

Scientometric analysis of phosphorus research in eutrophic lakes

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Abstract Eutrophication has become a top environmental issue for most lake ecosystems in the world and enhanced phosphorus (P) input is usually considered the primary stressor. Focused on the role of phosphorus in eutrophic lakes, a bibliometric approach was applied to quantitatively evaluate the main interests of research and trends in this area. Using data from the Science Citation Index Expanded database between 1900 and 2013, a total of 3,875 publications was returned by searching topic keywords. Spatial, temporal, and interactive characteristics of the articles, countries, and keywords are presented using time series, frequency, and co-occurrence analysis. Result shows that the annual publications on P in eutrophic lakes keep an exponential growth ($R^2 = 0.93$; $p < 0.0001$) over the last two decades, reflecting an increasing attraction in this area. However, publications of phosphorus research make up only 40 % of total records in eutrophic lakes, indicating that there are other significant topics in eutrophication problems of lakes. The USA is the largest output country in this area, contributing 23 % of the total articles, followed by China with a proportion of 15 %. However, China has replaced the USA as the largest output country in the world since 2011, but its citation per paper is significantly lower than the USA, indicating its' favor on quantity over quality. Based on international cooperation analysis, five regional groups were found, and the USA, the UK, P.R. China, Sweden, and German are the centers of their groups. The top 20 title keywords, author keywords and keywords plus were identified according to their frequency to assist our understanding of interests of research and modes. Surprisingly, nitrogen is a high co-occurrence keyword in this study, and its share of publications with P research in eutrophic lakes is increasing rapidly. Furthermore, the high correlation between P and N research in spatial distribution also indicates the increasing significance of N research in eutrophic lakes.

Keywords Eutrophication · Nutrient · Nitrogen · Phosphorus · Lake · Water quality

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Introduction

Eutrophication (the over enrichment of aquatic ecosystems with nutrients leading to algal blooms and anoxic events) is considered the leading cause for degradation of water quality in aquatic ecosystems (Carpenter 2005; Schindler et al. 2008; Smith and Schindler 2009). In freshwater ecosystems, lakes or reservoirs are vulnerable for eutrophication because of their relative short water retention time (Ma and Li 2002) and thus attract great concerns. Among the six major environmental problems occurring in lakes and reservoirs throughout the world, eutrophication is one of them (Tatuo 1997; Sala et al. 2000), and it is likely to intensify in coming decades because of increases in human actions (Carpenter 2005). Naturally, eutrophication occurs as lakes age and are filled in with sediments but only over centuries (Carpenter 1981). However, human activities such as food production and energy production have greatly improved nutrients inputs which accelerated the eutrophication process (Chislock et al. 2013; Erisman et al. 2013; Smil 2000). Generally, nitrogen and phosphorus are most concerned nutrients in the eutrophication issues. Although there is a debate on whether one or both nutrients should be controlled to reverse the detrimental effects of eutrophication of lakes (Conley et al. 2009; Griere and Gilles 1972; Paterson et al. 2011; Schindler 1971, 1980; Scott and McCarthy 2010; Wang and Wang 2009), the importance of phosphorus in eutrophication abatement of freshwater is well recognized (Elser et al. 2007) and reducing phosphorus is supposed to be a priority step in mitigating eutrophication freshwater lakes (Schindler et al. 2008).

Major advances in scientific understanding and management of phosphorus relevant eutrophication in lake ecosystems have been made since the 1960 s. It is important to investigate the research status and emerging trend of the area. In 1998, Correll (1998) firstly published a review on the role of phosphorus in the eutrophication of receiving waters, focusing on the relationship between nutrient concentrations and eutrophication in rivers, lakes, and estuaries. More than a decade has passed, publication of the topic has increased by about 85 % in 2013 and we believe analysis of these new outputs is significant to better understand this research area. Another research of interest is conducted by Yi and Jie (2011), who examined a research trend related to eutrophication using a bibliometric method. Since this research mainly focuses on the general eutrophic issues in all aquatic ecosystems, the study of phosphorus in eutrophic lakes is largely unexplored. Considering enhanced human-induced nutrient inputs to natural environment, eutrophication in lakes is supposed to be more serious in the coming future (Carpenter 2005). Phosphorus, the most concerned nutrient in eutrophic freshwater lakes, is of particular significance to environmental management and sustainability.

