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Review

A bibliometric review of nitrogen research in eutrophic lakes and reservoirs

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ABSTRACT

The global application of nitrogen is far greater than phosphorus, and it is widely involved in the eutrophication of lakes and reservoirs. We used a bibliometric method to quantitatively and qualitatively evaluate nitrogen research in eutrophic lakes and reservoirs to reveal research developments, current research hotspots, and emerging trends in this area. A total of 2695 articles in the past 25 years from the online database of the Scientific Citation Index Expended (SCI-Expanded) were analyzed. Articles in this area increased exponentially from 1991 to 2015. Although the USA was the most productive country over the past 25 years, China achieved the top position in terms of yearly publications after 2010. The most active keywords related to *nitrogen* in the past 25 years included *phosphorus*, *nutrients*, *sediment*, *chlorophyll-a*, *carbon*, *phytoplankton*, *cyanobacteria*, *water quality*, *modeling*, and *stable isotopes*, based on analysis within 5-year intervals from 1991 to 2015 as well as the entire past 25 years. In addition, researchers have drawn increasing attention to *denitrification*, *climate change*, and *internal loading*. Future trends in this area should focus on: (1) nutrient amounts, ratios, and major nitrogen sources leading to eutrophication; (2) nitrogen transformation and the bioavailability of different nitrogen forms; (3) nitrogen budget, mass balance model, control, and management; (4) ecosystem responses to nitrogen enrichment and reduction, as well as the relationships between these responses; and (5) interactions between nitrogen and other stressors (*e.g.*, light intensity, carbon, phosphorus, toxic contaminants, climate change, and hydrological variations) in terms of eutrophication.

Contents

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Introduction

Both nitrogen and phosphorus are required to support aquatic plant growth and are the key limiting nutrients in most aquatic and terrestrial ecosystems (Conley et al., 2009; Glibert et al., 2005; Ma et al., 2015). However, nitrogen has received far more attention because it limits primary production and its global application (form synthetic fertilizers) is far greater than phosphorus (Glibert et al., 2005). The anthropogenic addition of reactive nitrogen to aquatic systems from fertilizer use, crop nitrogen fixation, urban and agricultural nitrogen wastes, atmospheric nitrogen deposition, fossil fuel combustion and other sources has increased in recent decades (Finlay et al., 2013; Galloway et al., 2004; Liu et al., 2011; Mulholland et al., 2008; Paerl et al., 2014a). The excessive input of nitrogen into aquatic systems may fuel excessive rates of plant growth and lead to eutrophication, which refers to the nutrient enrichment of water (Seitzinger, 2008). The most common effects of nutrient enrichment in aquatic systems are manifested as increases in the abundance of algae and aquatic plants (Smith et al., 1999). However, the effects of nutrient enrichment are more serious and complex. Many studies have shown that eutrophication was one of most important factors contributing to the expansion of some harmful algal blooms (HABs), especially cyanobacterial blooms (Anderson et al., 2002; Paerl and Huisman, 2009). Some cyanobacterial species form massive surface growths that produce toxins, cause oxygen depletion, alter food webs, and lead to deteriorated water quality (Paerl and Huisman, 2009; Smith, 1998; Smith et al., 1999; Ye et al., 2011). The consequences of cyanobacterial blooms may pose a major threat to the drinking and irrigation water supply (Paerl and Huisman, 2009). For example, the drinking water crisis in Wuxi City in May 2007 was caused by massive cyanobacterial blooms around the drinking water source, which caused 2 million local residents to be without water for a week (Liu et al., 2011; Qin et al., 2010; Yang et al., 2008; Zhang et al., 2010b).

Several reviews have discussed the relationships between the nitrogen dynamics (enrichment, sources, composition, transformation) and eutrophication, especially harmful cyanobacterial blooms (Anderson et al., 2002; Conley et al., 2009; Glibert et al., 2005; Smith et al., 1999). Due to the limited literature, it is still difficult to gain a comprehensive understanding of the research hotspots of the past and the emerging trends of nitrogen research in eutrophic lakes or reservoirs. Bibliometrics, first introduced by Pritchard (1969), utilizes quantitative analysis and statistical methods to describe the characteristics of articles (*e.g.*, yearly publication, title, authors, institutions, and keywords) within a given topic or field (Fu et al., 2013). These methods have been widely used to analyze research development, current research hotspots, and future trends in specific fields, such as particulate matter and health (Feifei et al., 2016; Jia et al., 2013), climate change (Li et al., 2011), drinking water (Fu et al., 2013; Hu et al., 2010), carbon cycling (Zhi et al., 2015), estuary pollution (Sun et al., 2012), aquatic ecosystems (Liao and Huang, 2013), and remote sensing (Zhuang et al., 2012). Yi and Jie (2011) conducted a bibliometric analysis related to eutrophication, and they mainly focused on general eutrophic issues, in which the role of nitrogen was not thoroughly analyzed. Gao et al. (2015) examined a research trend related to phosphorus research in eutrophic lakes. Although they found that publications about phosphorus were significantly correlated with publications about nitrogen in various countries, the total publications and research focuses differed from nitrogen to phosphorus. Fundamental differences exist between nitrogen cycling and phosphorus biogeochemical processes. For example, transformations between different nitrogen forms were more complex than those of phosphorus, including nitrogen fixation, nitrification, denitrification, anammox, among others. Because of the increased nitrogen input (mainly anthropogenic) to lakes and reservoirs over the past decades, the eutrophication issue may become more difficult to resolve. It is important to investigate the development, current research hotspots, and future tendencies of nitrogen relevant to eutrophication of lakes and reservoirs to provide a better understanding of the global research status.

In this study, we conducted a bibliometric analysis and historical review of nitrogen research in eutrophic lakes and reservoirs. The aims of this study were to 1) quantitatively and qualitatively summarize the characteristics of yearly publication output, subject categories, mainstream journals, leading countries and institutions, 2) reveal the current hotspots related to nitrogen research, and 3) discuss research tendencies to provide a potential guide for nitrogen research.

1. Data and methodology

1.1. Data

The data used in this study were based on the online database of the Scientific Citation Index Expanded (SCI-Expanded) of the Web of Science from Thomson Reuters on March 2, 2016.

