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Lake eutrophication and its ecosystem response

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China is a country with many lakes, about one-third of which are freshwater mainly distributed in the middle and lower reaches of the Yangtze River. Currently most of the lakes are mesotrophic or eutrophic. Lake eutrophication has become one of the major ecological and environmental problems faced by lakes in China and can lead to a series of abnormal ecosystem responses, including extinction of submerged plants, frequent occurrence of cyanobacterial blooms, increased microbial biomass and productivity, decreased biodiversity, accelerated cycles, and a change in the efficient use of nutrients. With development of eutrophication, the whole lake ecosystem suffers decreased biodiversity, simplification of biotic community structure, instability of the ecosystem, and ultimately the clear-water, macrophyte-dominated ecosystem gradually shifts to a turbid-water, algae-dominated ecosystem. This ecosystem succession mechanism is speculated to be caused by different nutrient utilization efficiencies of macrophytes and phytoplankton. The ultimate ecosystem succession trend of seriously eutrophic lakes is that a phytoplankton-dominated autotrophic lake shifts to a heterotrophic lake dominated by micro-organisms, protozoans.

aquatic plant, biodiversity, ecosystem succession, lake, eutrophication, microorganism, phytoplankton

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Lake eutrophication refers to the substantial increase of essential biological elements (including nitrogen and phosphorus) needed by plants, which increases the productivity (or the rate of photosynthesis) of the aquatic ecosystem. Based on early limnology research, Vollenweider [1] took the lead in quantitative classification of trophic status based on phosphorus and nitrogen and proposed a 5-level provisional classification system. The Organization for Economic Cooperation and Development (OECD, 1982) [2] expanded the indicators of trophic status by adding chlorophyll *a* and transparency, and developed a system of open borders with group mean value and standard deviation of each variable. Today, eutrophication generally refers to trophic state arising from increased nitrogen and phosphorus input, specifically, increased discharge of plant nutrients (mainly nitrogen and phosphorus) from industrialization, agricultural modernization, and urbanization.

Nitrogen, phosphorus, and some other elements are essential for plant growth; however, if a water body receives more nitrogen and phosphorus than necessary, the ecosystem can experience changes such as algal blooms; therefore, eutrophication can be considered as a biological or ecological concept. In this sense, using nitrogen, phosphorus, or other environmental factors is not the most appropriate way to evaluate the trophic level of a lake or reservoir; instead, the evaluation should be based on primary productivity of macrophytes and phytoplankton, but these indicators are difficult to assess. Alternatively, nitrogen, phosphorus, transparency, and chlorophyll *a* are commonly used as indicators for evaluation of eutrophication.

OECD proposed the following thresholds of eutrophication in 1982: average total phosphorus concentration >0.035 mg/L; average chlorophyll *a* concentration >0.008 mg/L; and average transparency <3 m [2]. According to these thresholds, many lakes in China have become eutrophic. An assessment of the trophic status of lakes in the middle and

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lower reaches of the Yangtze River, where most of the freshwater lakes are located, shows that most suffer from eutrophication; the rest are nearing eutrophication and will gradually become eutrophic with growing economic development. It has been shown that lakes, especially shallow lakes, are more prone to eutrophication [3]. Recent investigation concerning lake trophic status in middle and lower reach of Yangtze River showed that most lakes have been eutrophic as most lakes could be categorized into the mid-eutrophic or eutrophic status [4]. Eutrophication has therefore become the most important ecological environmental problem facing China's freshwater lakes (Table 1).

Eutrophication and the concomitant algal blooms seriously impact ecological functions and water quality of rivers and lakes. The cause of the Wuxi drinking water crisis in 2007 was cyanobacterial blooms, which resulted from eutrophication that led to pollution of the water works intake [18]. Cyanobacterial bloom is only one aspect of lake eutrophication, however. Lake eutrophication exerts other profound impacts on lake ecosystems, such as disrupting structure and function, but many of these impacts are likely unknown. Based on recent research on this issue, this study reviews the progress in this field and thus addresses future research directions and potential key breakthroughs to provide theoretical guidance and support for treatment of increasingly degenerating lake ecosystems and eutrophication as well as to advance sustainable lake management.

1 Ecosystem response to lake eutrophication

Lake eutrophication is enrichment of nutrients, including nitrogen and phosphorus, that can lead to a series of abnormal ecosystem responses. The most prominent symptom is the increase of phytoplankton biomass and occurrence of algal blooms [19], and sometimes together with algae toxins [20]. Nitrogen and phosphorus are biological elements necessary for plant growth, so an increased content of these elements inevitably causes an increase in phytoplankton. Long-term monitoring data from Taihu Lake also show a strong correlation between chlorophyll *a* concentration in the central lake, which reflects algal biomass, and total phosphorus concentration (Figure 1). The central lake area is far from human activities and discharge of pollutants along the shore and thus is relatively stable. The total phosphorus concentration of central Taihu Lake has increased since 1998 but stabilized after a drinking water crisis in 2007; variation in chlorophyll *a* concentration and total phosphorus concentration are closely linked (Figure 1).

