

## A bibliometric analysis of scientific trends in phytoplankton research

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**Abstract** – We summarize the scientific trends in phytoplankton studies between 1991 and 2013 based on bibliometric analysis. The annual publication output on phytoplankton demonstrated a rapid linear increasing tendency during the past two decades, and its contribution to total scientific articles remained below 10%. Under the context of fast scientific research development, the yearly numbers of dependent publications (in terms of multi-aquatic ecosystems and international collaborations) indicate a linear increasing trend. The variations of keywords associated with research regions are mainly contributed by geographic adjacent countries, which are also generally the top contributors. Various trends of all the keywords relating to research methods, research contents and environmental factors indicate that phytoplankton studies carried out on large scale and long term are showing a significantly ascending trend, while traditional and local scale studies are showing a descending trend.

**Key words:** Phytoplankton / bibliometric analysis / research trend

### Introduction

This is an era of information explosion, and around 6000 new research articles come out every day. It is actually difficult for researchers to catch up with the scientific development, even in a specific research field. For beginners, who are starting with their new research topic, the difficulties to understand both the background and the frontier of their own research field are substantial. Phytoplankton is a collective of photosynthetic microorganisms, adapted to live partly or continuously in open waters, and a major primary producer of organic carbon in both marine and inland waters (Reynolds, 2006). Phytoplankton research and its literature as such are of basic importance in all studies related to trophic and biogeochemical functioning of aquatic ecosystems.

Bibliometric analysis is a common research method which has already been widely applied for the scientific production and research trends in many disciplines of

science (Keiser and Utzinger, 2005; Van Raan, 2005; Li *et al.*, 2009; Zhang *et al.*, 2013; Liao and Huang, 2014). The Science Citation Index (SCI), from the Institute for Scientific Information (ISI) Web of Science databases is the most frequently used database (Bayer and Folger, 1966; Ho, 2014). The article of Carneiro *et al.* (2008) in *Limnology*, titled “Trends in the scientific literature on phytoplankton”, mainly summarized the information associated with affiliations (journals, countries and regions) and applications (citation and impact factor) of phytoplankton publications. However, the research trends based on keyword analysis are still unknown, and thus needed.

In order to study the global trend of phytoplankton research, this paper used a bibliometric method to measure scientific evolution especially the research trends of phytoplankton during the period of 1991–2013. The analysis results could help to illustrate the global trends of phytoplankton research and potentially give some guidance to scholars for developing and deepening their respective researches.

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## Methods

### Data sources

Any articles containing the keyword “phytoplankton” in title, abstract and keywords fields, published between 1991 and 2013, were queried from all citation indexes on Web of Science (Thomson Reuters). An XML file containing titles, keywords, abstracts, year of publication, authors’ names and authors’ affiliations, cited times and cited reference counts was exported. The search query was constructed as below: (TITLE-ABSTRACT-KEYWORDS: “phytoplankton”).

### Aquatic ecosystems extraction

Aquatic ecosystem name(s) were extracted from the titles, keywords and abstracts. The six types of aquatic ecosystems (river, lake, reservoir, sea, bay and estuary) selected are the most common names of natural aquatic ecosystems for phytoplankton studies. The “other\_waterbodies” represent all other phytoplankton publications, including those both in other aquatic ecosystems and in other research fields, except for the above six ecosystems.

### Country names extraction

Country name (s) of all citation indexes were extracted from the authors’ affiliations. The ones originating from England, Scotland, Northern Ireland and Wales were grouped under United Kingdom (UK), and the ones from Hong Kong were treated as from China. Other former country names were renewed including “Yugoslavia” (Serbia and Montenegro), “Federal Republic Germany” and “Democratic Republic Germany” (Germany). The authors’ affiliations with only states/provinces names but without country names were not taken into account. Publications with only one country name presented in the affiliation were considered as within-country cooperation, the ones with more than one country name appeared were treated as international cooperation.

### Co-word analysis of keywords and cooperation among countries

Co-word analysis is an established bibliometric method to explore the network of terms based on their paired presence (co-occurrence) within a specified content of document in scientific discipline (Callon *et al.*, 1991; Cheng *et al.*, 2014).

The procedure for co-word analysis of cooperation among countries was: (1) country names extraction as describe above; (2) preparation of country name library, *e.g.*, selecting top 30 most productive country names; (3) co-occurrence matrix construction: firstly, a term-document matrix was built for the selected country names

library, *e.g.*, top 30 of them from 1000 publications, which generated a  $30 \times 1000$  matrix; secondly, the term-document matrix was transformed into a co-occurrence matrix, *e.g.*,  $30 \times 30$  matrix; (4) visualization of cooperation among countries: a plot was generated, in which the countries were represented by nodes and their associations represented by lines between each of the nodes. The widths of lines and nodes were adjusted for readers.