SCI-Expanded is a well-known multidisciplinary database in natural science, covering 8659 notable journals across 176 Web of Science categories according to the Journal Citation Reports (JCR) of 2014. Because no abstracts were indexed in articles before 1991, only articles published beginning 1991 were discussed. The search function was defined as "TS = nitrogen AND TS = eutroph* AND TS = (lake* or reservoir*)," and the publication years of 1991 to 2015 were chosen. For the country analysis, publications from England, Scotland, North Ireland, and Wales were sorted to the UK, and publications from Hong Kong, Macao, and Taiwan were not sorted to China. The impact factor (IF) of each journal was obtained from the JCR. A publication was designated as internationally collaborative if the paper was co-authored by researchers from more than one country.

All articles referring to nitrogen research in lakes or reservoirs during the past 25 years were assessed for the following characteristics: document types and languages, publication outputs, subject categories, authors, journals, countries, institutions, and author keywords. The research status and future development trends were analyzed using the author keywords, which contain the most critical information, such as research topics and methodologies related to nitrogen.

1.2. Analysis method

A frequency calculation, a citation analysis, a co-occurrence analysis, a correlation analysis and graphing were conducted in this study. Frequency calculations are widely used in bibliometrics to investigate research hotspots by counting words of interest (*e.g.*, keywords). In this study, the frequency calculation was conducted using HistCite™ 12.03.17 (Thomson Reuters Co., Philadelphia, PA, USA) and Thomson Data Analyzer (TDA, Thomson Reuters Co., New York, NY, USA). The citation analysis and the co-occurrence analysis were conducted using HistCite and TDA, respectively. The correlation analysis and general data manipulation were conducted using Excel 2016 (Microsoft Co., Redmond, Washington, USA). The visualized network graph was prepared using Ucinet 6.0 software (Analytic Technologies Co., Lexington, KY, USA). HistCite, which is widely used to identify key authors, institutions, journals, countries, and research fields, is a powerful software tool for output analysis and citation-based analysis (Garfield et al., 2006). In this study, HistCite was used for identifying yearly outputs, key countries, institutions, authors, journals, languages, and citations and to calculate citations. TDA, which offers an efficient and accurate automatic data cleaning tool (Feifei et al., 2016), was used to process data cleaning, the bibliographic information analysis, and the co-occurrence analysis. Ucinet is considered the most popular social network analysis software and features a strong matrix analysis function (Feifei et al., 2016). Network graphs generated by Ucinet visualize complex links and relationships among different terms (*e.g.*, keywords, authors, and countries).

A co-occurrence analysis is a basic and important approach for the exploration of themes (Feifei et al., 2016). In this study, co-occurrence frequency matrices were created based on keywords, countries, and publication years using TDA. Frequency matrices were subsequently visualized using Ucinet or Microsoft Excel 2016. Since many keywords had different forms with the same meaning, the keywords were standardized manually before frequency analysis using TDA. For example, *sediment*, *sediments*, *surface sediments*, and *lake sediment* were all aggregated into *sediment*.

2. Results and discussion

2.1. Performance of publication

2.1.1. Document type, yearly output, language of publications and citations

Nine document types were identified among a total of 2783 publications over the past 25 years. Article (2471) was the most common document type, comprising 89% of the total publications, followed by proceeding papers (224; 8%) and reviews (67; 2%). Other document types included editorials (12), notes (3), letters (2), meeting abstracts (2), reprints (1) and book chapters (1). Because peer-reviewed journal articles comprised the majority of the document types and contain original work by scientists around the world, only 2695 original articles (2471 published papers plus 224 proceedings papers) were used for further analysis. The yearly and cumulative publication number of peer-reviewed journal articles increased exponentially from 1991 to 2015 (Fig. 1a). Yearly articles increased from 35 in 1991 to 285 in 2015. The number of citations by publications in Web of Science was highest in 1998 (Fig. 1b, 4342); the number of citations per article by other papers in the present collection (6) and Web of Science (63) were also highest in 1998.

Of 2695 journal articles, a total of 2661, or 98.7%, were published in English. The other eight languages found were Polish (12; 0.45%), Spanish (9; 0.33%), Portuguese (4; 0.15%), Japanese (3; 0.11%), French (2; 0.07%), German (2; 0.07%), Chinese (1; 0.04%) and Turkish (1; 0.04%). Thus, English was the predominant language in academic publications on nitrogen research.

2.1.2. Web of science categories and journals

The Institute for Scientific Information (ISI) grouped the publications on nitrogen research into 55 categories. Table 1 shows the top 20 subject categories in nitrogen research. The category of Environmental Sciences & Ecology encompassed the most of the 2695 articles (1331; 49.4%), followed by Marine & Freshwater Biology (1213; 45%) and Water Resources (394; 14.6%).

The 2695 articles were contained in 352 journals. Table 2 shows the 20 most active journals, which accounted for 43.3% of the total publications. *Hydrobiologia* published the most articles (243; 9%), followed by *Freshwater Biology* (105; 3.9%) and *Limnology and Oceanography* (84; 3.1%). Table 2 also shows the subject category and 5-year IF of the top 20 journals. *Journal of Environmental Sciences* is among the top 20 journals with 5-year IF ranked 9th position.

2.1.3. National publication performance and cooperation

Publications on nitrogen research from 1991 to 2015 covered 91 countries. The USA and China were the two most productive countries, contributing to 24.7% and 23.7% of the

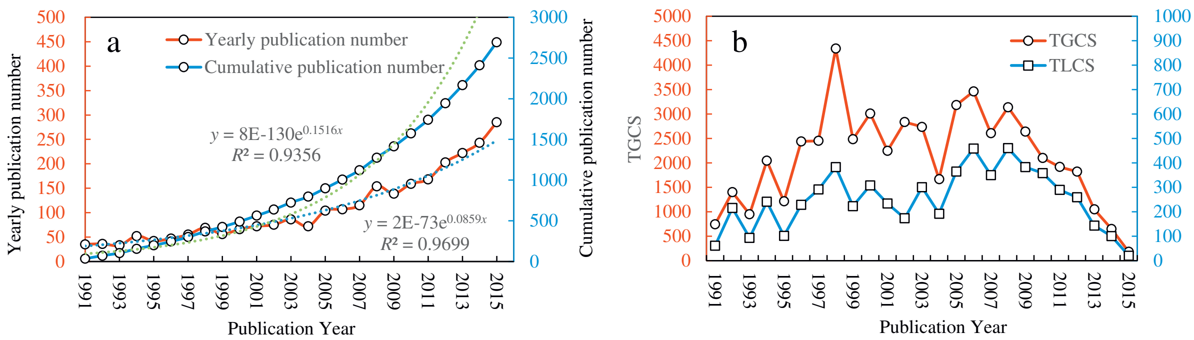

Fig. 1 – Temporal variation of publications and citations from 1991 to 2015 (a: yearly and cumulative publication number of journal articles; b: Total Local Citations Score (TLCS), which is the number of citations by other papers in the present collection, and Total Global Citations Score (TGCS), which is the number of citations by the papers in Web of Science).