Lake eutrophication increases phytoplankton biomass and decreases water transparency. The correlation between total phosphorus concentration and transparency in 13 eutrophic lakes in Denmark (Figure 2) indicates that water transparency decreases as the total phosphorus concentration increases, and the sensory water quality decreases with transparency.

Table 1 Nutritional status of major lakes in the middle and lower reaches of the Yangtze River

Lake name	Region	Area (km^2)	Maximum depth (m)	SD (m)	COD (mg/L)	TN (mg/L)	TP (mg/L)	Nutrient type	Data source
Poyang Lake	Jiangxi	2933	5.1	0.54	11.37	1.30	0.0640	Eutrophic	[5]
Dongting Lake	Hunan	2433	6.4	0.39	2.87	1.16	0.033	Mesotrophic	[6]
Honghu Lake	Hubei	344.4	2.3		4.02	1.38	0.078	Mesotrophic	[7]
Liangzi Lake	Hubei	304.3	6.2	2.23	4.46	0.38	0.050	Mesotrophic	[8]
Changhu Lake	Hubei	129.1	3.3	0.62		2.33	0.115	Eutrophic	[9]
Futou Lake	Hubei	114.7	4.3	1.61	5.06	0.14	0.069	Mesotrophic	[8]
Diaocha Lake	Hubei	70.6	2.4	0.80	3.60	0.54	0.073	Mesotrophic	[10]
Dazhi Lake	Hubei	68.7	3.4	0.76	3.79	0.82	0.073	Mesotrophic	[10]
Taibai Lake	Hubei	26		0.42	8.32	4.87	0.403	Eutrophic	[11]
East Lake	Hubei	33.7	2.8	0.25	7.10	2.77	0.356	Eutrophic	[12]
Longgan Lake	Anhui	316.2	4.6		1.35	0.774	0.051	Mesotrophic	[13]
Huangda Lake	Anhui	299.2	5.3		2.94	1.23	0.128	Eutrophic	[10]
Chengxi Lake	Anhui	199	3.9		4.47	1.53	0.019	Eutrophic	[10]
Chengdong Lake	Anhui	120	2.6	0.25	3.56	1.27	0.013	Mesotrophic	[10]
Nvshan Lake	Anhui	104.6	2.4	0.23	3.70	0.46	0.262	Eutrophic	[14]
Yangcheng Lake	Jiangsu	119.04	2.5		8.01	2.66	0.04	Eutrophic	[15]
Dianshan Lake	Shanghai	62	3.59	0.37	5.34	2.49	0.15	Eutrophic	[16]
Luoma Lake	Jiangsu			0.54	5.30	1.78	0.077	Mesoeutrophic	[17]
Baoying Lake	Jiangsu	43	2.2	1.05	5.89	0.62	0.11	Mesotrophic	[10]

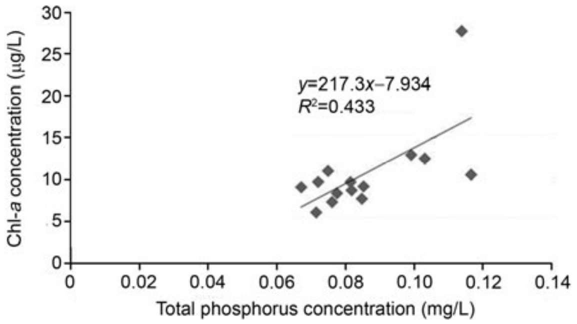

Figure 1 Correlation diagram of the annual average total phosphorus concentration and chlorophyll concentration in the central lake area of Taihu Lake (monitoring data provided by Taihu Laboratory for Lake Ecosystem Research, Chinese Academy of Sciences).

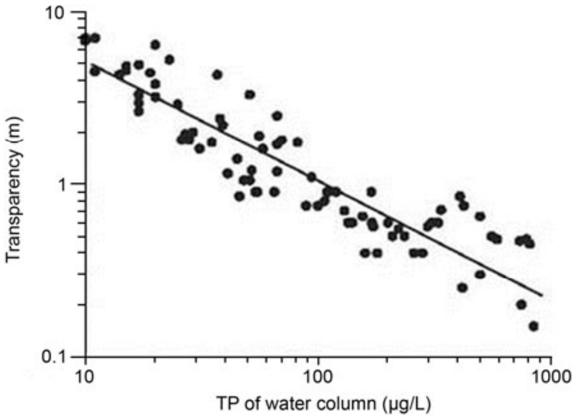

Figure 2 Correlation between the total phosphorus concentration and transparency in 13 eutrophic lakes in Denmark [21].

Increased phytoplankton biomass from lake eutrophication increases organic aggregates in the water column. Organic aggregates are irregular, porous particles originating from living or dead phytoplankton and zooplankton, protozoa, and microbes and their metabolites combined with organic (mainly aquatic or terrestrial animal and plant debris) or inorganic particles adhered by flocculation or autocrine mucus [22]. In eutrophic waters, organic aggregates formed by algal colonies increase significantly. In Lake Taihu, organic aggregates are attached with large amounts of bacteria (Figure 3), the main carrier of microorganisms [19], far more than planktonic bacteria. These bacteria are the core of organic matter decomposition and nutrient regeneration in lakes and are largely responsible for routine nutrient cycling. In lakes with high algal biomass (indicated by high chlorophyll *a* concentration), the concentrations of soluble reactive phosphorus (SRP) and total dissolved phosphorus (TDP) are high after a period of degradation and mineralization (Figure 4). In these lakes, microorganisms play an important role, significantly increasing microbial biomass and productivity in heavily polluted areas (Figure 5) [24].