In this paper, a bibliometric analysis of phosphorus studies that are associated with eutrophication issues in lakes is firstly presented. The main objectives are to assess the current and potential future of the topic using the bibliographic statistics by analyzing publications, keywords, and countries. We provide an overview of phosphorus researches in eutrophic lakes for displaying bibliometric maps. The main districts and hotpots in the topic were then elaborated by frequency and co-occurrence analysis. To identify research focus in different areas, two typical countries from developed and developing countries were compared in terms of publications, keywords and total citations. Finally, records of both phosphorus and nitrogen in eutrophic lakes are analyzed from the perspective of co-occurrence in publications and spatial distribution to examine the role of both nutrients in eutrophication control of lakes. This study will serve as a reference to understand the state of phosphorus in eutrophic lakes and its emerging topics.

Materials and methods

Data sources

Science Citation Index Expanded (SCI-Expanded) is a well-known multidisciplinary database in natural sciences, covering over 6,650 notable journals across 150 scientific disciplines. Because of its comprehensiveness and high quality, the SCI-Expanded database is widely used in a variety of disciplines for bibliometric research (Cao et al. 2013; Ho 2013; Monge-Najera and Ho 2012; Zhi and Ji 2012). The topic of this study is related to phosphorus in eutrophic lakes, which is mainly involved with subjects in environmental sciences, marine freshwater biology, water resources, ecology and limnology. Most top journals of these subjects are included in the SCI-Expanded database, such as Nature, Science, Proceedings of the National Academy of the Sciences of the United States of America, Environmental Science & Technology, Water Research, and Limnology & Oceanography. In this study, we use the SCI-Expanded databases of the Web of Science from Thomson Reuters to conduct the phosphorus research in eutrophic lakes.

In bibliometric study, selection of filter has an important influence on data, and careless use of filter may lead to inaccurate results and misleading conclusions (Chuang and Ho 2012). Main concerns in selecting filters are defining synonymous and abbreviated keywords. To avoid underestimating data, the effect of synonymous and abbreviated keywords on data is assessed before selecting appropriate filters. In this study, the words “phosphorus”, “eutrophication” and “lake” were used as main filter words. For the keyword “phosphorus”, “p” and “phosphate” are mostly related; for “eutrophication”, its adjective form “eutrophic” is often used to reflect eutrophication issues; for “lake”, we consider “reservoir” as its synonymous since they share a lot in common in natural regime and characteristics of eutrophication processes (Holddren et al. 2001). The results of searched records using different filters are showed in Table 1. Compare to the first filter which used basic keywords without synonymous or abbreviated forms, introduction of “phosphate” and “reservoir” in filter conditions has little effect on data while introduction of “p” and “eutrophic” increased the data by 11 and 46 % respectively. Thus, inclusion of alternative words may contribute a more accurate result and conclusions. However, add “p” to the filter may bring uncertainty in the data because “p” may indicate statistical significance level as well, such as “ $p < 0.05$ ”. In the 270 “p” exclusive publications, “p” works as significance level sign in 95 times. Furthermore, most the “p” exclusive articles focus on “phytoplankton” and “macrophytes” research. Thus, we don’t use “p” as a keywords in this study. Given the above, the search function in this study is defined as “TS = (phosphorus OR phosphate) AND TS = (eutrophication OR eutrophic) AND TS = (lake OR

Table 1 Comparison of number of publications using different filters

No.	Filter ^a	Records	Difference to I (%)
I	TS = (phosphorus AND eutrophication AND lake)	2,437	0
II	TS = (phosphorus OR phosphate) AND TS = (eutrophication AND lake)	2,554	5
III	TS = (phosphorus OR p) AND TS = (eutrophication AND lake)	2,707	11
IV	TS = (phosphorus AND lake) AND TS = (eutrophication OR eutrophic)	3,552	46
V	TS = (phosphorus AND eutrophication) AND TS = (lake OR reservoir)	2,558	5

^a All results are from SCI-Expanded database from 1900 to 2013

reservoir) AND PY = (1900–2013)”. TS stands for topic words which incorporate title, abstract and key words in Web of Science. To obtain publications in nitrogen research field, a filter “TS = (nitrogen OR nitrate OR ammonia) AND TS = (eutrophication OR eutrophic) AND TS = (lake OR reservoir) AND PY = (1900–2013)” is applied in the SCI-Expanded databases.