total publication number (TPN) from 1991 to 2015. As for some other research fields (Gao et al., 2015; Gao and Guo, 2014), the USA had the highest TLCS (Total Local Citations Score, 2348) and TGCS (Total Global Citations Score, 19,399). Because China and Brazil were the only two developing countries, developed countries dominated the top 20 producers list. The yearly publication number of the top 10 countries is shown in Fig. 2. The yearly publication number in China exceeded that of the USA and ranked first after 2010. Yearly publication number in 2015 on nitrogen research was 64 and 144 in the USA and China, respectively. The total number of times a country's publications were cited indicates the quality of its publications. Although the yearly publications on nitrogen research in eutrophic lakes or reservoirs of China exceeded those of the USA in 2010, the quality of publications in China requires improvement. Similar to phosphorus research (Gao et al., 2015), the gap between China and the USA was large regarding citations.

International cooperation among the top 20 most productive countries was studied by a co-occurrence analysis (Fig. 3). The USA had not only the largest total number of publications but also the most connections with other countries. USA–China collaborations ranked the first with 79 cooperative articles, followed by USA–Canada (45). Within the top 20 most productive countries, the USA, China, Canada, the UK, Germany, Sweden, Netherlands, Denmark, and France were connected to more than 15 countries that had at least one co-published article. Apart from the USA, Denmark, Australia and the UK had more than 15 articles co-published with China.

The top 20 institutions were ranked by the TPN of co-published articles (Table 3). Six of these institutions were located both in the USA and China, two were located both in Canada and Finland, and one institution each was located in Denmark, New Zealand, England, and Japan. The Chinese Academy of Sciences ranked first with 11.5% of total publications, followed by the University of Florida with 2.4% of total publications. However, the Global Citation Score per Article (GCSA) was highest for the University of Wisconsin (89.8 times), followed by the University of Alberta (51.2 times). The Chinese Academy of Science was only ranked as the 15the highest in terms of the GCSA. In the top 20 most productive institutions, all institutions in China ranked last, indicating that the quality of articles in China should be improved.

2.1.4. Author distribution

An increasing number of authors published articles related to nitrogen research in eutrophic lakes or reservoirs from 1991 to 2015, with 7205 authors recorded among the 2695 articles in 2015. The number of authors per article ranged from 1 to 29, with 3 authors per article in dominance (20.2%), followed by 2 and 4 authors, which accounts for 18.6% and 17.3%. The most number of authors of a single article (29 authors) was published in *Freshwater Biology*, 2005, which conducted research on lake response to reduced nutrient loading using long-term data

Table 1 – Distributions of the subject categories (top 20).

Subject category	TPN (%)	Subject category	TPN (%)
Environmental Sciences & Ecology	1331 (49.4%)	Meteorology & Atmospheric Sciences	57 (2.1%)
Marine & Freshwater Biology	1213 (45%)	Science & Technology - Other Topics	51 (1.9%)
Water Resources	394 (14.6%)	Biotechnology & Applied Microbiology	42 (1.6%)
Engineering	303 (11.2%)	Chemistry	40 (1.5%)
Geology	229 (8.5%)	Biodiversity & Conservation	37 (1.4%)
Oceanography	209 (7.8%)	Life Sciences & Biomedicine - Other Topics	30 (1.1%)
Fisheries	114 (4.2%)	Physical Geography	28 (1%)
Agriculture	78 (2.9%)	Geochemistry & Geophysics	25 (0.9%)
Plant Sciences	75 (2.8%)	Toxicology	22 (0.8%)
Microbiology	73 (2.7%)	Biochemistry & Molecular Biology	15 (0.6%)

TPN: total publication number; percentage (%): percentage of publication number for a certain subject category to total publication number (2695).

Table 2 – Top 20 most productive journals (1991–2015) with total publication number (TPN), subject category and 5-year impact factor (IF) (2010–2014).

Journal title	TPN (%)	Subject category	5-year IF
Hydrobiologia	243 (9%)	Marine & Freshwater Biology	2.236 (14)
Freshwater Biology	105 (3.9%)	Marine & Freshwater Biology	3.826 (5)
Limnology and Oceanography	84 (3.1%)	Limnology	4.280 (3)
Canadian Journal of Fisheries and Aquatic Sciences	55 (2%)	Marine & Freshwater Biology	2.683 (10)
Water Science and Technology	55 (2%)	Environmental Sciences	1.195 (18)
Environmental Monitoring and Assessment	54 (2%)	Environmental Sciences	1.921 (15)
Lake and Reservoir Management	54 (2%)	Marine & Freshwater Biology	1.103 (19)
Ecological Engineering	51 (1.9%)	Environmental Sciences	3.223 (6)
Journal of Paleolimnology	51 (1.9%)	Environmental Sciences	2.255 (13)
Archiv Fur Hydrobiologie	48 (1.8%)	Marine & Freshwater Biology	1.481 (17)
Water Research	48 (1.8%)	Environmental Sciences	6.769 (1)
Ecological Modelling	43 (1.6%)	Ecology	2.594 (11)
Journal of Great Lakes Research	43 (1.6%)	Environmental Sciences	2.461 (12)
Science of The Total Environment	40 (1.5%)	Environmental Sciences	4.317 (2)
Fresenius Environmental Bulletin	35 (1.3%)	Environmental Sciences	0.413 (20)
Water Air and Soil Pollution	35 (1.3%)	Environmental Sciences	1.833 (16)
Environmental Science and Pollution Research	34 (1.3%)	Environmental Sciences	2.876 (8)
Journal of Environmental Sciences	30 (1.1%)	Environmental Sciences	2.699 (9)
Aquatic Sciences	29 (1.1%)	Marine & Freshwater Biology	3.164 (7)
Biogeochemistry	29 (1.1%)	Environmental Sciences	4.008 (4)

TPN: total publication number; percentage (%): percentage of publications for a certain journal to total publications number (2695); IF: impact factor; and R: rank.