The procedure for co-word analysis of keywords was: (1) keywords extraction and normalization: keywords of each publication provided by Web of Science were extracted. The numbers and punctuations from keywords and phrases were removed, coerced to lowercase and stemmed to minimize the variation of keyword expression from different authors, *e.g.*, “marine-phytoplankton” versus “marine phytoplankton”; (2) the keyword library preparation: *e.g.*, top 30 most frequent keywords; (3) co-occurrence matrix construction: first, a term-document matrix was built for the selected keywords, *e.g.*, 30 hot keywords out of 100 keywords from 50 publications, which generated a  $30 \times 100$  matrix; second, the term-document matrix was transformed into a co-occurrence matrix, *e.g.*,  $30 \times 30$  matrix; (4) visualization of keywords co-word analysis was as described above.

### Keyword trend analysis

The yearly percentages of occurrence of each keyword was calculated as the yearly frequency divided by total frequency during a specified period of time, and then adjusted (divided) by the numbers of yearly total publications to compensate for the general increase of total amount of publications. Mann–Kendal (MK) trend test was performed thereafter on each keyword. When *P*-value  $< 0.05$ , the trend was recognized as significant, otherwise, neither an increasing nor a decreasing trend was retained.

### Statistical analysis

All the data processing, plot generating and statistical analysis were performed by self-composed R code. The MK trend test was performed to test the increasing/decreasing trends of the frequencies of keywords and counted numbers/percentages of phytoplankton-related publications occurred throughout years.

The journal titles for some journals of which the names had changed during the period considered had been manually renewed.

## Results

From 1991 to 2013, the total publication output on phytoplankton was 39150, and the annual numbers of publication demonstrated a linear increasing tendency in the past two decades, from only about 800 in 1991 to 2600 in 2013, *i.e.*, a more than threefolds increase during

the last 20 years (Fig. 1). However, the proportion of phytoplankton publications to total numbers of scientific articles remained below 0.1%.

Temporal variations of the relative proportions of phytoplankton research papers in six major aquatic ecosystems and others (including those in other aquatic ecosystems and those in other research fields) were shown in Figure 2. The results indicated that the publications related to the six aquatic systems contributed the most (>80%) to total phytoplankton publications, and the temporal variations of their sum values showed a slight increasing trend during the last 20 years. However, the relative proportion of different aquatic systems maintained steady, and publications in marine systems contributed the largest part (~50%). While the sum proportion of freshwater ecosystems fluctuated around 25%. Publications in the river ecosystems showed a slight increasing trend.

Considering articles related to different aquatic ecosystems, 15401 articles were published in the single-aquatic system category and 16346 articles were published in multi-aquatic system category. While both categories represent a comparable number of articles, the linear positive ascending trend (around 15% increase) of publications in multi-aquatic ecosystems (Fig. 3) implied that publications in single-aquatic system (independent research) were previously more dominant, but gradually overtaken by publications in multi-aquatic systems during the last 20 years.

At the country level, a majority of 27946 articles were published in the single-country category versus 11204 articles in the multi-country category. However, the linear positive ascending trend (around 20% increases) of publications in the multi-country category (Fig. 4) implied an increase of international collaborations for publications on phytoplankton research.

The top 20 countries contributing most to phytoplankton publications and their collaboration relationships were visualized in Figure 5. The size of nodes stand for the specific country's degree of contributions and the thickness of links stand for the strength of correlation. In this study, the United States (USA) contributed most and played the most important role in the international collaboration network (Fig. 5). Britain, Germany, France and Canada were also principal collaborators and major productive countries in the network. These countries showed stronger international collaborations than others. The strongest correlation was established between the USA and Canada.

The top 50 keywords with ascending trend and their temporal trends are shown in Figure 6. All the above keywords could be classified into four categories: (1) research regions, (2) research methods, (3) research contents and (4) environments. The keywords belonging to research regions included "baltic sea", "atlantic ocean", "north atlantic oscillation", "gulf of mexico", "brazil", "east China sea", "arctic ocean", "south China sea" and "shallow lake". The keywords belonging to research methods included "stable isotope", "remote sensing",

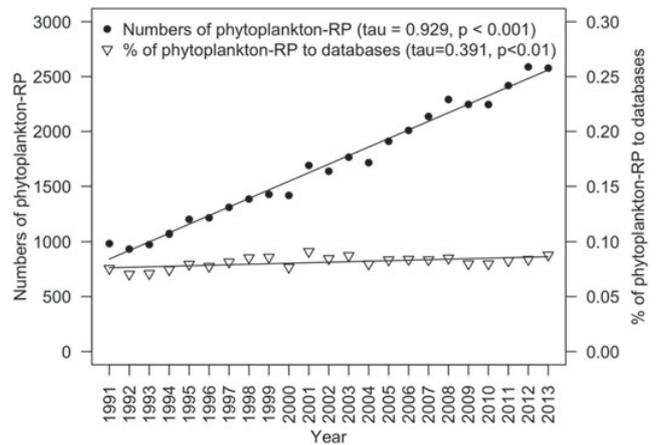


Fig. 1 Temporal trend of the number of phytoplankton research papers and its proportion in total databases. RP – research paper.

