reported in other research (Yu et al. 2012). Among countries, the USA ranked first in terms of the number of articles, TLCS, and TGCS. In the quality of publications as assessed by the LCSA and GCSA indices, the USA was also in the leading position. This is not a surprise because the USA has been well known for its numerous and high-quality institutions and scientists in other fields (Ho 2013; Sun et al. 2012). In addition to the USA, the UK, Sweden, the Netherlands, and Denmark also have

Table 2 Top 20 most productive countries publishing articles on nitrogen in watersheds from 1959 to 2011

Country	Number of articles	Percentage	TLCS	TGCS	LCSA	GCSA
USA	3,847	39.5	17,656	94,835	4.6	24.7
UK	753	7.7	3,271	16,138	4.3	21.4
Canada	707	7.3	2,440	15,138	3.5	21.4
Peoples R China	555	5.7	933	5,538	1.7	10.0
Germany	482	4.9	902	7,567	1.9	15.7
Australia	452	4.6	1,328	8,515	2.9	18.8
France	420	4.3	1,552	8,747	3.7	20.8
Japan	375	3.8	573	3,574	1.5	9.5
Sweden	323	3.3	1,484	6,460	4.6	20.0
Spain	281	2.9	568	4,478	2.0	15.9
Netherlands	242	2.5	1,107	6,026	4.6	24.9
Italy	220	2.3	474	3,347	2.2	15.2
Brazil	205	2.1	538	4,447	2.6	21.7
New Zealand	171	1.8	473	2,732	2.8	16.0
Denmark	141	1.4	708	4,081	5.0	28.9
Norway	141	1.4	538	2,672	3.8	19.0
Finland	138	1.4	361	1,910	2.6	13.8
India	112	1.1	89	1,179	0.8	10.5
Poland	104	1.1	42	667	0.4	6.4
Switzerland	103	1.1	226	1,801	2.2	17.5

Because some addresses were not available in early publications, the number of countries presented here is underestimated, but has a relative error <5 %

substantial impact in the studied area with high values for LCSA. However, P R China, Germany, Japan, India and Poland rank at the bottom of the LCSA, indicating a more confined influence in this field (Table 2).

The research patterns by nation were studied based on their regional impact and geographical location. The USA, the UK, Canada, China, German, Australia, France, Japan, Brazil, and India were selected as the primary contributors to the literature and represent different economic and social situations. Featured author keywords in the countries are listed in Table 3. Apart from the 31 common keywords among different countries, each country has its own specific author keywords. For the USA, best management practice and wetland are its featured keywords. For the UK, water framework directive, nitrous oxides, ammonium, and acidification were listed as high frequency terms in addition to the shared terms. China placed more emphasis on important regions and soil characteristics, which is consistent with its national environmental protection policy. For Germany, the Baltic Sea and the North Sea were the featured research areas. For Australia, studies on agriculture and marine habitats separate it from other countries. For France, research in the riparian zone and Seine River was prevalent. For Japan, Lake Biwa and nitrogen in agriculture activities received most of the attention among N studies. For Brazil, the Amazon basin and deforestation are the gravest problems. For India, statistical methods such as cluster analysis, discriminant analysis and factor analysis were widely used in nitrogen studies.

Of the 31 frequent keywords, eutrophication, water quality, denitrification, land use, nitrate, phosphorus, groundwater, nutrient, agriculture, model, sediment were among the

Table 3 Featured author keywords in ten important countries (research words and country name were omitted)

Country	Keywords
USA	Best management practice, Wetland
UK	Water framework directive, nitrous oxide, ammonium, acidification
Canada	Paleolimnology, Boreal forest, Lake, Paleolimnology
People's Republic of China	Changjiang river, Lake taihu, loess Plateau, soil nutrients, soil organic carbon, soil properties
Germany	Baltic sea, North Sea, retention
Australia	Apsim, Floodplain, deep drainage, great barrier reef, salinity, soil water, urbanization
France	Riparian zone, seine river
Japan	Forested Watershed, Lake Biwa, nitrogen fertilizer, nitrogen saturation, paddy field
Brazil	Amazon, deforestation, nutrient limitation, pasture, Rondonia, Tropical forest, tropical pasture
India	Cluster analysis, discriminant analysis, factor analysis, biomass, cotton, crop, drain spacing, drip irrigation, Gomti river, holocene, paired sowing, rice, subsurface drainage

most common in no fewer than seven countries. The remaining 20 keywords were shared among five countries or fewer, except for India which only used seven out of the 31 keywords. The other nine countries shared more than 12, of which USA and UK had the most (Fig. 7).