When nutrient enrichment occurs, phytoplankton biomass increases, and the organic aggregates formed after the death of phytoplankton which in turn increases adhesive bacteria. The increased microbial biomass enhances metabolism and consumes the dissolved oxygen in water, a process Smith and Schindler called an anoxia-driven "vicious cycle" [25]. According to the monitoring data of eutrophic Lake Erie in North America, the weighted average dissolved oxygen depletion rate in the water below the thermocline is proportional to the input of total amount of phosphorus of the previous year (Figure 6) [26]; the same result is seen in eutrophic Chesapeake Bay, United States [27]. Compared to oligotrophic waters, the dissolved oxygen content is higher during the day due to increased photosynthesis of phytoplankton and lower at night due to increased respiration and microbial oxygen consumption, so that the variation of dissolved oxygen concentration between day and night in eutrophic waters is higher than in oligotrophic lakes [28].

Eutrophication of waters will not only lead to algal blooms occurrence, but also to the extinction of submerged plants, as widely reported in other countries [29–34]. For example, the area of macrophytes in Lake Kasumigaura, Japan, varies with the total phosphorus concentration (Figure 7). The total phosphorus concentration of the lake has been increasing since the 1970s, while the macrophyte coverage, especially submerged plants, has been significantly decreasing [34]. Observations in Chesapeake Bay reveal that eutrophication has rapidly reduced submerged plants in the middle and upper part of the bay since the 1970s (Figure 8) [35].

The impact of eutrophication on lake ecosystem diversity and stability has not attracted much attention, despite a basic ecological rule that only diverse ecosystems are stable. If eutrophication reduces ecosystem diversity, it should also affect the stability of ecosystems, yet few studies show that eutrophication can undermine the diversity of ecosystems. James et al. [36] investigated the relationship between total nitrogen and nitrate nitrogen and submerged plant richness of 60 lakes in the United Kingdom and Poland and found that the diversity of macrophytes decreases with increasing

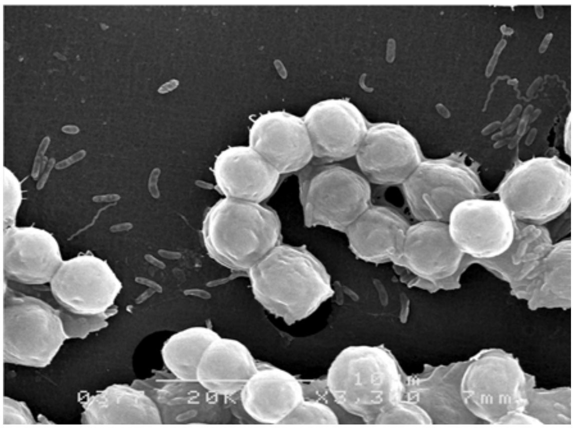

Figure 3 SEM photograph of Lake Taihu algae aggregates and the adhesive bacteria.