"algorithm", "stoichiometric", "seawif", "ecosystem model", "classification" and "in situ". The keywords belonging to environments included "climate change", "water quality", "phosphorus limit", "atmospheric corrosion", "sea surface temperature", "iron fertilization", "dissolved oxygen" and "hypoxia". The keywords belonging to phytoplankton research contents included 25 words, and they could be further classified into five sub-categories. The first sub-category was associated with bloom, including "phytoplankton bloom", "harm algal bloom", "algal bloom" and "cyanobacteria bloom". The second sub-category was associated with diversity, including "diversity", "biodiversity" and "species richness". The third sub-category was associated with temporal variations, including "interannual variable", "time series", "long term change" and "seasonal dynamics". The fourth sub-category was associated with ecosystem, including "marine ecosystem" and "aquatic ecosystem". The fifth sub-category was associated with other topics, including "allelopathic", "management", "sensitivity", "picophytoplankton", "trophic cascade", "community composition", "microcystin", "evolution", "*microcystis aeruginosa*", "submerged macrophyte", "regime shift" and "ocean acidification".

The top 50 keywords with descending trend and their temporal trends are shown in Figure 7. All the above keywords could also be classified into four categories: research regions, research methods, research contents and environments. The keywords belonging to research regions included "seawater", "north atlantic", "chesapeake bay", "sargasso sea", "north sea", "marine", "ocean", "water", "sediment", "lake", "sea", "freshwater" and "estuarine". The keywords belonging to research methods only included "model". The keywords belonging to research contents included 29 words, and they could be further classified into five sub-categories. The first sub-category was associated with algae, including "alga", "bacteria", "plankton", "diatom", "chlorophyll", "marine phytoplankton", "spring bloom", "bacterioplankton" and "microalga". The second sub-category was associated with

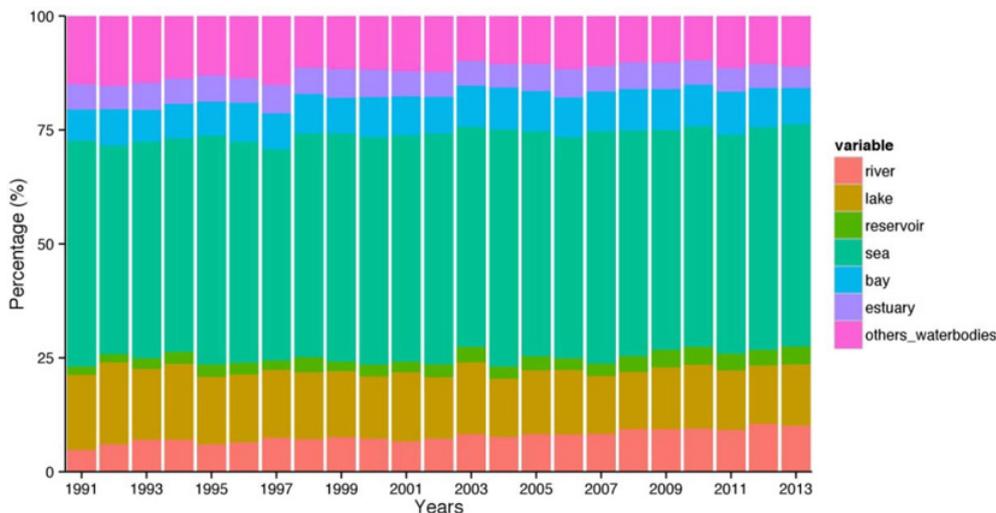


Fig. 2 Temporal trend of relative contributions of phytoplankton articles in different types of aquatic systems.