Data analysis

Main analysis used in this study is frequency calculation, co-occurrence analysis, correlation analysis, and spatial mapping. Frequency calculation is used to figure out important research areas and topics by counting words of interest, such as keywords, author names or country names. In this study, frequency analysis is conducted using BibExcel 1.0.0.0 and HistCite™ 12.03.17. BibExcel is developed by Persson et al. (2009) for bibliometric analysis. Data downloaded from Web of Science can be read by BibExcel and then be used for citation analysis, co-occurrence analysis, and frequency analysis. The software is very flexible in data format and allows users to interact in any step during the analysis. HistCite, short for history of citations (Thomson Reuters, Philadelphia, PA, USA; <http://www.histcite.com>), is a free bibliometric toolbox with a powerful function in output analysis and citation-based analysis (Garfield et al. 2006). The HistCite software has been widely used for identifying key authors, journals, countries, and research fields in multiple disciplines (Bornmann and Marx 2012; Garfield and Pudovkin 2003; Garfield et al. 2002, 2003, 2010; Rajagopal et al. 2013). In this study, HistCite was mainly used as a tool to identify high frequency countries, keywords, and citations and calculate citations. Correlation analysis was performed by Office Excel 2013. Graph making for cooperation analysis and spatial distribution is performed by Pajek 1.0.0.1 (De Nooy et al. 2005) and ArcGIS 9.3.

The relationship between nitrogen and phosphorus is assessed by an index called percent of common publications, which is suggested in the study. The index is calculated using the following formula:

$$PC = \frac{PP \cap PN}{PP \cup PN} \quad (1)$$

where PC is percent of common publications; PP and PN indicate publication sets in phosphorus and nitrogen areas respectively; \cap and \cup indicate set symbol for intersection and union. The higher the value of PC , the closer relationship between the two nutrients research.

Results and discussion

Basic information of document for analysis

A total of 3,916 publications in 12 document types were found in the SCI-Expanded databases using the search words mentioned above. The dominant document type is articles (3,763) comprising 96 % of the total documents, followed by proceedings papers (436; 11 %) and reviews (110; 3.0 %). The other nine categories represented <0.5 % in each item. This distribution pattern of documents types is similar to other bibliometric research in nutrients and eutrophication using the Web of Science database (Gao and Guo 2014; Yi and Jie 2011), which is why articles are most chosen for bibliometric analysis. Considering the representativeness and impact of publications, records from the document types of

articles, reviewer, and letter were chosen as data for analysis in this study. As a result, there are a total of 3,875 publications selected which represent work by 8,422 authors, 523 journals and 105 countries or districts. These 3,875 publications were then downloaded in the bibliographic style of Web of Science with information in title, author, publication year, country name, author keywords, keywords plus, citations, and references. Based on the information, current status and potential future of phosphorus research in eutrophic lakes from 1900 to 2013 were studied.

Temporal trend of publication output

Temporal change of publication is usually used to examine the history and potential future of a specific topic. The publications collected in this study span from 1971 to 2013. Because abstracts are not available in the SCI-Expand databases before 1991, the publications found before that year are often underestimated and are not comparable to other years. Although most researchers tend to discard that period by using the research period starting from 1991, data from 1971 and 1990 were included in this study but presented by one aggregated value in the figure to avoid the over interpretation of unrealistic results (Fig. 1). Over the studied period, a significant uptrend in the number of publications was found, increasing from 80 in 1971–1990 to 353 in 2013. The trajectory of annual publication was perfectly fitted by an exponential curve ($R^2 = 0.93$; $p < 0.0001$), indicating that the topic in this study is in the stage of rapid development and shows a promising future. Compared to publications in eutrophic lakes searched by “TS = (eutrophication OR eutrophic) AND TS = (lake OR reservoir) AND PY = (1900–2013)”, annual records from the topic in this study is proportional to the research of eutrophic lakes, making up about 40 % of the publications. The stable proportion of phosphorus research in eutrophic lakes may suggest that the importance of phosphorus in eutrophication of lakes has not faded over time. To assess the influence of these publications, the age-weighted citation

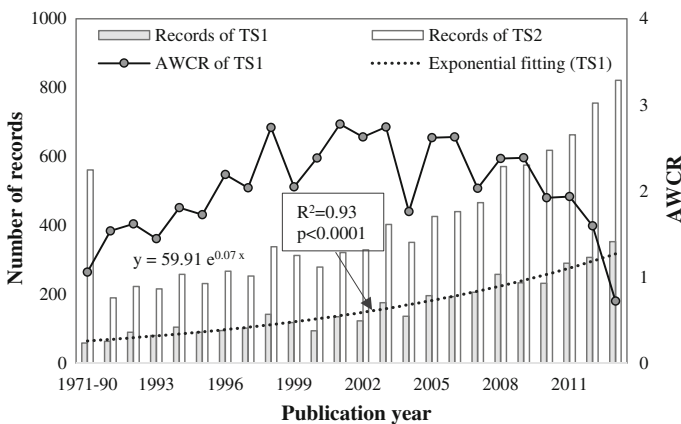


Fig. 1 Temporal change of publications and citations between 1971 and 2013. (a) TS1 refers to publications collected by research function: “TS = (phosphorus OR phosphate) AND TS = (eutrophication OR eutrophic) AND TS = (lake OR reservoir) AND PY = (1900–2013)”, (b) TS2 refers to publications collected by research function: “TS = (eutrophication OR eutrophic) AND TS = (lake OR reservoir) AND PY = (1900–2013)”, (c) AWCR refers to age-weighted citation rate, where the number of citations to a given paper is divided by the age of that paper