Regionalization and globalization is a significant trend in nitrogen research at the watershed scale. To capture important information about international cooperation, 58 countries with more than 15 articles were chosen. Bibexcel and Pajeck programs were used to explore the cluster cooperation characteristics between these countries (Fig. 8). In this figure, the link merely represents cooperation in terms of papers produced by authors from two countries and the size of country (circle) is the total cooperation value for the country, while the color identifies its group. Countries in the same cluster have cooperative relationships with each other. However, cooperation only exists between clusters when a link presented between them. For example, Belgium, Bulgaria, and France are in the same cluster because they have identical color. This cluster has a link with the cluster that is centered on the USA, indicating that there are cooperative relationships between the members of the two clusters. As the figure shows, USA was in the core of the cooperative web system, acting as the most important county in global communication about N research, and several regional groups were identified. On a country-to-country basis, the USA-Canada collaborations ranked first, with 127 cooperation articles, followed by USA-China (91), USA-Brazil (75), USA-UK (73), and USA-Netherlands (53). On a regional basis, five regional groups could be identified through connections among cooperating countries. Germany, the UK, Japan, France and the Netherlands were the centers of those five groups. Germany and its six group members have a close geographical correlation; UK and its seven group members are mainly located in Northern Europe. The group around Japan has three members in Southeast Asia, indicating a strong connection between Japan and those countries in Southeast Asia. The other two groups have a relatively smaller size and the connections are more difficult to identify.

