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Mitigation of lake eutrophication: Loosen nitrogen control and focus on phosphorus abatement

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Abstract

Traditionally, nitrogen control is generally considered an important component of reducing lake eutrophication and cyanobacteria blooms. However, this viewpoint is refuted recently by researchers in China and North America. In the present paper, the traditional viewpoint of nitrogen control is pointed out to lack a scientific basis: the N/P hypothesis is just a subjective assumption; bottle bioassay experiments fail to simulate the natural process of nitrogen fixation. Our multi-year comparative research in more than 40 Yangtze lakes indicates that phosphorus is the key factor determining phytoplankton growth regardless of nitrogen concentrations and that total phytoplankton biomass is determined by total phosphorus and not by total nitrogen concentrations. These results imply that, in the field, nitrogen control will not decrease phytoplankton biomass. This finding is supported by a long-term whole-lake experiment from North America. These outcomes can be generalized in terms that a reduction in nitrogen loading may not decrease the biomass of total phytoplankton as it can stimulate blooms of nitrogen-fixing cyanobacteria. To mitigate eutrophication, it is not nitrogen but phosphorus that should be reduced, unless nitrogen concentrations are too high to induce direct toxic impacts on human beings or other organisms. Finally, details are provided on how to reduce controls on nitrogen and how to mitigate eutrophication.

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Keywords: Lake eutrophication; Cyanobacteria blooms; Lake restoration

1. Introduction

Eutrophication of waters is the phenomenon of an ecosystem becoming more productive by nutrient enrichment, stimulating primary producers. It is usually characterized by algal blooms, causing water quality deterioration and fish kills. It is becoming a global environmental crisis. In China, the problem of lake eutrophication is extremely severe, with frequent cyanobacteria blooms threatening the ecology of waters, economic development and society stability. The most representative case is the cyanobacteria bloom that occurred in Lake Taihu in 2007, resulting in a shortage of drinking water and domestic water for 5 mil-

lion citizens in Wuxi, Jiangsu Province. Therefore, mitigation of lake eutrophication and cyanobacterial bloom is of great importance in China and the world.

To mitigate eutrophication and cyanobacterial blooms, nutrient control is a fundamental process. Traditionally, besides phosphorus control, nitrogen control is generally considered a necessary practice. Abundant funds have been spent on nitrogen removal during wastewater treatment processes. However, recent researches in China [1] and North America [2] suggest a change to the traditional practice of nitrogen removal for inland waters: to mitigate eutrophication, it is not nitrogen but phosphorus that should be reduced. This finding is of critical importance for the practice of lake restoration.

In this paper, the traditional viewpoint of nitrogen control is pointed out first to lack a conclusive scientific basis.

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Then, new researches are introduced to elaborate a general rule: reduction in nitrogen loading cannot decrease total phytoplankton biomass, but stimulates blooms of nitrogen-fixing cyanobacteria. Further analyses proceeded to elaborate on the significance of this general rule for the strategy to control the source of nutrients. In the end, suggestions on lake restoration are proposed in detail.

2. The traditional viewpoint of nitrogen control lacks conclusive scientific bases

The traditional viewpoint of limiting nutrient control on phytoplankton biomass is based mostly on considerations of N/P (ratio of total nitrogen to total phosphorus) and on bottle bioassay experiments. However, the following analyses indicate that both the hypothesis and the experiment are not conclusive.

2.1. The N/P hypothesis is a subjective assumption

The ratio of total nitrogen to total phosphorus of water (TN/TP, usually measured by mass) has long been used to discriminate the nutrient limiting phytoplankton. Generally, lakes have been regarded as limited by phosphorus if TN/TP was relatively large (such as $TN/TP > 17$), limited by nitrogen if TN/TP was relatively small (such as $TN/TP < 10$) and colimited by nitrogen and phosphorus when TN/TP was intermediate (such as $10 < TN/TP < 17$). However, the thresholds of TN/TP to indicate nutrient limitation vary greatly in the literature, being for instance 10–17 [3], 10–30 [4], and 7–15 [5]. The variation itself implies that this method is not reliable. Some limnologists have used the ratio C:N:P (106:16:1 by atoms; 41:7:1 by mass) proposed by Redfield et al. [6] as a criterion to assess nutrient limitation. Again, the Redfield ratio is not a universal optimum ratio, but an average of species-specific ratios. The optimum N/P ratios vary greatly among various freshwater phytoplankton species, from 4.1 to 133.3 [7,8]. Obviously, it is almost impossible to set a specific “cut-off” ratio to identify a limiting nutrient(s) for a multi-species community.