rate (AWCR; Harzing, A.W. 2007 Publish or Perish, available from <http://www.harzing.com/pop.htm>) was firstly included in temporal analysis of publications. The AWCR is adjusted from AR-index (Jin et al. 2007) to measure the average number of citations to a publication divided by the age of the paper. Different from average citations per year or average citations per article, the AWCR is a more effective index for assessing the influence of publication because it eliminates the influence of time and quantity in citation calculation. From 1971 to late 1990s, the AWCR is growing steadily, rising from approximately 1 to over 2. This period demonstrates the growing influence of this research topic. The value of AWCR becomes relatively stable over the first decade in the twenty first century, around 2.3, indicating the coming of a relatively mature development period. Although there is an obvious decreasing trend of AWCR since 2010, the decline of AWCR in the last 5 years may result from the short age of these publications. Overall, research on phosphorus in eutrophic lakes has clearly been a hot topic with a rapid increase trend. Considering the publications in the topic is in its relatively primary development stage, this study is supposed to attract more researchers' interest and be more productive in the foreseeable future.

National publication performance and cooperation

The records of different countries/territories were estimated by the address information of at least one author of the published article using the HistCite tool. There are a total of 105 countries/territories represented in the 3,875 articles. Top 20 with the most publications was showed in Table 2, accounting for over 90 % of the total publications. It is not a surprise that the USA ranked first in terms of the number of articles, TLCS (total local citations score), and TGCS (total global citations score), which repeats itself many times in other research (Gao and Guo 2014; Ho 2013; Yi and Jie 2011). Another expected phenomenon found in this study is the absolute dominance of developed countries (countries in North America and Europe) in this top productive list. Among the 20 countries, China is the only country with GDP per person lower than \$10,000 (\$6,091 in 2012). In the quality of publications as assessed by the LCSA (local citation score per publication) and GCSA (global citation score per publication), Denmark, Sweden, the USA, Canada, the UK, and Norway were in the leading position, suggesting their substantial influence in this field. Although some highly productive countries enjoy large citations, the relationship between quantity and quality of publications is very complex and no statistically significant linear relationship exists between records and citations in the top 20 countries (Fig. 2). Three countries were found outside the main field of relationships. Denmark is the highest citation per publication country with relatively small number of articles. China is opposite to Denmark, which is high in quantity but low in citations. The USA is kind of in the middle ground, ranking high in both quantity and quality. Compared to bibliometric research in eutrophication (Yi and Jie 2011) and nitrogen (Gao and Guo 2014), publications in China and Canada are more significant in this study.

Regionalization is a common phenomenon in international cooperation of scientific research. To capture important information about international cooperation, 34 countries with more than 20 articles were chosen as study samples, which were firstly grouped into different clusters in BibExcel program with an algorithm developed by Persson (1994) and then graphed by Pajeck program (Fig. 3). In this figure, each circle represents a country. The size of the circle is the total publications produced from a country and the width of link refers to cooperation in terms of papers produced by authors from two countries, while the color identifies its group. As the figure shows, there are five regional groups varying in size

Table 2 Top 20 most productive countries publishing articles on topic of interest from 1971 to 2013

Country	Number of articles	Percentage	TLCS ^a	TGCS ^b	LCSA ^c	GCSA ^d
USA	889	22.9	3,988	25,028	4.5	28.2
Peoples R China	563	14.5	1,264	4,763	2.2	8.5
Canada	327	8.4	1,839	8,566	5.6	26.2
UK	277	7.1	1,847	7,239	6.7	26.1
Germany	223	5.8	976	3,838	4.4	17.2
Netherlands	167	4.3	807	3,767	4.8	22.6
Sweden	160	4.1	907	4,572	5.7	28.6
Denmark	142	3.7	1,795	5,918	12.6	41.7
Finland	127	3.3	496	2,394	3.9	18.9
Japan	114	2.9	191	1,602	1.7	14.1
France	109	2.8	422	2,027	3.9	18.6
Poland	109	2.8	181	899	1.7	8.2
Spain	108	2.8	311	1,711	2.9	15.8
Brazil	96	2.5	215	1,223	2.2	12.7
Australia	86	2.2	212	1,395	2.5	16.2
Switzerland	81	2.1	380	1,653	4.7	20.4
Italy	73	1.9	255	1,364	3.5	18.7
New Zealand	57	1.5	208	744	3.6	13.1
Turkey	54	1.4	109	481	2.0	8.9
Norway	49	1.3	230	1,207	4.7	24.6