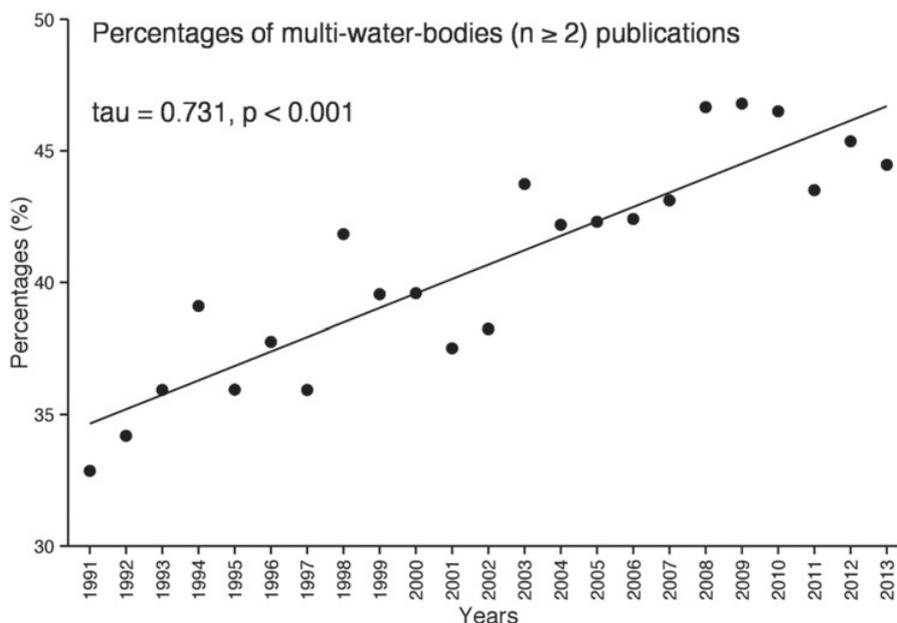


Fig. 3 Temporal trends of percentages of phytoplankton articles referring to  $\geq 2$  aquatic ecosystems in total phytoplankton articles.

growth, including “growth”, “phytoplankton growth”, “growth rate” and “rate”. The third sub-category was associated with phytoplankton production, including “organic matter”, “production”, “primary production”, “carbon” and “dissolved organic carbon”. The fourth sub-category was associated with phytoplankton community, including “community”, “biomass”, “dynamic”, “pattern”, “abundance” and “population”. The fifth sub-category was associated with other topics, including “limit”, “fish”, “zooplankton”, “photosynthesis” and “ecosystem”. The keywords belonging to environments included “iron”, “nutrient limit”, “nutrient”, “phosphorus”, “nitrogen”, “temperature” and “light”.

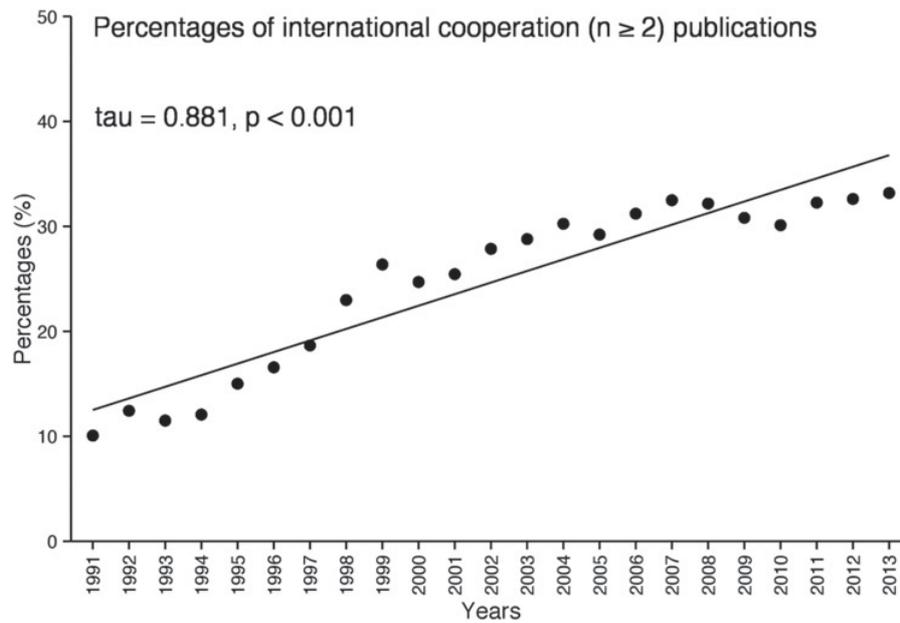
The top 20 high-frequency keywords and their correlations were visualized in Figure 8. The size of nodes stands for the proportion to the occurrence frequency. The lines

depicted the connection relationship between two keywords and the thickness of links stands for the strength of correlation. In this study, “growth” had the highest occurrence frequency, followed by “water”, “zooplankton” and “marine phytoplankton”. The strongest correlation was established between the words “nitrogen” and “phosphorus”.