(Jeppesen et al., 2005). Most authors (1950; 72%) published less than 10 articles. The top 10 most productive authors are listed in Table 4. Erik Jeppesen from Aarhus University published the most articles (45 articles), followed by Xie Ping from the Institute of Hydrobiology, Chinese Academy of Sciences (34 articles) and Qin Boqiang from the Nanjing Institute of Limnology and Oceanography, Chinese Academy of Sciences (33 articles). However, they were not the first authors of most of these articles. Xie Ping ranked first as the most frequent corresponding author with 19 articles, followed by Qin Boqiang with 16 articles. Only the publications of Qin Boqiang showed a marked increasing trend from 2009 to 2015.

2.2. Research hotspots and tendencies

2.2.1. Author keywords analysis

Author keywords contain information on current research hotspots and future research trends (Hu et al., 2010). Using author keywords in different intervals to investigate hotspots and trends has been widely conducted by others (Ho et al., 2010; Li et al., 2011; Xie et al., 2008; Zhang et al., 2010c). In this study, the 2695 articles contained 4682 author keywords. Most keywords appeared less than 3 times (4104; 88%), and only 105 keywords appeared more than 10 times. We analyzed the 50 most frequently used keywords in 5-year intervals during the past 25 years (Appendix A Fig. S1). The relationships among the keywords were complicated. Because we focused on the nitrogen research in eutrophic lakes or reservoirs for the current study, keywords related to *nitrogen* were analyzed (Table 5). All keywords included in the filters such as *eutrophication*, *lake/reservoir* were not included in the analysis. From 1991 to 1995, in addition to *eutrophication* and *lake/reservoir*, *nitrogen* had strong relationships with *phosphorus*, *nutrients*, *sediment*, *chlorophyll-a*, *primary production*, *lake restoration*, and *carbon* (the number of co-occurrences was more than 2). From 1996 to 2000, *nitrogen* had strong relationships with *phosphorus*, *nutrients*, *sediment*, *chlorophyll-a*, *carbon*, *rivers*, *zooplankton*, and *periphyton* (the number of co-occurrences was greater than 3). From 2001 to 2005, *nitrogen* was strongly related to *phosphorus*, *nutrients*, *sediment*, *carbon*, *phytoplankton*, *model*, *chlorophyll-a*, *watershed*, *estuaries*, *river*, and *oxygen* (the number of co-occurrences was greater than 3). From 2006 to 2010, *nitrogen* was strongly related to *phosphorus*, *nutrients*, *sediment*, *chlorophyll-a*, *carbon*, *cyanobacteria*, *phytoplankton*, *denitrification*, *water quality*, *climate change*, and *restoration* (the number of co-occurrences was greater than 3). From 2011 to 2015, *nitrogen* was strongly related to *phosphorus*, *nutrients*, *sediment*, *water quality*, *cyanobacteria*, *chlorophyll-a*, *carbon*, *phytoplankton*, *Microcystis aeruginosa*, *cyanobacterial blooms*, *climate change*, *land use*, and *iron* (the number of co-occurrences was greater than 4). From 1991 to 2015, *nitrogen* showed strong relationships with *phosphorus*, *nutrients*, *sediment*, *chlorophyll-a*, *carbon*, *phytoplankton*, *cyanobacteria*, *water quality*, *modeling*, *stable isotopes*, *denitrification*, *river*, *climate change*, *agriculture*, *estuary*, and *internal loading* (the number of co-occurrences was greater than 10). These results may indicate a wide range of research interest on nitrogen in eutrophic lakes or reservoirs from 1991 to 2015.

2.2.2. Hot issues

2.2.2.1. Nutrient amounts, ratios, and major nitrogen sources leading to eutrophication. Not surprisingly, *nitrogen* was most relevant to *phosphorus*, *nutrients*, and *sediment* in all 5-year intervals and the last 25 years from 1991 to 2015. Fig. 4 shows the trends for *nutrients*, *phosphorus*, *nitrogen*, and *sediment*. Excessive nitrogen and phosphorus input to lakes and reservoirs is the key driver of eutrophication (Ma et al., 2015; Paerl et al., 2015; Smith, 1998). One mechanism by which eutrophication can shift the community structure toward

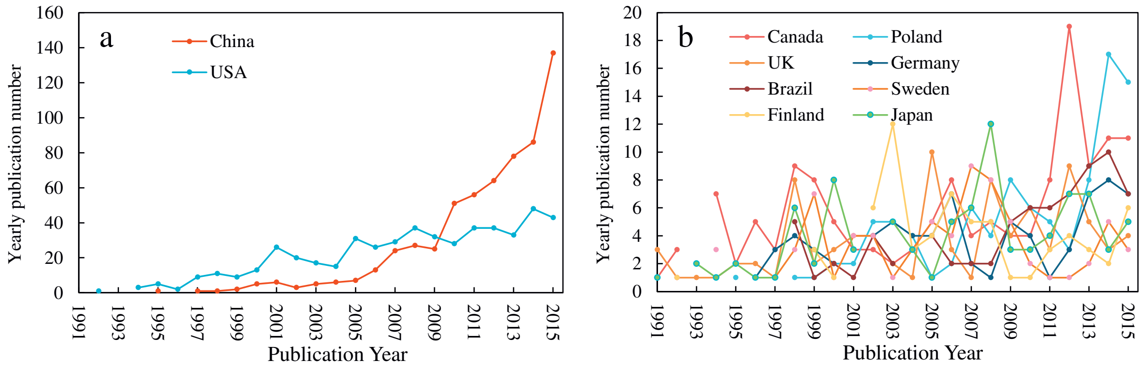

Fig. 2 – Yearly publication number of articles in the top 10 most productive countries (a: China and the USA; b: the other 8 countries among top 10 countries).