By analyzing the regressions and scatterplots of phytoplankton chlorophyll *a* (Chl *a*) with nitrogen and phosphorus, Sakamoto [3] first proposed the N/P hypothesis. However, when probing into the evidence, we find that his conclusion is just a subjective judgment on the patterns of the scatterplots. Points far below the $\log(TN) - \log(Chl\ a)$ regression line are generally regarded as limited by phosphorus. In his analysis, he noted three points with a N/P ratio larger than 15–17 deviating below the $\log(TN) - \log(Chl\ a)$ regression line. He concluded that phosphorus became the critical limiting factor if the N/P ratio was larger than 15–17. In fact, there are ten points with this level of N/P ratio and the left seven points fell exactly on the regression line. Obviously, such a reasoning based on minor points is not right. Similarly, he concluded that phytoplankton was limited by nitrogen when N/P was less than 9–10 based on two outlier points, when analyzing

the regression relationship between $\log(TN)$ and $\log(Chl\ a)$. Therefore, this earliest empirical evidence does not support the N/P hypothesis.

Many researchers have followed the principles espoused by Sakamoto [3] to analyze the limiting nutrient, by comparing the differences between Chl *a*/TP and Chl *a*/TN, and Chl *a* variations under different N/P ratios [7,9,10]. However, all the analyses have been performed without strict statistical tests, failing to prove that the dependence of phytoplankton on nitrogen and phosphorus are significantly different under different N/P ratios.

In conclusion, through logical reasoning and empirical analyses, the N/P hypothesis is found to be just a subjective assumption without conclusive evidence. In Section 3.1, our recent researches will be introduced to disprove this hypothesis.

2.2. Bottle bioassay experiments are too small in scale to simulate the natural process of nitrogen fixation

Bottle bioassay experiments have also long been used to demonstrate the limiting nutrient of phytoplankton in a waterbody. The experiments are usually performed in an enclosed container to discriminate the limiting nutrient by observing the growth of phytoplankton after nutrient addition. They generally last a period between several hours to 1 week. If growth of phytoplankton is stimulated by the addition of some nutrient, this nutrient is considered to be the limiting factor. Due to their small scale in time and space, these experiments fail to simulate some important processes in real open systems such as biological nitrogen fixation. Therefore, bottle bioassay experiments cannot prove the long-term existence of nitrogen limitation in the field. In Section 3.2, whole-lake experiments in North America are introduced to indicate that deficiency in nitrogen may stimulate growth of nitrogen-fixing cyanobacteria.

3. New researches find that nitrogen control fails to restrain total phytoplankton, but stimulates blooms of nitrogen-fixing cyanobacteria

In May 2008, our article disproved the N/P hypothesis based on regional comparative studies [1]. In August 2008, an article by researchers from North America indicated that nitrogen control might stimulate nitrogen-fixing cyanobacteria based on a long-term whole-lake experiment [2]. Accordingly, it appears that reduction in nitrogen loading cannot decrease the biomass of total phytoplankton. It is also logical when comparing the cycling characteristics of nitrogen and phosphorus.

3.1. Regional research in the Yangtze Basin

To test the N/P hypothesis on a large scale, we analyzed the relationships of chlorophyll *a* with total nitrogen and total phosphorus based on multi-year investigations of more than 40 Yangtze lakes [1].