## Discussion

### Research trend based on publications

Although the number of phytoplankton publications showed a linear increasing trend during the last 20 years, its proportion to total databases remained a steady



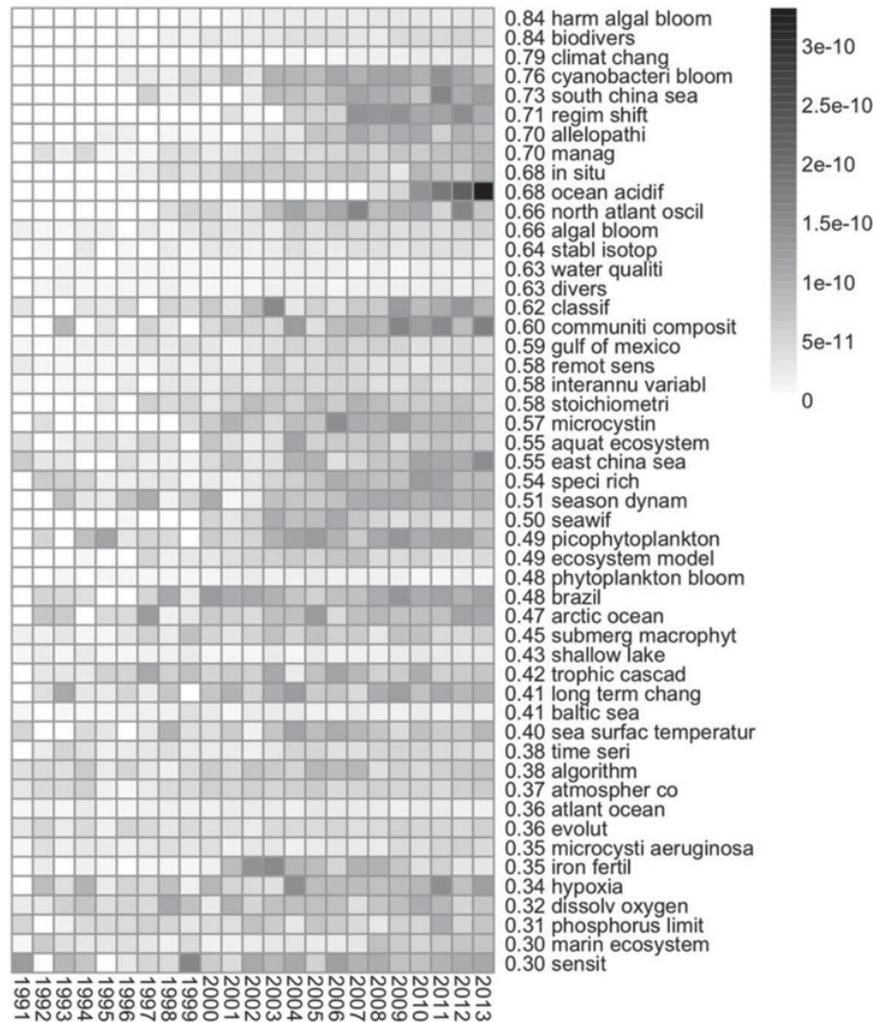
**Fig. 4** Temporal trend of percentages of phytoplankton articles based on cooperation between  $\geq 2$  countries in total phytoplankton articles.



**Fig. 5** Top 20 countries for phytoplankton articles publications and cooperation correlations.

low value. This seemed to be a common phenomenon in other research fields (Ohniwa *et al.*, 2010; Wen and Huang, 2012; Ma *et al.*, 2013; Niu *et al.*, 2014). And increasing trend of publications on phytoplankton could also be found when considering the sum of six classic aquatic ecosystems (river, lake, reservoir, sea, bay and

estuary), but their relative contributions remained steady, only the proportion of river showed a slight increasing trend. Since the classic lotic aquatic ecosystem was considered as an important link between other aquatic ecosystems in water resource network, and increasing studies are focusing on rivers as well as their linkage with



**Fig. 6** Top 50 key words with ascending trend in phytoplankton articles. The values of each keyword represent the ascending trend coefficient, and the scale at the right is the MK trend test result.

other aquatic ecosystems during the past two decades (Talling and Prowse, 2010; Li *et al.*, 2013; Battauz *et al.*, 2014; Yu *et al.*, 2014). While rivers are classically considered as phytoplankton-poor systems (Vannote *et al.*, 1980), the crucial presence of phytoplankton in rivers has been exploited lately (Améziane *et al.*, 2003; Tekwani *et al.*, 2013; Abonyi *et al.*, 2014).