^a TLCS refers to total local citations score, which is used to measure how many times the author’s paper included in this collection have been cited by other papers also in the collection

^b TGCS refers to total global citations score, which is calculated from the times cited score retrieved from the Web of Science

^c LCSA is local citation score per publication, which is the TLCS divided by the total number of publications

^d GCSA is global citation score per publication, which is the TGCS divided by the total number of publications

of countries and publications. The largest group in terms of number of countries is the group around the UK with 15 countries, followed by the USA centered group (7), Sweden centered group (5), China centered group (5), and German centered group (4). However, the group around the USA has the largest number of publications with 1,355 articles in total. Furthermore, the most significant connection among cooperating countries are also found in the USA centered group. The USA-Canada collaborations ranked first, with 61 cooperation articles, followed by USA-China (60). Compared to nitrogen research at watershed scales in which the USA is the center of international cooperation web (Gao and Guo 2014), it is clear that phosphorus research in eutrophic lakes is more disperse in geographic distribution. In this study, collaborative countries are more geographic correlated since most countries in each group are adjacent to each other.

The USA and China are the top two countries in terms of publications from 1971 to 2013, making up 23 and 15 % of global articles. However, the socioeconomic and natural conditions in the two countries differ quite a lot from each other. The USA is a typical developed country with GDP per capita of \$49,965 (2012) while China is a typical

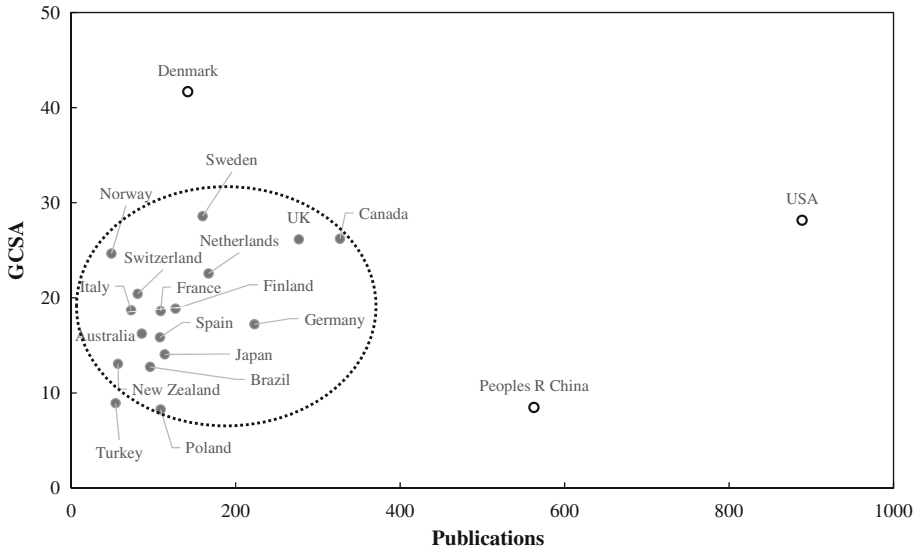


Fig. 2 Relationship between publications and GCSA in top 20 productive countries. (a) GCSA is global citation score per publication, which is the TGCS divided by the total number of publications

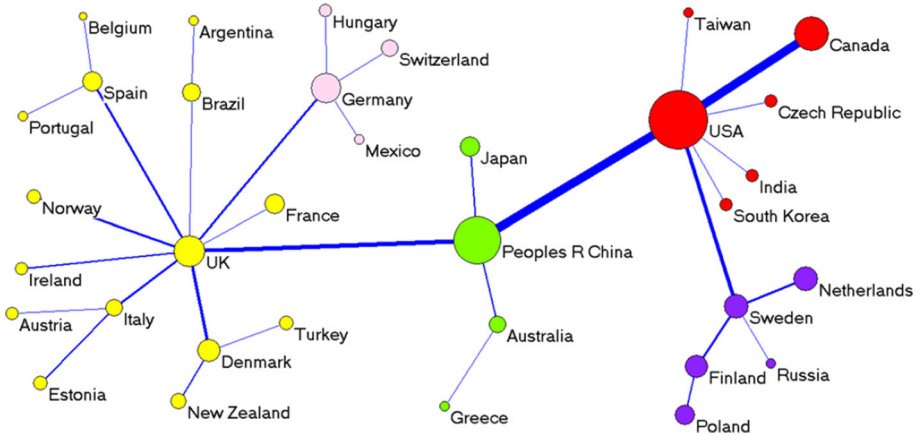


Fig. 3 Country cooperation network among countries with more than 20 publications