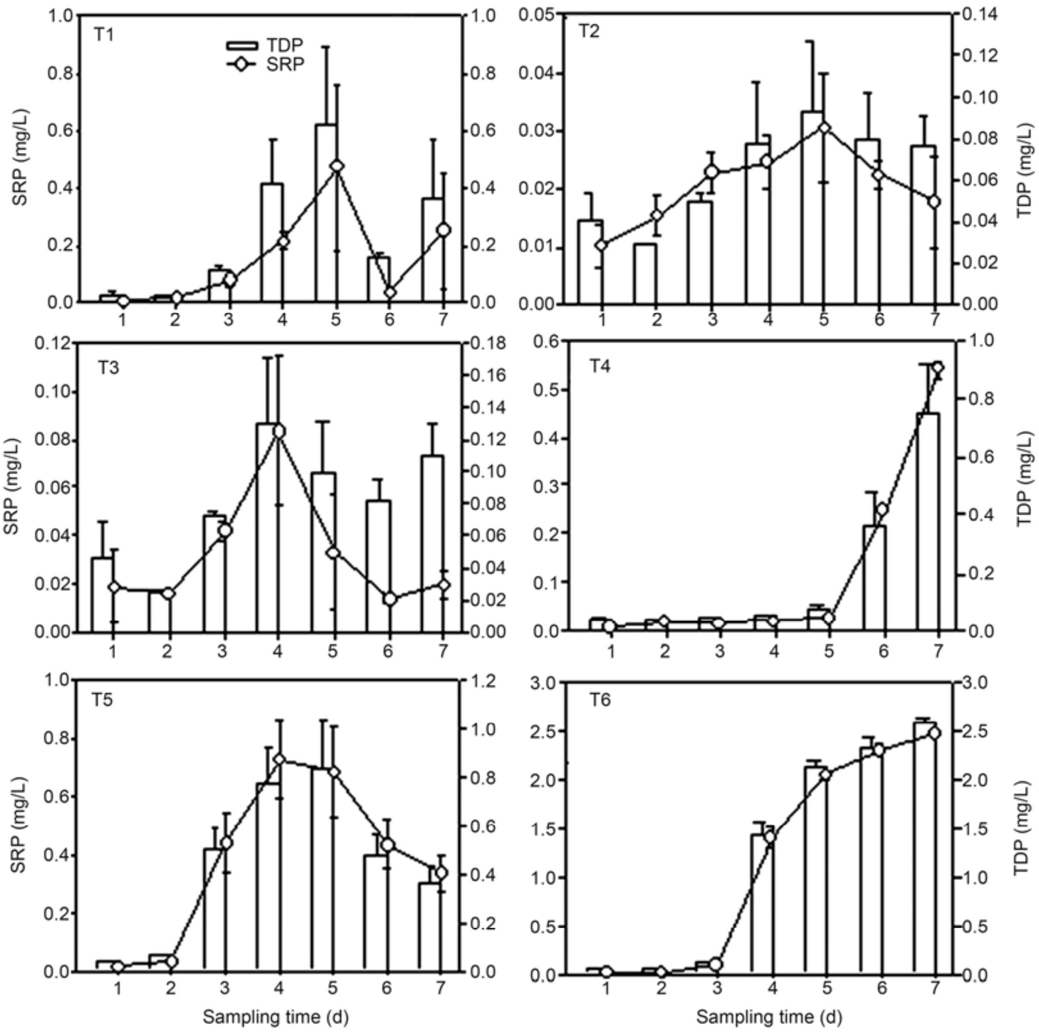

Figure 4 Phosphorus concentration (SRP and TDP) changes during algal aggregates degradation under different conditions in Taihu Lake [23].

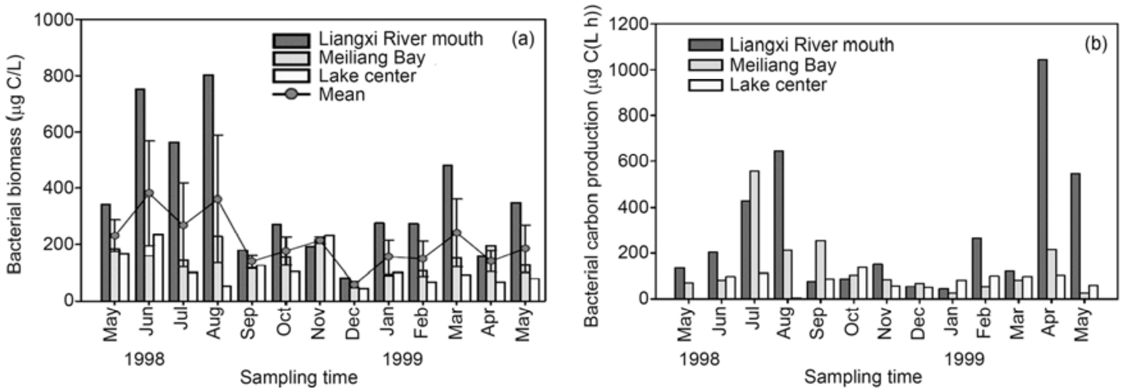

Figure 5 Microbial biomass (a) and microbial productivity (b) in three waters with different nutrients concentrations [24].

nitrogen concentration (Figure 9), especially with increasing concentrations of nitrate nitrogen in winter, followed by impacts of phosphorus.

The macrophyte species richness and area also declined during the eutrophication process in Lake Taihu. According to a 1960 survey, there were 66 species of macrophyte belonging to 48 genera and 29 families [34]; the dominant species of submerged plants was *Potamogeton malaianus Miq.* Submerged plants not only grew in large areas along East Taihu Bay and west Lake Taihu, but also appeared in

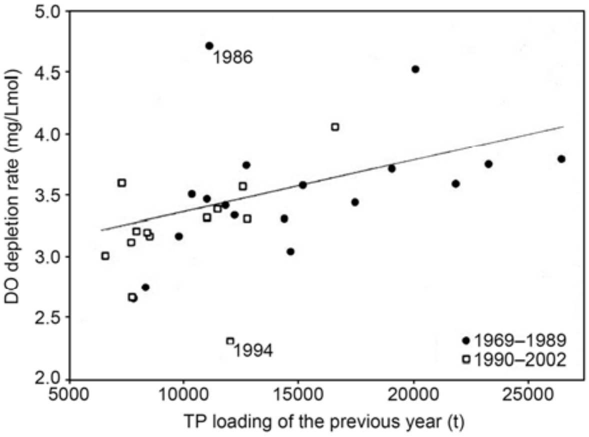

Figure 6 Correlation between weighted average dissolved oxygen depletion rate in water below the thermocline and the total input phosphorus load in the previous year in the U.S. Lake Erie [26].

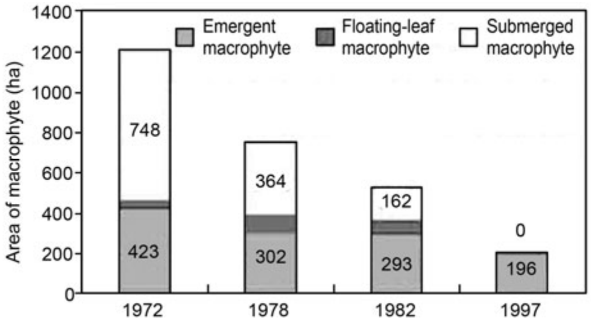

Figure 7 Changes in macrophyte coverage area of Lake Kasumigaura, Japan [34].