Separate regressions of $\log(\text{Chl } a)$ on $\log(\text{TN})$ and $\log(\text{TP})$ were analyzed for lakes with different TN/TP ratios by mass (according to the TN/TP thresholds proposed by Sakamoto [3]). Almost all the TP-Chl a regressions had higher R^2 values and lower percentage predictive error than those of TN-Chl a regressions, indicating the superiority of TP over TN as a predictor and failure of TN/TP to indicate nutrient limitation.

Because different thresholds of TN/TP ratios have been proposed in the literature, we further compared the differences of R^2 values between TP-Chl a and TN-Chl a regressions over the complete TN/TP spectrum. The results showed that 28 R^2 values (70%) of TP-Chl a regressions were higher than those of TN-Chl a regressions over the entire TN/TP spectrum. According to the traditional N/P hypothesis, these cases should be limited by phosphorus and have relatively high TN/TP ratios. However, they were not confined to any specific region of higher TN/TP ratios, but distributed evenly between 5 and 50. It further demonstrates the failure of TN/TP to indicate nutrient limitation.

To differentiate the effects of TN and TP on Chl a , we further regressed Chl a /TP to TN/TP and Chl a /TN to TP/TN. For a given amount of TP, Chl a varied regardless of the changes of TN. That is, within the TN/TP range of the present research, Chl a /TP tends towards a specific value. However, for a given amount of TN, Chl a increased rapidly with the increase in TP. Therefore, in the field, the total phytoplankton biomass is not determined by TN but by TP.

Our research disproved the traditional viewpoint of using N/P as an index to discriminate nutrient limiting phytoplankton. We are of the opinion that TP is the primary factor regulating phytoplankton Chl a regardless of the concentration of TN. In the field, the amount of total phytoplankton is not determined by TN but by TP. Therefore, reduction in nitrogen loading cannot decrease the amount of total phytoplankton.

3.2. Long-term whole-lake experiments in Canada

In Lake 227, a small lake in the Experimental Lakes Area (ELA) of Ontario, Canada, researchers from Canada and the USA have performed whole-lake fertilization experiments for 37 years [2]. The lake has been fertilized with constant phosphorus and decreasing nitrogen addition. In the end, nitrogen addition ceased. The lake remained highly eutrophic throughout the experiments, with frequent blooms of cyanobacteria and other algae.

For the first 6 years (1969–1974), the ratio of nitrogen to phosphorus added in fertilizer was 12:1 by mass. Lake 227 became highly eutrophic as the result of this fertilization, and phytoplankton developed rapidly and formed blooms. The average Chl a was 0.03 mg/L. The algal assemblage was dominated by small unicellular desmids with large populations of *Limnithrix redekei*. No nitrogen-fixing alga was found. For the next 15 years (1975–1989), the ratio of nitrogen to phosphorus in fertilizer added to the lake was decreased to about 5. Nitrogen-fixing *Aphanizomenon*

schindlerii appeared in significant numbers after several weeks, and by the early 1980s, it dominated the summer assemblage and formed blooms. Total nitrogen stayed constant for 3 years after nitrogen fertilizer was decreased and even increased 3 years later. Chl a was generally over 0.025 mg/L. For the final 16 years (1990–2005), the lake was fertilized with phosphorus alone. Total nitrogen and Chl a stayed at high levels. The nitrogen-fixing algae (mainly *A. schindlerii*) always formed >50% of the total phytoplankton biomass and bloomed frequently. During the latter two experimental periods, non-fixing cyanobacteria, most notably *L. redekei*, also remained prominent, but tended to increase after midsummer blooms of nitrogen-fixing cyanobacteria, suggesting a competitive advantage of nitrogen-fixers when nitrogen became deficient and of non-fixers when recycled fixed nitrogen became available.

This experiment indicates that reduction in nitrogen loading may stimulate blooms of nitrogen-fixing cyanobacteria. Given enough phosphorus and with sufficient time, the process of nitrogen fixation is sufficient to allow biomass to continue to be produced in proportion to phosphorus, and the lake is still highly eutrophic.