HABs species is by changing the ratio of individual nutrients relative to other nutrients such as the nitrogen: phosphorus ratio (N:P) (Glibert et al., 2005; Ma et al., 2015; Wang et al., 2010). Low N:P favors N_2-fixing cyanobacteria in dominance, which hypothetically could alleviate nitrogen limitation in lakes and reservoirs (Schindler et al., 2008; Smith, 1983), and this paradigm has led to widespread reductions in phosphorus inputs to control eutrophication in freshwater lakes (National Research Council, 1992). However, controlling phosphorus only is no longer adequate for many lakes or reservoirs (Ma et al., 2015; Paerl et al., 2014a; Xu et al., 2010; Zhu et al., 2010), and the P-limitation paradigm has been challenged (Lewis and Wurtsbaugh, 2008). Firstly, nitrogen fixation cannot always compensate for nitrogen loss (Paerl et al., 2014b; Scott and McCarthy, 2010). Secondly, nitrogen may escape *via* denitrification, leading to perpetual nitrogen deficits (Paerl et al., 2016). Thus, dual nutrient (nitrogen and phosphorus) reductions are needed to reduce HABs in lakes and reservoirs (Ma et al., 2015; Paerl et al., 2016). Recently, researchers have been determined critical nutrient thresholds and nutrient ratio needed to control HABs in eutrophic Lake Taihu, China (Ma et al., 2015; Xu et al., 2014).

As indicated by the keywords *sediment*, *internal loading*, *rivers*, *estuaries*, *land use*, *nonpoint sources*, and *agriculture* (Table 5), nitrogen sources were research interests on current topic. Nitrogen sources mainly include external runoff, atmospheric deposition, and internal sediment release (Xu et al., 2010). The high frequency of the keyword *sediment* indicates that sediment plays a more important role in eutrophication research. Nitrogen release and cycling across the sediment–water interface is an important mechanism leading to eutrophication (Marsden, 1989; Søndergaard et al., 2003; Zhang et al., 2010a). In lakes or reservoirs in which external loading has been reduced, internal nutrient loading may prevent the reduction of eutrophication (Xu et al., 2010). Examining sediment nitrogen contents and profiles (Yu et al., 2016), clarifying sediment nitrogen metabolism processes in the presence of microorganisms or macrobenthos (McCarthy et al., 2007; Shang et al., 2013), quantifying fluxes across sediment–water interface (Qu et al., 2007), calculating nitrogen budgets originating from sediments (Newell et al., 2016), and controlling sediment nitrogen release (Yu et al., 2016) are active issues. In addition, sediment is an information archive of environmental change (Silva and Rezende, 2002; Yao et al., 2006; Zan et al., 2012). Future studies may focus on the following aspects: (1) the nitrogen threshold and appropriate N:P ratio for the target of controlling HABs; (2) finding out and quantifying important nitrogen sources leading to HABs.

2.2.2.2. Nitrogen transformation and the bioavailability of different nitrogen forms. Over the past ten years, *denitrification*

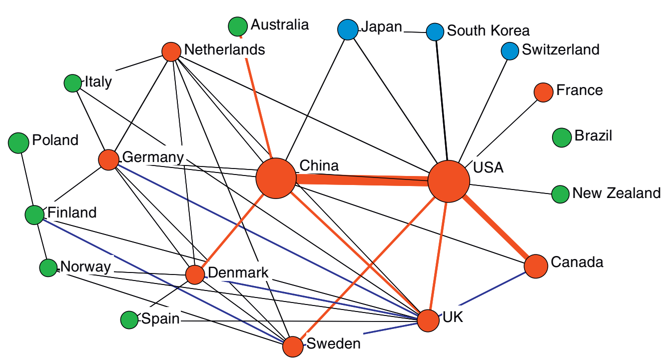

Fig. 3 – Cooperation network between the top 20 most productive countries (the color of lines represents the group of co-occurrence times: red lines > 15, 10 < blue lines ≤ 15, 5 < black lines ≤ 10; the color of nodes represents the number of countries that has at least one co-published articles with other nodes: red nodes > 15, 10 < blue nodes ≤ 15, green nodes ≤ 10; the size of the circle represents the total publications produced from a country).

Table 3 – Top 20 most productive institutions from 1991 to 2015.

Institution	Country	Records	TLCS [a]	TGCS [b]	LCSA [c]	GCSA [d]
Chinese Academy of Sciences	China	310(11.5%)	846	3743	2.7	12.1
University of Florida	USA	65 (2.4%)	332	1611	5.1	24.8
Chinese Research Academy of Environmental Sciences	China	58 (2.2%)	76	287	1.3	4.9
Aarhus University	Denmark	40 (1.5%)	152	1096	3.8	27.4
Beijing Normal University	China	39 (1.4%)	22	171	0.6	4.4
Nanjing University	China	38 (1.4%)	68	322	1.8	8.5
University of Chinese Academy of Sciences	China	38 (1.4%)	20	89	0.5	2.3
United States Geological Survey	USA	36 (1.3%)	109	1082	3.0	30.1
University of Wisconsin	USA	35 (1.3%)	302	3142	8.6	89.8
University of Alberta	Canada	34 (1.3%)	323	1740	9.5	51.2
University of Helsinki	Finland	32 (1.2%)	53	549	1.7	17.2
Environment Canada	Canada	30 (1.1%)	48	434	1.6	14.5
Hohai University	China	30 (1.1%)	83	318	2.8	10.6
University of Liverpool	England	28 (1%)	225	1246	8.0	44.5
University of Waikato	New Zealand	28 (1%)	127	511	4.5	18.3
Louisiana State University	USA	27 (1%)	40	472	1.5	17.5
South Florida Water Management District	USA	27 (1%)	177	896	6.6	33.2
Finnish Environment Institute	Finland	26 (1%)	56	762	2.2	29.3
United States Environmental Protection Agency	USA	25 (0.9%)	63	792	2.5	31.7
National Institute for Environmental Studies	Japan	24 (0.9%)	58	547	2.4	22.8

[a] TLCS: Total Local Citations Score, which is the number of citations by other papers in the present collection.
[b] TGCS: Total Global Citations Score, which is the number of citations by the papers of Web of Science.
[c] LCSA: Local Citation Score per Article, which is the TLCS divided by the TPN.
[d] GCSA: Global Citation Score per Article, which is the TGCS divided by the TPN.