developing country with GDP per capita of \$6,091 (2012). Furthermore, water resources per capita in China is 2,093 m³ in 2011, only 23 % of the USA (9,044). The vast difference between these two countries may present as a good case study for comparing the characteristics of eutrophic research in developed and developing countries. Annual publication and average citations per paper is showed in Fig. 4. It is clear that the USA has a much longer history of research in this topic than China. The USA published its first paper in 1974 and it is 18 years later that China has its first paper. However, publications in China has increased rapidly since 2000 and exceeded the USA in 2011 becoming the most productive country in the world in this area. This rapid increase of publications in China

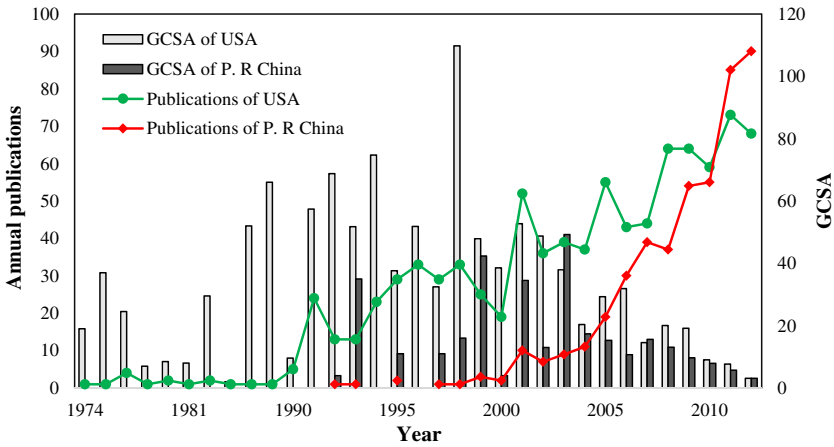


Fig. 4 Annual publications and citations of USA and China over 1974 and 2013. (a) GCSA is global citation score per publication, which is the TGCS divided by the total number of publications

Table 3 The 20 most frequent title words, author keywords and keywords plus from 1971 to 2013^a

Rank	Title words	Author keywords	Keywords plus
1	Sediment	Sediment	Phytoplankton
2	Nutrient	Nutrient	Sediment
3	Shallow	Nitrogen	Nitrogen
4	Effect	Model	Shallow
5	Phytoplankton	Quality	Community
6	Model	Phytoplankton	Nutrient
7	Quality	Load	Fresh
8	Change	Restoration	Release
9	China	Management	Quality
10	River	Cyanobacteria	Ecosystem
11	Community	Shallow	Dynamics
12	Nitrogen	Macrophyte	River
13	Load	Diatom	Organic
14	Response	River	Growth
15	Dynamics	Chlorophyll	Limitation
16	Impact	Bloom	Model
17	Ecosystem	Zooplankton	Zooplankton
18	Management	Wetland	Macrophyte
19	Concentration	Algae	Soil
20	Release	Internal	Marine

^a All keywords related to filters, such as “lake”, “eutrophic”, and “phosphorus” are not included in this table

may be the result of both growing investment in science research and deteriorating eutrophication issues (Le et al. 2010). When it comes to quality of publications, the gap between China and the USA is obvious in terms of average citations per paper. Therefore,

it is still too early to say that China has risen as a global leader in this research field, apparently quantity is being favored over quality in China.