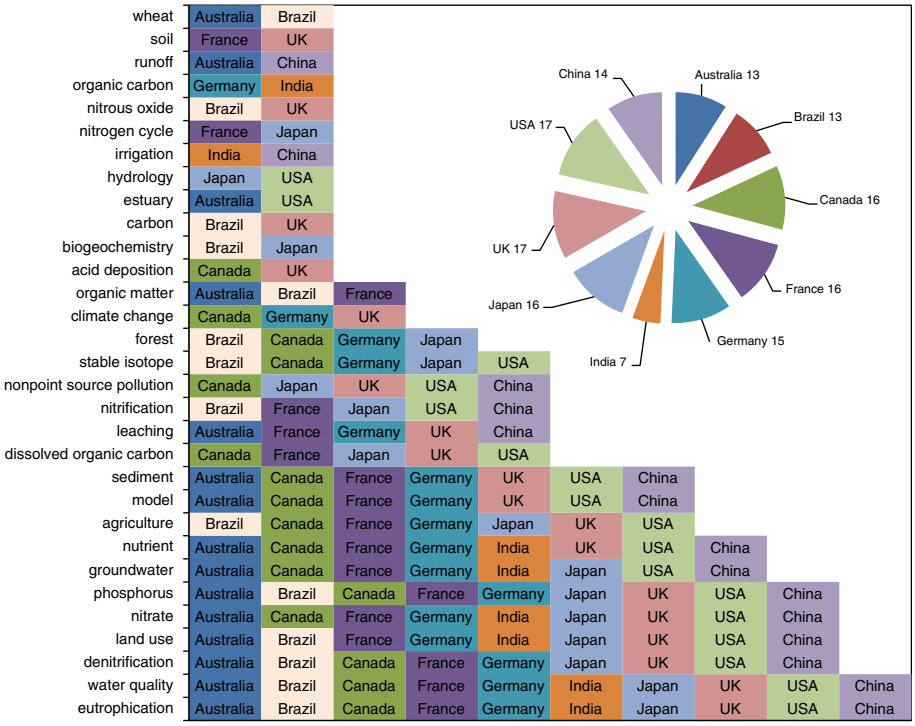

Fig. 7 Co-occurrence of author keywords among countries

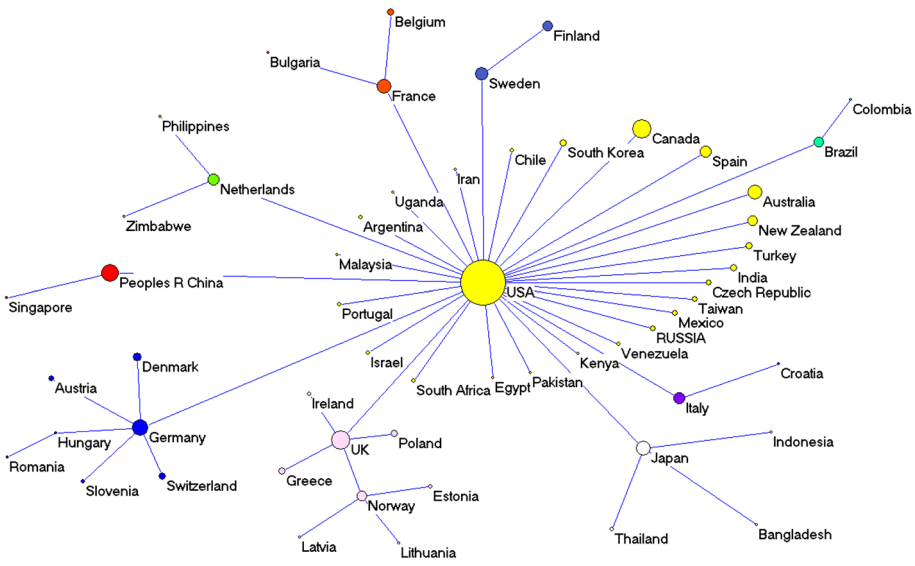

Fig. 8 Country cooperation network among countries with more than 15 shared publications. *Circles* represent the frequency of international cooperation, the larger the *circle*, the more frequent it is

Emerging topics and future trends

Author keywords describe the main topics of the articles and are usually used to analyze the emerging trends in research (Yu et al. 2012; Zhang et al. 2010a). A total of 40,802 author keywords were found in the 9,748 articles, and 15,495 clustered author keywords were identified using the author keywords cluster function in the HistCite software. Among the 15,495 author keywords, the top 20 were selected according to their frequency (Table 4). "Phosphorus", "water quality", "nutrient", "nitrate" and "eutrophication" were the most popular keywords, which suggests that nutrients and their influence on water quality were the most popular topics in the research. Other keywords such as "leaching", "denitrification", and "nitrification" indicate that nitrogen processes were also attractive areas of study. In addition, the high frequency of the keywords "soil", "agriculture", "land use", "nonpoint pollution source" implies a key role of agricultural activities on nitrogen dynamics. "Model" and "stable isotopes" suggest that there is an emphasis on quantitative measures in this area.

Nitrogen research at the watershed scale has received attention by more countries over recent years (Fig. 9). The first country publishing an article in this area was the Democratic Republic of the Congo (a colony of Belgium between 1908 and 1960), which published the first article in the 184 issue of Nature in 1959 on the contribution of nitrogen in rain water to the nitrogen budget of the Congo River basin.

Before the year 1980, nitrogen research at the watershed scale was only carried out in the USA, Canada, France, UK and other nine countries, most of which were western countries. However, the number of countries may be underestimated because Web of

Table 4 The 20 most frequent author keywords

Author keyword	Recs	Percent	TLCS	TGCS
Phosphorus	750	7.7	3,175	13,931
Water quality	649	6.7	2,379	10,526
Nutrient	537	5.6	1,688	9,434
Nitrate	483	5.0	2,511	8,670
Eutrophication	393	4.0	1,791	8,221
Model	380	3.9	1,308	6,011
Leaching	342	3.5	1,439	5,830
Soil	305	3.2	840	5,501
Denitrification	264	2.7	1,306	5,507
Nonpoint source pollution	247	2.6	942	3,538
Agriculture	204	2.1	995	4,017
Land use	204	2.1	766	3,553
Sediment	196	2	486	3,361
Ground water	162	1.6	570	2,851
Stable isotopes	156	1.6	445	3,277
Nitrogen cycle	146	1.6	1,226	4,748
Wetland	137	1.4	487	2,635
Nitrification	135	1.4	611	3,137
Dissolved organic carbon	125	1.3	646	2,755
Runoff	125	1.3	356	1,775