and *stable isotopes* were among the most frequent keywords. In addition to *denitrification*, processes in nitrogen cycling include *nitrification*, *nitrogen fixation*, *anammox*, and *dissimilatory nitrate reduction to ammonium (DNRA)*, *etc.* (Brandes et al., 2007). Fig. 5 shows the annual trends of these keywords. *Denitrification* transforms nitrates into gaseous products such as molecular dinitrogen (N_2) and nitrous oxide (N_2O) gas (Seitzinger, 2008; Wang et al., 2013), and its study showed a rapid increase after 2010. Denitrification is the predominant mechanism for the substantial removal of fixed nitrogen from the biosphere (Altabet et al., 1995; Finlay et al., 2013). Articles on *nitrification* and *nitrogen fixation* also increased after 2009. The terms *anammox* and *DNRA* were found to occur later than *denitrification*, *nitrification*, and *nitrogen fixation*; they appeared between 2005 and 2015 in articles about nitrogen research. It is also worth noting that N_2O generated in nitrogen cycling (*e.g.*, denitrification and nitrification), whose greenhouse effect was greater than CO_2, was an active issue of nitrogen research. The atmospheric concentrations of N_2O are increasing at approximately 0.25% per year, being responsible for approximately 5% to 10% of global warming (IPCC, 2007). Most aquatic ecosystems contribute elevated N_2O to atmosphere due to increasing anthropogenic nitrogen loading (Wang et al., 2017). Thus, it is important to quantify N_2O emissions and its influence on climate change. All nitrogen metabolism processes mentioned above can be studied using *stable isotopes*. Stable isotope tracer technique, which has unparalleled advantages than other methods (Groffman et al., 2006), is widely used to directly follow and trace details of element cycling (Fry, 2007). Using ^{15}N isotope as a tracer can quantify nitrogen metabolism rates by phytoplankton and/or bacteria, examine sources and fates of nitrogen compounds, and help understand the structure of

Table 4 – Top 10 most productive authors from 1991 to 2015.

Author name	TP (%) [a]	Author name	FA (%) [b]	Author name	RA (%) [c]
Jeppesen, E	45 (1.7)	Gu, B H	8 (0.3)	Xie P	19 (0.7)
Xie, P	34 (1.3)	Havens, K E	7 (0.3)	Qin BQ	16 (0.6)
Qin, BQ	33 (1.2)	Huo, S L	7 (0.3)	Wang SR	14 (0.5)
Moss, B	25 (0.9)	Jeppesen, E	7 (0.3)	Huo SL	9 (0.3)
Hamilton, DP	24 (0.9)	Xu, J	7 (0.3)	Gu BH	8 (0.3)
Sondergaard, M	24 (0.9)	Zhang, Y	7 (0.3)	Jeppesen E	8 (0.3)
Zhang, M	22 (0.8)	An, K G	6 (0.2)	Havens KE	7 (0.3)
Zhu, GW	21 (0.8)	Bachmann, R W	6 (0.2)	Moss B	7 (0.3)
Leavitt, PR	19 (0.7)	Dodds, W K	6 (0.2)	Scott JT	7 (0.3)
Xi, BD	19 (0.7)	Ekholm, P	6 (0.2)	White JR	7 (0.3)

[a] TP: total publications.
[b] FA: first author publications.
[c] RA: corresponding author publications.

Table 5 – Top 20 author keywords related to *nitrogen* within 5-year intervals from 1991 to 2015 as well as the entire past 25 years.

Rank	1991–1995	1996–2000	2001–2005	2006–2010	2011–2015	1991–2015
1	*Phosphorus*	*Phosphorus*	*Phosphorus*	*Phosphorus*	*Phosphorus*	*Phosphorus*
2	*Nutrients*	*Nutrients*	*Nutrients*	*Nutrients*	*Nutrients*	*Nutrients*
3	*Sediment*	*Sediment*	*Sediment*	*Sediment*	*Sediment*	*Sediment*
4	*Chlorophyll-a*	*Chlorophyll-a*	*Carbon*	*Chlorophyll-a*	*Water quality*	*Chlorophyll-a*
5	*Primary production*	*Carbon*	*Phytoplankton*	*Carbon*	*Cyanobacteria*	*Carbon*
6	*Lake restoration*	*Rivers*	*Model*	*Cyanobacteria*	*Chlorophyll-a*	*Phytoplankton*
7	*Carbon*	*Zooplankton*	*Chlorophyll-a*	*Phytoplankton*	*Carbon*	*Cyanobacteria*
8	*Modeling*	*Periphyton*	*Watershed*	*Denitrification*	*Phytoplankton*	*Water quality*
9	*Water quality*	*Phytoplankton*	*Estuaries*	*Water quality*	*Microcystis aeruginosa*	*Modeling*
10	*Estuary*	*Water quality*	*Rivers*	*Climate change*	*Cyanobacterial blooms*	*Stable isotopes*
11	*Chemical oxygen demand*	*Model*	*Oxygen*	*Restoration*	*Climate change*	*Denitrification*
12	*Agriculture*	*Streams*	*Stable isotopes*	*Stable isotopes*	*Land use*	*Rivers*
13	*Wetlands*	*Cyanobacteria*	*Ammonium*	*Trophic state*	*Iron*	*Climate change*
14	*Internal loading*	*Macrophytes*	*Agriculture*	*Model*	*Stable isotopes*	*Agriculture*
15	*Light*	*Agriculture*	*Nitrification*	*Pollution*	*Microcystin*	*Estuary*
16	*Nonpoint sources*	*Algae*	*Silicon*	*Internal loading*	*Denitrification*	*Internal loading*
17	*Phytoplankton*	*Organic matter*	*Denitrification*	*Algae*	*Organic matter*	*Land use*
18	*Denitrification*	*Growth*	*Macrophytes*	*Macrophytes*	*Modeling*	*Lake restoration*
19	*Management*	*Food webs*	*Wetlands*	*Diatoms*	*China*	*Iron*
20	*Zooplankton*	*Silicon*	*Stratification*	*Microcystin*	*Lake restoration*	*Zooplankton*

microbial food webs (Bronk et al., 1994; McCarthy et al., 2007; Shang et al., 2013).