Keywords frequency and future trends

Title words, author keywords, and keywords plus describe the main topics of the articles and are often selected to analyze the hotspots and emerging trends in scientific research. In this study, 5,347 title words, 4,177 author keywords, and 5,510 keywords plus were found in the 3,875 publications. Since the existing of equivalent words or different forms for many keywords, top 200 keywords were standardized manually before frequency analysis. For example, “model”, “models”, “modelling” and “modeling” were all aggregated to “model”. Using the standard keywords, the top 20 most frequent keywords in title words, author keywords, and keywords plus were showed in Table 3. Generally, “sediment”, “nutrient”, “nitrogen”, “shallow”, “phytoplankton”, “model”, “quality”, and “river” were the most popular keywords, implying that the research is mainly concentrated on nutrient sources, water quality index, quantitative simulation, and shallow lakes. It is interesting that “sediment” rank top in all the three types of keywords list, which suggests that sediment in lake was most attractive topic of study. One possible reason is that sediment is considered to play a significant role in the process of eutrophication of lakes. It is well documented that phosphorus recycled from sediment can hinder the effect of eutrophication control measures, leading to persistent high eutrophic status in lake (Mehner et al. 2008; Sondergaard et al. 2003, 2013). The high frequency of the keyword “nitrogen” implies the importance of nitrogen in eutrophication research although there is a debate on whether nitrogen should be controlled to mitigate eutrophication (Moss et al. 2013; Schindler et al. 2008; Scott and McCarthy 2010; Wang and Wang 2009).

To investigate the potential future of the studied area, 12 title words ranking top 20 at a three years basis from 1971 to 2013 were used and temporal change of records are graphed (Fig. 5). Overall, there is an obvious increase for all the studied keywords since 2000. However, keywords “sediment”, “nutrient”, “effect”, and “quality” have increased significantly, which suggests that research on these topics is expanding. In contrast, the number of articles with the other keywords has been quite flat or even decreased in recent

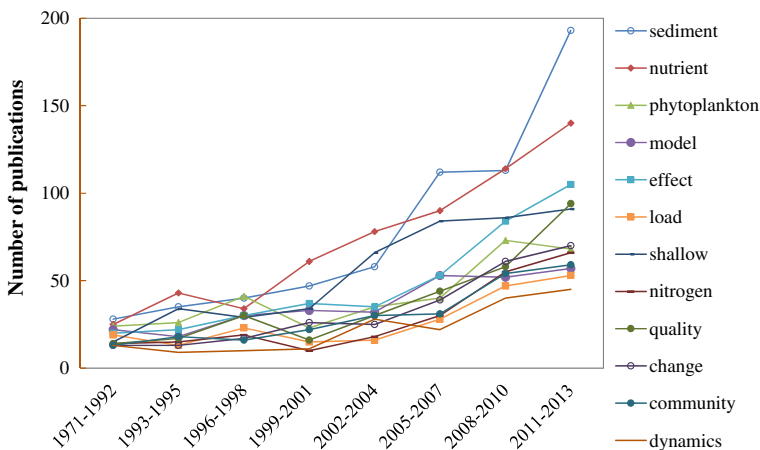


Fig. 5 Temporal change of for the key 12 title words from 1971 to 2013

years, suggesting a stable research status. The absolute dominance of sediment and nutrient in this trend may imply that controlling nutrient sources especially internal source is still the priority question in eutrophic lake research. The rapid increase of keyword “effect” suggests that research on interactions of eutrophication and other relevant factors may become more and more popular in the future.

Comparison with nitrogen research in eutrophic lakes

As the keywords analysis suggests, phosphorus and nitrogen are the two most concerned nutrients in eutrophication research. We try to analyze the relationship between these two nutrients in terms of spatial distribution and shared publications. A total of 2,539 publications in nitrogen research were obtained by using filter “TS = (nitrogen OR nitrate OR ammonia) AND TS = (eutrophication OR eutrophic) AND TS = (lake OR reservoir) AND PY = (1900–2013)” in the SCI-Expanded databases. The number of publications in nitrogen is only 66 % of that in phosphorus, indicating that phosphorus is more concerned than nitrogen in eutrophic lakes. However, a significant linear relationship ($R^2 = 0.98$; $p < 0.0001$) is found between publications in phosphorus and publications in nitrogen among different countries (Fig. 6). Therefore, there is no substantial difference in nitrogen and phosphorus study of eutrophic lakes among different regions in the world. To further investigate the relationship between these two nutrients, the trend of percent of common papers in the nitrogen and phosphorus areas is presented (Fig. 7).