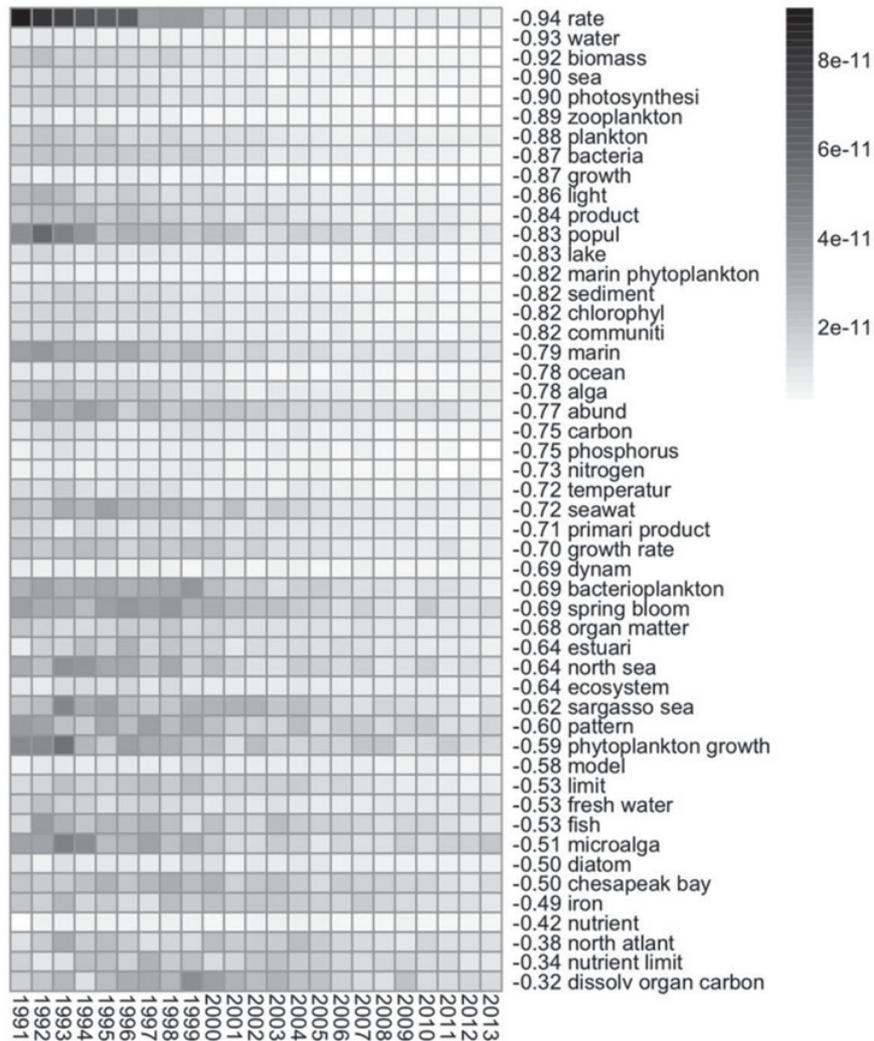
Generally, independent research is to collect the primary dataset, but more dependent publications would consider multi-aquatic ecosystems and international collaborations. For example, total 24 articles referring to all the six aquatic ecosystems were found and most of them focused on eutrophication (Grelowski *et al.*, 2000; Smith, 2003; Davis and Koop, 2006) and phytoplankton dynamics (Costa *et al.*, 2009; Sin *et al.*, 2013; Zhu *et al.*, 2013) in different aquatic ecosystems. And the most number of countries, where authors belonging to, was from an article “Deep carbon export from a Southern Ocean iron-fertilized diatom bloom” published in *Nature* reached 14 countries, which was funded internationally and carried out during RV *Polarstern* cruise ANT XXI/3 (Smetacek *et al.*, 2012). The increased cooperation among different

countries is probably the consequence of the needs to compare the responses of ecosystems across a wider spatial scale, and, to find common patterns, thus to find common solutions to the same problems, such as in the case of the implementation of the Water Framework Directive in Europe. Moreover, some collaborative publications are associated with geographic locations. For example, the researches about Laurentian Great Lakes basin promoted the cooperation of the USA and Canada (Biddanda *et al.*, 2006; Lunetta *et al.*, 2010). Other countries with frequent cooperation were also generally geographical neighbors. The linear increasing trend of dependent publications implied that collaborative research and publications would be the long-term trend for studies on phytoplankton.

## Research trend based on keywords

### Research regions

The vast ocean area occupies about 71% of the Earth’s surface, and publications in this largest aquatic ecosystem