Both the quantity and the composition of nutrient pool impact the dynamics of ecosystems (Heisler et al., 2008). For example, phytoplankton community composition has different responses to nitrate and ammonium enrichment (Glibert et al., 2016). Diatoms have a large capacity to take up and assimilate nitrate, while cyanobacteria have a large capacity to take up and assimilate ammonium (Glibert et al., 2016). In addition, phytoplankton community composition has dissimilar responses to inorganic and organic nutrients (Wang et al., 2010). For decades, dissolved inorganic nitrogen (DIN) forms such as nitrate (NO_3^-–N), ammonium (NH_4^+–N), and nitrite (NO_2^-–N) received far more attention in eutrophication due to their higher bioavailability. However, concentrations of dissolved organic nitrogen (DON) are frequently higher than DIN (Bronk et al., 2007) and the DON fraction often exceeds 50 % of the total dissolved nitrogen (TDN) pool in freshwaters (Berman and Bronk, 2003), especially in highly developed catchments (Petrone et al., 2009). In Lake Taihu, average DON concentrations in Lake Taihu in China accounted for up to 50 % of TDN (Zhang et al., 2015). These DON fractions in TDN have drawn renewed attention because evidences showed that phytoplankton can get substantial nitrogen nutrition from certain DON components (Bronk et al., 2007; Zhang et al., 2016). The composition of DON, which is related to its sources, is complicated (Melendez-Perez et al., 2016). It is largely unclear which component of DON is bioavailable to phytoplankton or bacteria (Bronk et al., 2007; Su et al., 2016). Therefore, the role of DON in the food web of aquatic systems, a large "black box", needs to be illuminated. The increasing frequency of keyword *dissolved organic nitrogen* in the past ten year indicates that DON may become a hotspot of future researches.

Therefore, future studies should answer the following questions: (1) How does different nitrogen forms transformed? How about the rates and influencing factors? (2) Who (phytoplankton or bacteria genus) is doing what (uptake, assimilate, and release what kind of nutrients) and when (the discipline of occurring time)? (3) Which components of DON

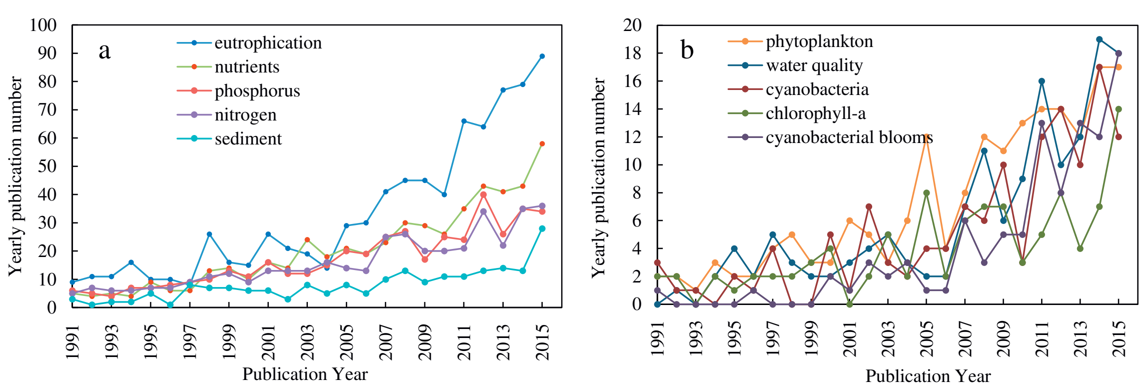

Fig. 4 – Trends of a: *nutrients*, *phosphorus*, *nitrogen*, *sediment*, *phytoplankton* and b: *phytoplankton*, *water quality*, *cyanobacteria*, *chlorophyll-a*, *cyanobacterial blooms*.

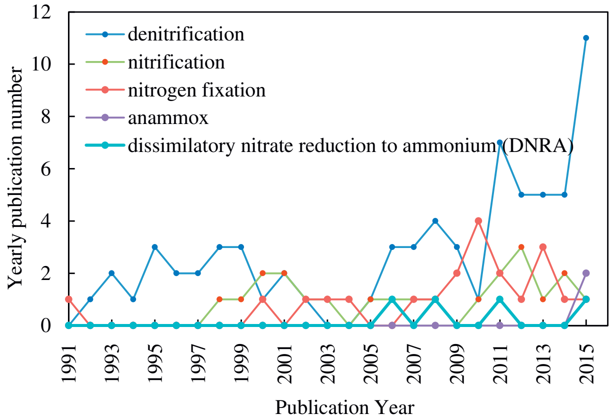

Fig. 5 – Trends of *denitrification, nitrification, nitrogen fixation, anammox* and *dissimilatory nitrate reduction to ammonium (DNRA)*.

can fuel HABs? Is current water quality standard reasonable without criteria of bioavailable DON?

2.2.2.3. Ecosystem responses, lake monitoring, forecast, restoration, and management. In addition to *phosphorus*, *nutrients* and *sediment*, research on nitrogen in eutrophic lakes or reservoirs from 1991 to 2005 mainly focused on *chlorophyll-a*, *primary production*, *carbon*, *restoration*, *model*, *phytoplankton*, *zooplankton*, *periphyton*, *and oxygen*. Basically, nutrient enrichment causes many changes in the structure and function of aquatic systems such as an increase in the biomass of *phytoplankton* and *periphyton* (Dodds et al., 1997), shifts in *phytoplankton* composition to bloom-forming species (Smith et al., 1999; Wang et al., 2007), depletion of the deepwater *oxygen* concentration (Vollenweider et al., 1992), changes in *primary production* and the species composition of vascular plants (Wetzel, 1964), and changes in the *zooplankton* composition toward less desirable species (Carpenter et al., 1985; Kerr and Ryder, 1992). The most commonly identified variable during eutrophication and HABs is the accumulation of algal biomass, which is easily observed by the public (Smith et al., 1999). The term *chlorophyll-a* is a common index used to characterize primary production and algal biomass (Carlson, 1977; Paerl et al., 2015). Combined with nitrogen, phosphorus, and other indexes, *chlorophyll-a* can help monitor and evaluate the trophic state and characterize a lake or reservoir ecosystem (Carlson, 1977; Dodds et al., 1998).