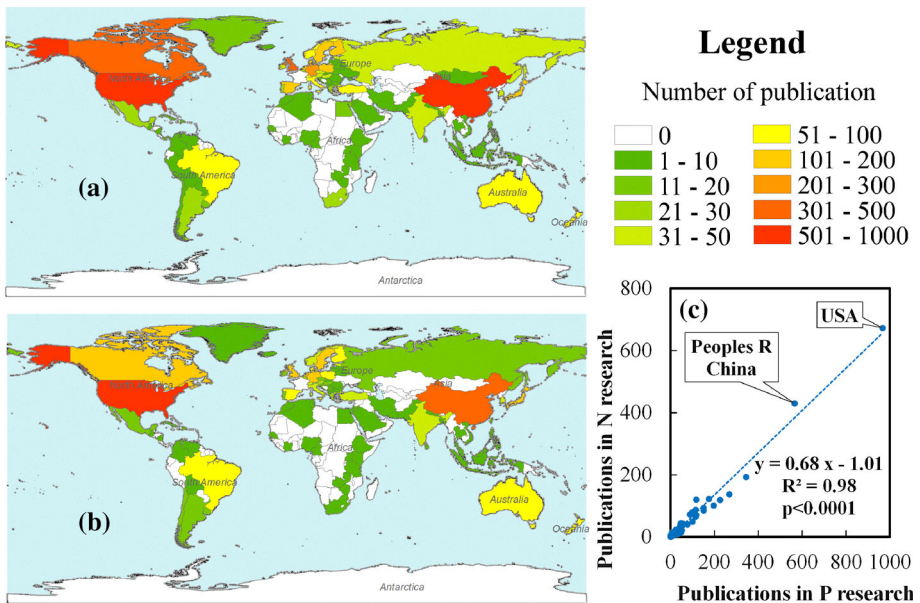


Fig. 6 Publications in phosphorus research and publication in nitrogen research. (a) Publications searched by TS = (phosphorus OR phosphate) AND TS = (eutrophication OR eutrophic) AND TS = (lake OR reservoir) AND PY = (1900–2013); (b) publications searched by TS = (nitrogen OR nitrate OR ammonia) AND TS = (eutrophication OR eutrophic) AND TS = (lake OR reservoir) AND PY = (1900–2013); (c) linear relationship between publications in phosphorus and nitrogen research

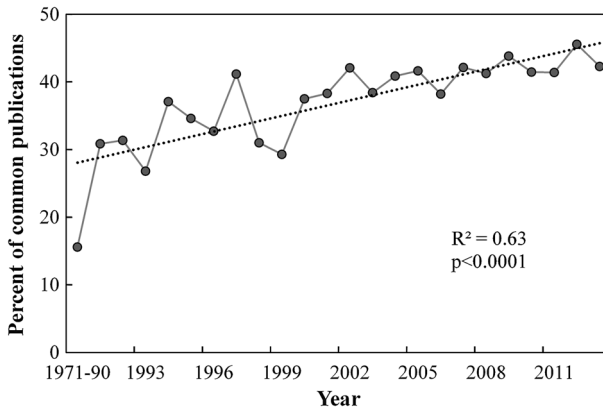


Fig. 7 Trajectory of proportion of common publications in nitrogen and phosphorus research field over time

PC has increased from 16 to 42 % over the studied period. A significant linear increase trend ($p < 0.0001$) is observed, indicating that co-occurrence of nitrogen and phosphorus is becoming more and more common. This increase trend may also suggest that both nitrogen and phosphorus are important for eutrophication control in lakes, which is consistent with previous studies (Elser et al. 2007; Moss et al. 2013).

Conclusions

Research of phosphorus in eutrophic lakes was assessed from the perspective of bibliometric analysis from 1900 to 2013. Using the SCI-Expand databases, a total of 3,875 publications was found from selected filters and document types, representing work by 8,422 authors, 523 journals and 105 countries or districts. Over the research period, publications in this area have increased with an exponential trend, and its share in research area of eutrophic lakes is quite stable, indicating a promising future. A country basis analysis suggested that the USA and China are the most productive countries, and China has replaced the USA as the top countries in this area since 2011. However, the USA ranks high in both quantity and quality while China favors more quantity than quality, which indicates a biased development of research in China. The frequency analysis on keywords from title words, author keywords, and keywords plus presents that “sediment”, “nutrient”, “nitrogen”, “shallow”, “phytoplankton”, “model”, “quality”, and “river” were most popular, implying that the research is mainly concentrated on nutrient sources, water quality index, quantitative simulation, and shallow lakes. In the foreseeable future, controlling nutrients sources especially internal source is still the priority question in eutrophic lake research while research on interactions of eutrophication and other relevant factors may become more and more popular. In terms of publications, phosphorus research clearly outnumber nitrogen research in eutrophic lakes, working as the dominant nutrient in eutrophication study. However, nitrogen is a top keyword in phosphorus research and it is highly correlated to phosphorus in spatial distribution. Furthermore, the shared publications in both phosphorus and nitrogen research is growing linearly ($p < 0.0001$) during the research period. Although there is a debate on the role of nitrogen in eutrophication, the

bibliometric analysis in this study suggest that both nitrogen and phosphorus are important for eutrophication control in lakes.

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