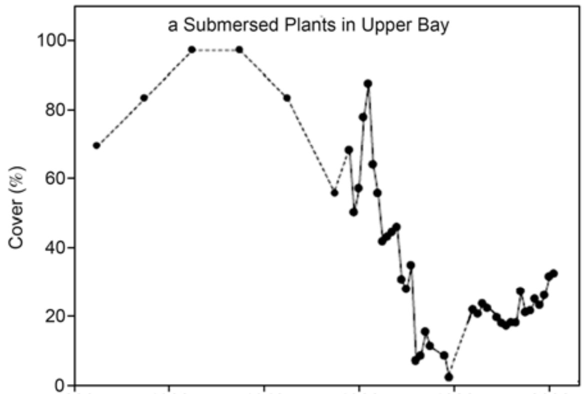

Figure 8 Changes of coverage of submerged plants in the middle and upper part of U.S. Chesapeake Bay [35].

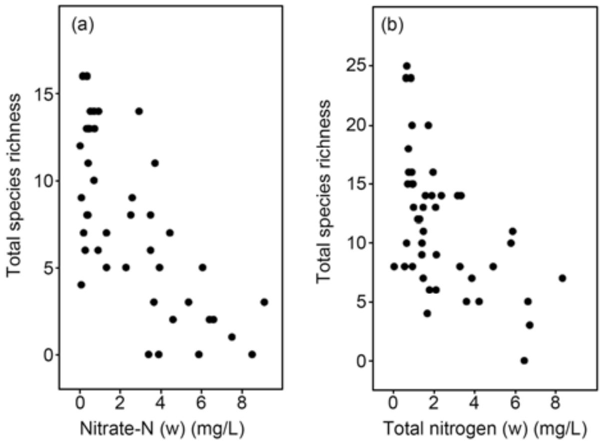

Figure 9 Correlation between macrophyte species richness and nitrate nitrogen and total nitrogen based on a survey conducted on more than 60 lakes in the United Kingdom and Poland [36].

large areas around Wuli Bay and other littoral zones [37]. In the late 1990s, macrophytes in Lake Taihu had dropped to 17 species, and the dominant species of submerged plants had shifted to *Vallisneria natan* [38]. Currently, 10 macrophytes are dominant in Lake Taihu: *Potamogeton malaianus Miq.*, *Nymphoides peltatum*, *Vallisneria natans*, *Hydrilla varticillata*, *Trapa natans* L., *Myriophyllum spicatum*, *Elodea nuttalli*, *Ceratophyllum demersum* L., and *Najas minor All.* These 10 species were associated with 6 vegetation species: *Potamogeton malaianus Miq.*, *Nymphoides peltatum*, *Nymphoides peltatum-Potamogeton malaianus Miq.*, *Vallisneria natans*, *Vallisneria natans - Elodea nuttalli*, and *Najas minor* [39]. The different time investigations show that the macrophyte diversity in Lake Taihu has significantly declined in the last decade, and eutrophication is clearly an important cause.

In addition to the decline in diversity, eutrophication also causes a significant reduction in the area of macrophyte coverage. Although macrophyte area has fluctuated since the 1960s, the overall trend is toward decline in the last half century. The area of submerged plants in Lake Taihu in the 1960s was about 530 km^2, was reduced to 400 km^2 in the late 1980s, and continued to decline until the early 1990s. Macrophyte area had somewhat recovered around 1997, attaining early 1980 levels. It was relatively stable after 2000, slightly increased by 2004, and significantly declined by 2007. Macrophytes reached their lowest area in history in 2009 but had increased somewhat by 2010 (Figure 10).

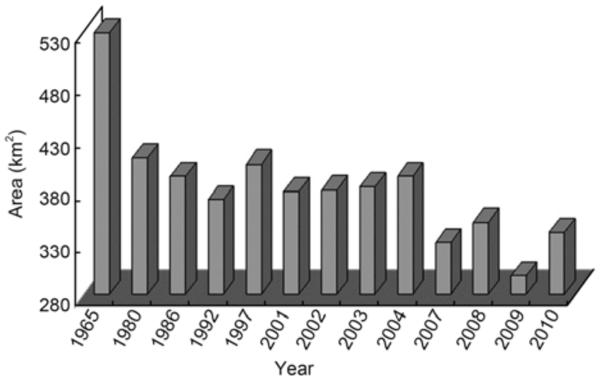

Figure 10 Changes of submerged plant area in Taihu Lake [40].

The impacts of eutrophication on phytoplankton diversity are relatively more complicated, with some studies indicating that eutrophication eventually undermines phytoplankton diversity [41]. One mesocosm experiment showed that phytoplankton diversity changes with the enrichment of nutrients (Figure 11). With increasing algal biomass, the phytoplankton biodiversity increased initially but eventually decreased significantly [41], indicating that eutrophication is harmful to phytoplankton biodiversity. We can thus derive that the dominant cyanobacterial bloom is only a transitional stage of lake eutrophication. With a continuous increase of nutrients, the ecosystem structure is bound to succession due to its instability. Some studies indicated that eutrophication also impacts microbial population structure and diversity, manifested by decreased autotrophic bacteria, increased heterotrophic bacteria, and lower diversity [42,43], indicating that eutrophication also leads to structural changes of the microbial ecosystem, mainly heterotrophic shifts.