During the past ten years, the keywords *cyanobacteria*, *climate change*, *denitrification*, *Microcystis aeruginosa*, *cyanobacterial blooms*, *water quality*, and *stable isotopes* were the most frequent keywords related to *nitrogen*, indicating a change in research interests over the past decade. The research direction regarding current topic tended to be more detailed and comprehensive. For example, the frequency of *cyanobacteria* and *M. aeruginosa* (the primary phylum and genus of the HABs, respectively) increased over the past ten years, indicating the effect of nutrients on the composition of phytoplankton. In addition to the biomass of phytoplankton, responses of phytoplankton community composition to nitrogen enrichment is a hot issue among articles of current topic (Paerl et al., 2015; Wang et al., 2010; Zhu et al., 2010). Eutrophic lakes or reservoirs had frequent cyanobacterial blooms in the past and received much attention from the public, especially during the past ten years (Liu et al., 2011; Paerl et al., 2014a). Some of the clearest examples of the relationship between the frequency of HABs and the increase in total nutrient enrichment of aquatic systems are from China (Glibert et al., 2005). Since the 1970s, when the use of chemical fertilizer began to escalate in China, the number of HABs outbreaks has increased over 20-fold, with blooms that are now geographically larger, more toxic, and more prolonged (Anderson et al., 2002). In most cases, the cyanobacterial blooms were dominated by *M. aeruginosa*, which is ubiquitous, of high frequency, and has detrimental effects on fisheries (Cao et al., 2006; Chen et al., 2003; Paerl et al., 2014a).

Nutrient enrichment in lakes or reservoirs resulted in many active issues, and all these issues can lead to the deterioration of the *water quality* and the ecosystem. Past efforts also included the development of nutrient loading *models* and quantitative *models* that linked nitrogen concentrations or nitrogen metabolism rates to the monitoring, prediction, evaluation, and management of water quality and HABs (Huo et al., 2013; Smith et al., 1999). Moreover, lake *restoration* by biomanipulation and other methods, such as external nutrient control, were also research hotspots from the first three 5-year intervals.

Considering research developments mentioned above, future studies should answer the following questions: (1) How does nitrogen-cyanobacterial bloom interact? What are the major sinks of nitrogen? What is the succession mechanism of the lake ecosystem to nitrogen enrichment and reduction? (2) How can we look out important nitrogen processes and build up an accurate nitrogen mass balance model for water management? (3) How can newly improved nitrogen dynamics be cooperated to models to contribute to water management and lake restoration?

2.2.2.4. Interactions between nitrogen and other stressors on eutrophication. The term *climate change*, an undeniable reality over the past decades (IPCC, 1996), was found to be a catalyst for the global expansion of harmful cyanobacterial blooms (O'neil et al., 2012; Paerl and Huisman, 2009). Climate change has resulted in higher temperatures, an enhancement of the vertical stratification of aquatic ecosystems and seasonal and interannual alterations, all of which benefit various species of harmful cyanobacteria by increasing their growth rates, dominance, persistence, geographic distribution, and activity (O'neil et al., 2012; Paerl and Huisman, 2009). Studies have shown that the Earth's lakes are warming faster than its air and the oceans around them due to climate change (O'Reilly et al., 2015), which could cause widespread damage to lake ecosystems including accelerated global warming (Kintisch, 2015) and HABs (Paerl and Huisman, 2009). Additionally, both nutrient concentration and temperature showed spatial–temporal variation. For example, the Earth's temperature is increasing more rapidly at night than during the daytime (IPCC, 2013). The interaction of eutrophication and climate change on HABs is complex and is likely to enhance the magnitude and frequency of these events (O'neil et al., 2012). Since current water quality management strategies are largely based on nutrient input and hydrologic controls, the effect of climate change (global warming) on HABs must receive more attention from researchers and the public (Paerl and Huisman, 2009). In addition to *climate change*, the availability of a photosynthetic *carbon* dioxide source for algal photosynthesis is a significant determining factor in the eutrophic process (King, 1970). Although nitrogen and a variety of other nutrients are required by algae, eutrophication seems to be ultimately a carbon-accumulation phenomenon (King, 1970). Moreover, nitrogen metabolism processes of phytoplankton and bacteria are tightly coupled to carbon metabolism, especially DON metabolism (Bertrand et al., 2015; Brookshire et al., 2005; Johnson et al., 2012; Petrone et al., 2009). In addition, interactions between nitrogen and other stressors on eutrophication are also important issues to address, such as light intensity, toxic contaminants, fishing harvests, aquaculture, and hydrological variations (Cao et al., 2011; Cloern, 2001; Racchetti et al., 2010). Therefore, future studies should answer the following questions: (1) What is the response of ecosystems to multiple stressors? (2) What are the relationships between these responses?

3. Conclusions

In this study, we analyzed the research development, current research hotspots, and future trends of nitrogen research in eutrophic lakes and reservoirs over the past 25 years by a bibliometric method. Our study suggested that publications on nitrogen research in eutrophic lakes and reservoirs increased exponentially from 1991 to 2015. Environmental Sciences & Ecology, Marine & Freshwater Biology, and Water Resources were the 3 most popular subject categories. Chinese Academy of Science was the most productive institution and Erik Jeppesen was the most productive author. Research hotspots were analyzed by a frequency analysis and a co-occurrence analysis of author keywords in 5-year intervals from 1991 to 2015 and the entire last 25 years. The results showed that the most active keywords related to nitrogen research in eutrophic lakes and reservoirs were *phosphorus*, *nutrients*, *sediment* and *chlorophyll-a*, *carbon*, *phytoplankton*, *cyanobacteria*, *water quality*, *modeling*, and *stable isotopes*. In addition, researchers paid increased attention to *denitrification*, *climate change*, and *internal loading*.

Future trends of nitrogen research in eutrophic lakes and reservoirs may focus on: (1) nutrient amounts, ratios, and major nitrogen sources leading to eutrophication; (2) nitrogen transformation and the bioavailability of different nitrogen forms; (3) nitrogen budget, mass balance model, control, and management; (4) ecosystem responses to nitrogen enrichment and reduction, as well as the relationships between these responses; and (5) interactions between nitrogen and other stressors on eutrophication (*e.g.*, carbon, phosphorus, toxic contaminants, climate change, and hydrological variations).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.jes.2016.10.022.

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