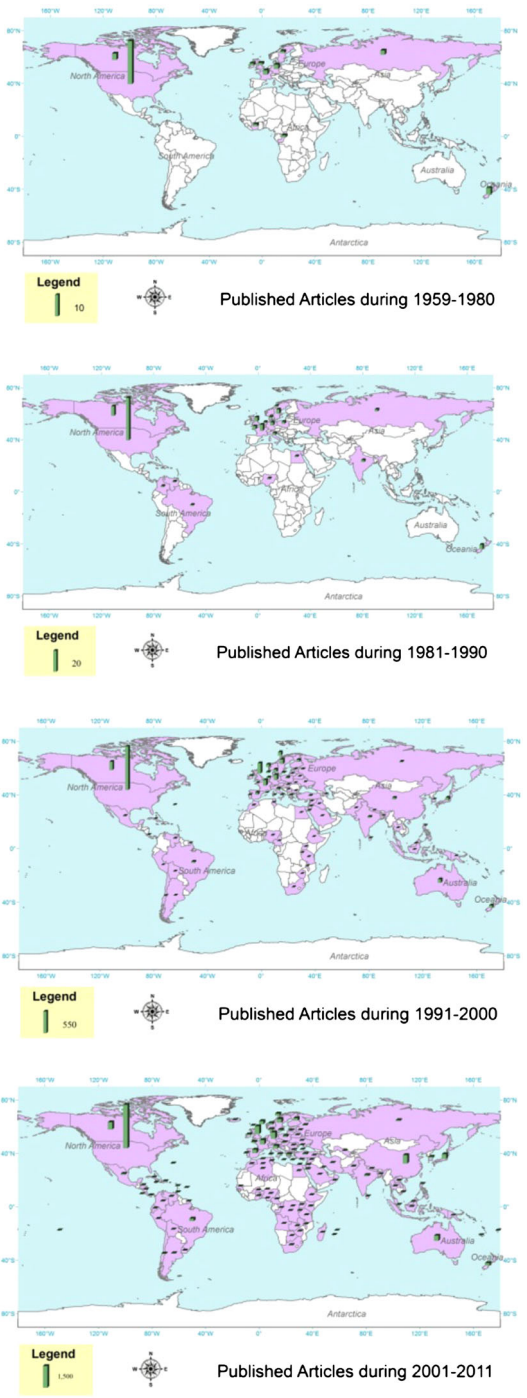

Fig. 9 Trends in international work and articles published on N in watersheds. Articles in Soviet Union before 1991 was included in Russia

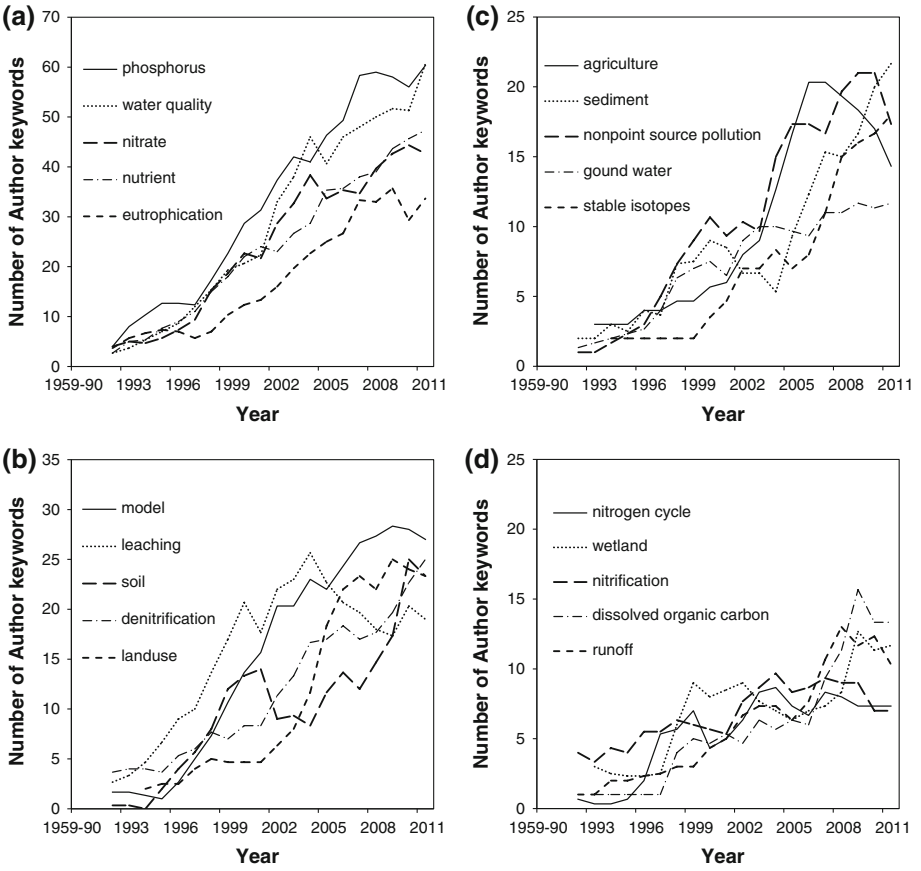

Fig. 10 A 3 year moving average for the top 20 author keywords during 1959 to 2011

Science could not extract address information from some early articles. The USA stood out among these countries by contributing 20 articles, accounting for 47.6 % of the total.