According 2005–2010 monitoring conducted by Taihu Laboratory for Lake Ecosystem Research, Chinese Academy of Sciences, Lake Taihu eutrophication reduces phytoplankton diversity (Figure 12). Analysis of different trophic levels in different zones of Lake Taihu shows that phytoplankton diversity (Shannon-Wiener biodiversity index) decreases with the eutrophication index (Figure 12); however, monitoring data suggest that phytoplankton species richness increases with increasing trophic level, and dominant species shift from widely distributed species to species associated with pollution (such as *Microcystis*, *Anabaena*). The species richness is unevenly distributed, however, and therefore the species diversity index tends to decrease.

2 Lake eutrophication and ecosystem succession

Two main ecosystem succession issues arise from lake eutrophication: nutrient concentrations and ratio related to phytoplankton composition, dominant species, and cyanobacterial blooms; and succession between a macrophyte-dominated ecosystem and an algae-dominated ecosystem.

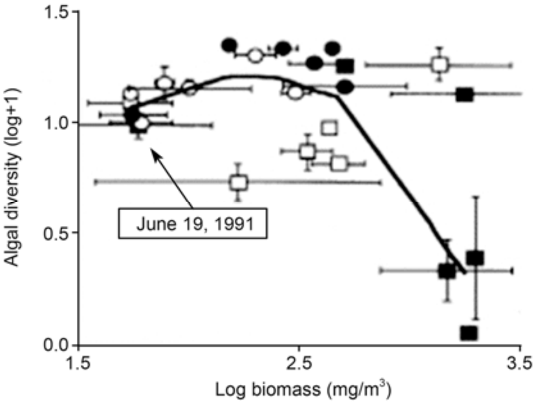

Figure 11 Increase of algal biomass and changes in algal biodiversity after addition of nutrients in a mesocosm experiment [41].

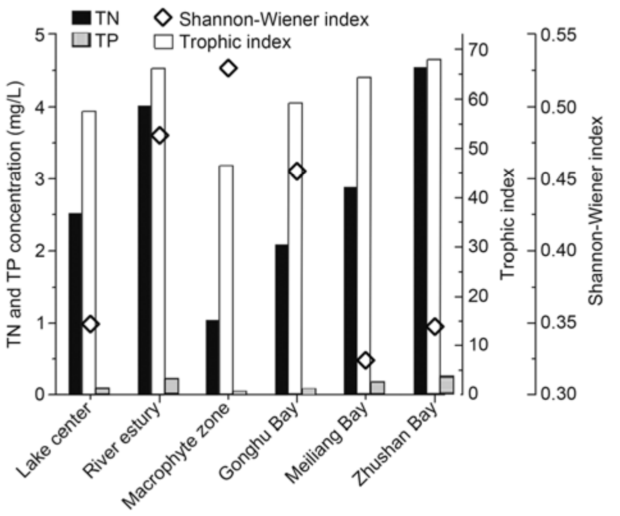

Figure 12 Summer (Jun.–Aug.) mean value of TN, TP, trophic index and Shannon-wiener index during 2005–2010 in different zones in Lake Taihu.

An increase of nitrogen and phosphorus in water promotes phytoplankton proliferation and even the occurrence of algal blooms. Investigations show that the proportion of cyanobacteria in the entire phytoplankton biomass increases with nutrients and chlorophyll *a* concentration, indicating that eutrophication and nutrient enrichment promote increased cyanobacterial biomass and cause it to become the dominant species in the phytoplankton composition (Figure 13) [44].

However, some eutrophic waters have shown that chlorophyta dominate when phosphorus concentration is high, cyanobacteria dominate, and phosphorus and nitrogen concentration is low [45]. We also noted in Lake Taihu and Meiliang Bay that the dominant species of cyanobacteria is replaced by chlorophyta in high concentrations of phosphorus [46]; however, if the phosphorus concentration is high and the nitrogen concentration is low, the dominant species is a nitrogen-fixing cyanophyta species (e.g. *Anabaena*), as

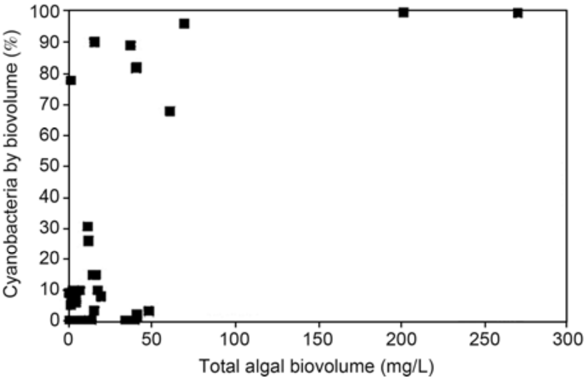

Figure 13 Based on nutrient level (phytoplankton biomass (mg/L) in summer) and proportion of cyanobacteria in phytoplankton biomass from 39 eutrophic lakes in Kansas, U.S. [44].

found in Okeechobee Lake in Florida, USA [47].