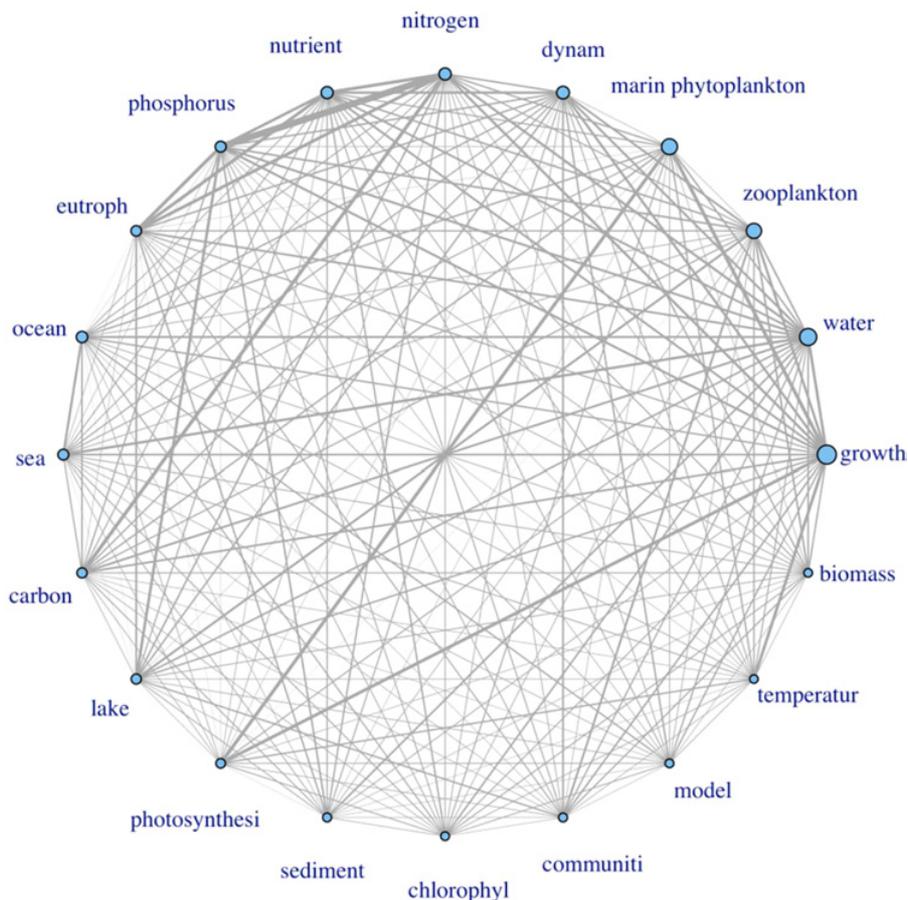
**Fig. 7** Top 50 key words with descending trend in phytoplankton articles. The values of each keyword represent the descending trend coefficient, and the scale at the right is the MK trend test result.

reach 50% of total phytoplankton articles. Consequently, the keywords “ocean” and “sea” could be found in the 10th and 11th position respectively among the top 20 keywords (Fig. 8). Moreover, the keywords with either ascending or descending trends associated with research regions are mostly in the sea (or ocean) area, and these trends are mainly contributed by geographic adjacent countries. These countries collaborated in their mutual marine areas. Either three ascending keywords “baltic sea”, “atlantic ocean”, “gulf of mexico” or four descending keywords “north atlantic”, “chesapeak bay”, “sargasso sea”, “north sea” are geographically adjacent. Furthermore, most of the adjacent countries could be found in the top 20. For example, the authors of a new article “Distinct responses of Gulf of Mexico phytoplankton communities to crude oil and the dispersant corexit (A (R)) Ec9500A under different nutrient regimes” in Gulf of Mexico (Ozhan and Bargu, 2014) are from the USA. The authors of an article “Phytoplankton distribution patterns in the northwestern Sargasso Sea revealed by small subunit rRNA genes from plastids” in Sargasso Sea

(Treich *et al.*, 2012) are also from the USA. Moreover, the two ascending keywords “east China sea” and “south China sea” represent the important sea area of China, which rank the sixth in top 20 countries for phytoplankton publications. With the fast development of economy, environmental pollution has currently become a key problem for Chinese government to deal with, and, recently, increasing numbers of research projects are funded to study the aquatic ecosystems, especially in the important sea area.

#### Research methods

Modeling is a useful way to analyze and explore a large and complex dataset. Ecological models have now been widely applied in studies of phytoplankton ecology (Elliott *et al.*, 2000, 2007; Mieleitner and Reichert, 2008) and algal dynamics (Serizawa *et al.*, 2009; Zhang *et al.*, 2013). Although the keyword “model” shows a descending trend, it ranked the 18th in top 20 keywords, and “ecosystem model” is found in ascending trend. The two keywords



**Fig. 8** Top 20 key words in phytoplankton articles and their correlations.

“remote sensing” and “seawif” in ascending trend are effective methods for large-scale studies, especially in ocean areas (Macias *et al.*, 2007; Alkawri and Gamoyo, 2014; Ben Mustapha *et al.*, 2014), in lakes (Odermatt *et al.*, 2012; Bolpagni *et al.*, 2014; Perkins *et al.*, 2014) and bays (Zhao *et al.*, 2014). Other methods also exhibit ascending trend, for example, “stable isotope” and “stoichiometric” are associated with trace element studies in phytoplankton (Sugimoto *et al.*, 2014; Van de Waal *et al.*, 2014); the increasing interest toward the stable isotope analysis is mainly due to the possibility to use this technique to reconstruct the trophic links inside atrophic web. And “classification” and “algorithm” indicate the importance of analysis in phytoplankton studies (Barron *et al.*, 2014; Mihaljevic *et al.*, 2014).