In the 1980s, 21 countries were involved in producing a total of 83 articles. In addition to western countries, Asian, African, and Latin American countries became newly emerging research members. However, the USA was still dominant, with publications accounting for 43.6 % of the total.

In the 1990s, a rapid international expansion of nitrogen research was observed, and the number of countries reached 86, more than twice the number in the 1980s. More large regional countries such as China, South Africa, and Argentina took part in this area of research, which indicates a trend of growing global popularity for the field. Unsurprisingly, the USA still produced a large proportion of publications on this topic (43.6 %), maintaining its dominant position. A notable phenomenon is that articles from the 15 European countries contributed 44.5 % of the total publications, which exceeded those by the USA for the first time, and making Europe the second largest research center in the world.

During 2000–2011, the number of countries involved in this research topic continued to increase. There were 126 new countries publishing research articles during this

period. Both in numbers of countries and articles, a great expansion was observed. By 2011, nitrogen research at the watershed scale had expanded through almost the whole world except Polar Regions, Saharan countries and islands where rivers are few. Based on the articles published, three core regions of watershed nitrogen research formed during this period. The USA, UK-France-Germany, and China-Japan-Australia had contributed 42.6, 19.1 and 17.9 % articles individually to the world, acting as three core areas in this topic.

As described above, both the quantity and geographic scope in N research at watershed scales have increased substantially, promoting us to ask whether the topics have altered. To investigate changes in the research focus, the top 20 keywords were selected for analysis on a yearly basis. To avoid missing any newly emerging key words, we ranked all author keywords used more than 20 times from 1959 to 2011, and no keyword other than the selected 20 top keywords entered the annual top 10 list. Thus, we believe these 20 author keywords can be used to represent the most important topics in the area. Because there is a strong fluctuation in the number of keywords in different years, a 3-year move average method was applied to display the growth trend for the 20 author keywords before 2000 (Fig. 10). Overall, there is an obvious increase for all the studied keywords since 2000. However, some of the 20 most frequently used keywords have changed since 2000. "Phosphorus", "water quality", "nutrient", "denitrification", "sediment", "stable isotopes" and "dissolved organic carbon" have increased significantly, which suggests that research on these topics is expanding. In contrast, the number of articles with the keywords "leaching" and "agriculture" decreased in recent years. Although we cannot conclude that research on those two topics is not important any more, researcher's interest seems to have turned away from them. For the other author keywords, no significant trend was observed, suggesting a stable research status.

Conclusions

The study of nitrogen at the watershed scale was analyzed in 10,163 publications in the SCI-Expand database in terms of document types, authors, keywords, institutions and countries. Among 10 types of publications, articles were dominant, accounting for 88.6 % of the total publications, and they were accordingly chosen as the research sample. The rapid increase in this area compared to others indicates that the watershed is an increasingly attractive scale for nitrogen research. An author analysis suggested that the topic is only concentrated within a small group of scientists, and 39.1 % (107 authors) of the total 274 authors are becoming increasing important to the field while 13.1 % (36 authors) published less on nitrogen in watersheds with time. The performance of institutions and countries was assessed by publications, LCSA, GCSA, and the USA had an absolute advantage in the field both in quantity and quality of articles. Furthermore, apart from 31 keywords used in common, each country had some specific keywords. The statistics on keywords indicate that nutrients and their influence on water quality were the hottest topics in the research. Nitrogen research at the watershed scale has expanded quickly, with more countries involved. By 2011, three core regions had formed. In addition, the interannual trend in keywords showed a rise in the use of all the keywords before 2000. "Phosphorus", "water quality", "nutrient", "denitrification", "sediment", "stable isotopes" and "dissolved organic carbon" had growth trends that imply a future focus on these aspects in the future.

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