Regarding impacts of nitrogen and phosphorus on phytoplankton, the nitrogen and phosphorus ratio is often used to forecast whether cyanobacterial blooms will occur. The approximate ratio of carbon to nitrogen to phosphorus in algal cells is 41∶7.2∶1 (in weight). If the nitrogen and phosphorus ratio is less than 7∶1, algal blooms are prone to occur [48]. However, recent studies have shown that the ratio of nitrogen and phosphorus is not accurate in judging whether cyanobacterial blooms will occur [49]. When the nitrogen and phosphorus concentrations in the water column, especially the concentrations of bioavailable nutrients (mainly including inorganic nitrogen and phosphorus and dissolved nutrients), are higher than the thresholds beyond which the growth of algae will be restricted, the impacts of the nitrogen to phosphorus ratio on algae does not make sense. In Lake Taihu, the threshold of phosphorus is 0.2 mg/L and that of nitrogen is 1.8 mg/L [50]. The annual average total nitrogen concentration in Lake Taihu is 2.0–3.0 mg/L, and the total phosphorus concentration is about 0.1 mg/L; therefore, in many areas, the nitrogen concentration is above this threshold, while the phosphorus concentration is below this threshold. Phosphorus-restricted algal growth occurs in many zones, including Meiliang Bay, Gonghu Bay, Zhushan Bay, and the central lake area, while nitrogen-restricted algal growth occurs mainly in Meiliang Bay, especially in summer and autumn [50]. Nitrogen and phosphorus concentrations vary greatly in space and time, however, and thus the above-mentioned thresholds are on a multiple-year basis. Nitrogen and phosphorus concentrations vary significantly in Lake Taihu, as does the nitrogen and phosphorus ratio. Both the ratio of total nitrogen and total phosphorus and the ratio of dissolved nitrogen and dissolved phosphorus reach the maximum (80–100) in spring and the minimum (<10) in summer. As a result, the algal growth in many waters may be restricted by phosphorus in spring and by both nitrogen and phosphorus in summer and autumn [50]. This conclusion reinforces eutrophic lake restoration strategies that control phosphorus loading solely [51] or control both nitrogen and phosphorus loading [52].

As nutrients increase, macrophytes (mainly submerged plants capable of growing in the pelagic zone) will gradually go extinct in the waterbody, and phytoplankton will gradually prosper and eventually replace macrophytes as the major contributor to primary production of the ecosystem, a process known as the steady state conversion theory (Figure 14) [53,54]. The causes of macrophyte extinction remain unclear, however. We compared the biomass and growth rate of adhesive algae attached to the same macrophyte species in two different trophic level bays, Gonghu Bay and Meiliang Bay (total nitrogen and total phosphorus 0.772 and 0.029 and 1.935 and 0.108 mg/L, respectively) in Lake Taihu. The results revealed that the higher the trophic level, the higher the biomass of algae attached to the macrophyte and the more the macrophyte's photosynthesis is inhibited by the attached organisms. Macrophyte photosynthesis with or without attached algae differed up to 60%–90% [55], indicating that eutrophication leads to a large increase in planktonic or adhesive algae, which inhibit photosynthesis of the macrophyte. This process is consistent with phytoplankton biomass increase and transparency decrease with eutrophication.

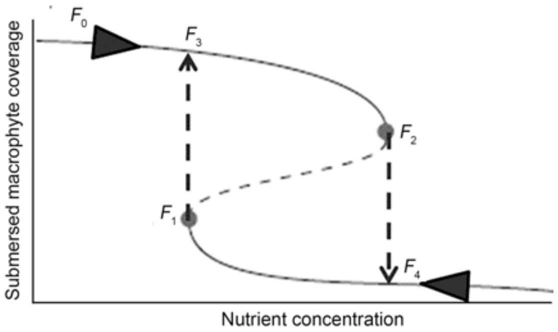

Figure 14 Process of lakes shifting from a macrophyte-dominated ecosystem to an algae-dominated ecosystem (F_0-F_2-F_4) due to eutrophication, followed by restoration to a macrophyte-dominated ecosystem (F_4-F_1-F_3) after reduction of nutrient loading [54].

What is the mechanism to replace a submersed macrophyte-dominated ecosystem with an algae-dominated ecosystem during eutrophication? In general, eutrophication leads to the extinction of macrophytes, resulting in large nutrient releases from the sediment, which accelerates eutrophication of lakes [56,25]. For instance, studies in Lake Taihu indicated that hydrodynamic disturbance inducing sediment phosphorus releasing might be the main pathway of internal P release in Lake Taihu [57]. Hence, sediment dredging is often used to improve the water quality [58]. However, our study suggests that eutrophication leads to a significant increase of biomass of phytoplankton and adhesive algae, resulting in the increase of organic particulate matter. As water transparency decreases, photosynthesis of macrophytes is restricted; however, the large amount of organic aggregates synthesized from algae and microorganisms significantly increases, and degradation and mineralization of organic matter with bacteria gradually facilitate the release of bioavailable nutrients and thus accelerate the growth of phytoplankton. With the increase of organic aggregates after eutrophication, the process of nutrient cycling from inorganic form to organic form due to algae uptake, and then back to inorganic form through degradation and mineralization, becomes continually shorter. Studies have shown that the average degradation rate of phosphorus in the most heavily polluted estuarine areas is 0.171 μmol/(h L); the rate in Meiliang Bay is 0.154 μmol/(h L), and that in the central lake is 0.139 μmol/(h L) [23,59]. The cycle and regeneration of nitrogen is basically similar to that of phosphorus [60]. This degradation and mineralization rate increases with eutrophication, reflecting increased microbial biomass and productivity.