*Research contents*

An ecosystem is a community of living organisms (plants, animals and microbes) in conjunction with the nonliving components of their environment (*e.g.*, air, water and mineral soil), interacting as a system. The stability of an ecosystem, especially the interactions among organisms, and between organisms and their environment, always attracts the ecologists’ attention. In the present study, the two keywords “marine ecosystem” and “aquatic

ecosystem” are in ascending trend, which may implies that there is a growing interest toward holistic studies against reductionist studies.

An ecosystem-scale experiment in the equatorial Pacific Ocean showed that a massive phytoplankton bloom was triggered by iron fertilization (Coale *et al.*, 1996). Bloom, an uncommon extreme growth of phytoplankton, becomes more and more frequent under the global climate change and territorial aggravating pollution, and it can also cause great financial losses. Although the keyword “spring bloom” exhibits a descending trend, all the other four keywords (“phytoplankton bloom”, “harmful algal bloom”, “algal bloom” and “cyanobacteria bloom”) associated with bloom show ascending trend. The number of articles is more than 2000 in the way of searching “bloom” in title and “phytoplankton” in subject. However, traditional keywords in phytoplankton publications, including “alga”, “plankton”, “diatom”, “chlorophyll”, “bacterioplankton” and “microalga” exhibit descending trend. But “picophytoplankton” is in ascending trend. Moreover, the keywords, associated with growth, community (or population) and production (carbon), also present descending trend.

Biodiversity affects ecosystem function, so as the processes of disturbance and succession. The global biodiversity patterns of plants and animals have always

attracted researchers' attention (Gaston, 2000; Willig *et al.*, 2003). Accordingly, the three keywords “diversity”, “biodiversity” and “species richness” are in ascending trend. But similar patterns of microorganisms are still less understood. The global biodiversity patterns of marine phytoplankton reported by Irigoien *et al.* (2004) indicate that marine phytoplankton diversity is a unimodal function of phytoplankton biomass, with maximum diversity at intermediate levels of phytoplankton biomass and minimum diversity during massive blooms. However, in recent years, a yearly ~ 1% decline of global phytoplankton biomass has been observed (Boyce *et al.*, 2010). Therefore, how does phytoplankton diversity respond to the decreasing phytoplankton biomass could be attractive.

Climate change is a significant time variation in weather patterns occurring over periods ranging from decades to millions of years, it is also the peripheral environment of any ecosystems. Many serious ecosystem consequences of climate change will take decades or even centuries to emerge (Luo *et al.*, 2010). Long-term ecological responses to global change are strongly regulated by slow processes. Therefore, keywords associated with time variation (“interannual variable”, “time series”, “long term change” and “seasonal dynamics”) are in an ascending trend. The increasing attention toward the analysis of the long-term series is not specific for phytoplankton studies. The reason could be that many countries started regular environmental monitoring of different biotic and abiotic parameters in aquatic ecosystems since the 1960s or 1970s, also thanks to the setup of large research programs, mainly promoted by eutrophication studies, such as IBP. This long-term monitoring provided good data sets, which only recently started to be analyzed in detail, also thanks to the introduction of new statistical tools.

### Environmental factors

Environmental factors can directly impact phytoplankton growth and community composition. Among all the environmental factors, nutrients are regarded as the most important one. Although traditional keywords associated with nutrient limitation (“iron”, “nutrient trend”, “nutrient”, “phosphorus” and “nitrogen”) are in descending trend, while “phosphorus limit” and “iron fertilization” actually show ascending trend, which may imply that under the global background of nitrogen eutrophication, the unbalance of N:P ratio may play an important role in phytoplankton dynamics. Moreover, several other keywords (“climate change”, “atmospheric corode” and “sea surface temperature”) in an ascending trend indicate that large-scale environmental variations attract researchers more attention now.

### Conclusion

Although phytoplankton publications showed a linear increasing trend during the last 20 years, their

contributions to total scientific articles remained a steady level. Under the background of fast scientific research development, dependent publications (reflecting in multi-aquatic ecosystems and international collaborations) showed a linear increasing trend. The variation of keywords associated with research regions was mostly due to the geographic adjacent countries, and these countries are generally recognized as the top contributors. Various trends of all the keywords relating to research methods, research contents and environmental factors indicate that phytoplankton studies carried out in large scale are in a significant ascending trend, whereas traditional and local scale studies are in a descending trend. Our results also have the possible indication that holistic studies are increasingly more applied in phytoplankton ecology.

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