In addition to bacteria, the distribution and characteristics of protozoa in Lake Taihu show it also is higher in the heavily polluted Meiliang Bay than in the lightly polluted central lake area [61], indicating that the more serious the lake water pollution, the higher the microbial biomass and productivity and the faster the nutrients cycle. In turn, this will increase the lake eutrophying process, forming a vicious cycle of nutrients supply.

This mechanism indicates that ecosystem succession arising from eutrophication is related to the nutrient utilization efficiency of biotic communities in waters. In macrophyte-dominated areas, the aquatic vascular plants germinate, grow to wither taking for a few months. When the nutrient supply exceeds demand, however excess nutrients can only be utilized by phytoplankton and adhesive algae, resulting in a significant increase in phytoplankton biomass and chlorophyll *a* concentration. The increased organic aggregates associated with the phytoplankton provide a steady supply to the bacterial biomass causing bacterial production to increase, which in turn accelerates degradation and mineralization and increases the bio-availability of nutrients. Meanwhile, with lower transparency and reduced dissolved oxygen, macrophytes are gradually replaced by phytoplankton. The nutrient cycle during the life of the macrophyte (i.e., from absorbing nutrients and forming organisms to degradation and mineralization after death to releasing nutrients) is obviously longer than that of phytoplankton. This is likely the actual mechanism of succession between aquatic-plant-dominated ecosystems and algae-dominated ecosystems.

3 Lake eutrophication research proepect

Through the efforts of many scientists in fields related to lake eutrophication, eutrophic lake restoration, and biodiversity conservation, the basic consensus is that eutrophic lake restoration must be based on the diversion of effluents from the watershed and reduction of internal loading, followed by implementation of ecological restoration and biodiversity protection. This plan must be implemented by administrative departments and produce tangible results. Recently in Lake Taihu, the maximum area and frequency of cyanobacteria blooms have shown a decreasing trend.

Although much has been learned regarding the impacts of lake eutrophication on ecosystems, many questions remain unclear. For example, what are the outbreak dynamics of cyanobacterial blooms after eutrophication? Why do algal blooms appear and disappear suddenly? Although the answers are clearer now that nutrients, light, temperature and hydrodynamic force have all have been shown to influence formation of cyanobacterial blooms, the mechanism of a specific cyanobacterial bloom remains unknown. The key question is how these environmental factors act during the development of cell division and colony proliferation to form sufficient cyanobacterial biomass. For instance, during the formation process of cyanobacterial blooms, how do the cyanobacteria colonies form and eventually float up to form blooms? Because the mechanisms of cyanobacterial blooms is still not clear, prediction and early warning of cyanobacterial blooms remain short-term, hydrodynamic-based, onshore migration and accumulation forecasts.

In addition, we recognize that lake eutrophication results in the gradual replacement of macrophyte communities with phytoplankton communities; in other words, macrophyte-dominated lake ecosystems gradually shift to algae-dominated lake ecosystems. If nutrients continue to increase, a cyanobacteria-dominated ecosystem is likely to be replaced by chlorophyta-dominated ecosystem, but the causes of such succession remain unclear. If nutrients are further enriched, the algae-dominated ecosystem may disappear, and the heterotrophic-organism-dominated ecosystem may replace the phytoplankton-dominated autotrophic ecosystem. The mechanism of such ecosystem succession is likely related to the competitive strategy of nutrients between submersed macrophyte and phytoplankton.

We already know that eutrophication leads to biodiversity loss, which means that the stability of ecosystems declines, but what causes the decline in the diversity? Decreasing phytoplankton diversity caused by eutrophication is bound to affect zooplankton and nekton diversity as a bottom-up effect of the food chain. The decline in the diversity of these top-level species leads to a decline in the diversity and stability of the whole ecosystem. In-depth work on this subject is still lacking. For example, we know that fluctuations in diversity are closely related to habitat conditions for macrophytes and animals. In oligotrophic waters, nutrient enrichment can improve the habitat environment and increase its diversity; but if nutrients continue to increase, will biological diversity ultimately decline? This speculation requires future verification.

Finally, can ecosystems of eutrophic lakes be restored to their original state and population level? The answer may be no. Studies have shown that although water quality and ecosystems can be restored in eutrophic lakes, a comparison of gene fragments of some zooplankton indicates changes in their evolution tracks that prevent them from returning to their original state and population level [62], and that some can no longer evolve to the original species. If this is true, the effects of eutrophication and pollution on ecological communities have been greatly underestimated, and further studies are needed to address unanswered questions.

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