In China, the blooming sequence of algae in Lake Chao-hu, Lake Dianchi and Lake Erhai is similar to that in the Canadian experiment lake. Nitrogen-fixing cyanobacteria (such as *Anabaena* sp. and *Aphanizomenon* sp.) generally form blooms in spring, while non-fixers (such as *Microcystis* sp.) generally form blooms in summer. This phenomenon may imply that in these lakes a cyclical process of denitrification and nitrogen fixation occurs, and it also indicates that nitrogen control does not exactly help the mitigation of eutrophication and cyanobacteria bloom.

3.3. Characteristics of nitrogen and phosphorus cycles

The nitrogen cycle in the biosphere is a gaseous process. The Earth's atmosphere contains about 78% N_2 , making it the largest pool of nitrogen. Fixation is necessary to convert gaseous nitrogen into forms usable by living organisms. There are four ways to convert N_2 into more chemically reactive forms: biological fixation e.g., the formation of organic nitrogen by algae and bacteria (comprising 53% of the total), lightning (the formation of NO_x from N_2 and O_2) (2%), combustion of fossil fuels (automobile engines and thermal power plants, which releases various nitrogen oxides, NO_x) (10%) and industrial nitrogen fixation (N_2 is converted into NH_3 to make fertilizer and explosives) (36%) [11,12].

In anaerobic conditions, fixed nitrogen is reduced back into N_2O and N_2 by denitrifying bacteria. The complete nitrogen cycle provides almost boundless nitrogen for algae in lakes. In eutrophic lakes, the average contribution of nitrogen fixed by algae to the total nitrogen loading reaches 28% (6–82%) [13]. In Lake Erken, Sweden [14] and Lake Mize, USA [15], the natural rates of nitrogen fixation are 3 g m^{-2} per year and 7 g m^{-2} per year, respectively, amounting to fertilizing 141 kg ha^{-1} per year and

330 kg ha⁻¹ per year with (NH₄)₂SO₄ for these two lakes. Therefore, in the long term, growth of algae in lakes will not be limited by nitrogen deficiency even if nitrogen loading can be controlled effectively.

The phosphorus cycle is a sedimentary process. Phosphorus enters the environment from rocks or soils. Much of the phosphate is washed into the water from erosion and mining. These phosphates tend to settle on lake and ocean floors. It may reenter the cycle through geological processes. However, the process usually takes millions of years. In the phosphorus cycle, some phosphates enter lakes through surface runoff and discharge of sewage and wastes. In lakes, most of the phosphate load is absorbed by living organisms or settles on the lake bottom. Due to its finite source and tendency to settle out, limitation by phosphorus on primary production in lakes will be definitely stronger than that of nitrogen in the long term.

According to the recent researches and the comparisons between nitrogen and phosphorus cycles, a general rule can be deduced: on a scale of several months to years, reduction in nitrogen loading cannot decrease the phytoplankton biomass; only phosphorus abatement can effectively mitigate eutrophication and cyanobacteria bloom. This rule can be applied in lakes, reservoirs and ponds with low water turnover rates. It can also be generalized to estuarine waters [2].

4. To mitigate eutrophication, it is not nitrogen but phosphorus that should be reduced

The new-found general rule is of great practical value for lake management. It indicates that, for the practices of nutrient control, it is not nitrogen but phosphorus that should be reduced to mitigate eutrophication unless the nitrogen concentration is too high to the extent of being toxic to human beings or other organisms. In fact, this has been proved to be true by whole-lake experiments and practices of lake restoration. It should be so according to logical reasoning and cost comparison.

4.1. Whole-lake experiments indicate that phosphorus alone can effectively mitigate eutrophication

To explore the mechanism of eutrophication, whole-lake fertilization experiments were performed in two lakes in the Canadian Experimental Lakes Area, one in Lake 304 (3.62 ha in area) and the other one in Lake 226 (16.1 ha in area). The one in Lake 304 lasted 3 years (1971–1973) [16]. During the 3 years, prior to fertilization, phytoplankton Chl *a* was generally below 0.01 mg/L. In the first two experimental years, 5.5 g/m² carbon, 5.2 g/m² nitrogen, and 0.4 g/m² phosphorus were added to the lakes each year. Algae blooms occurred in these 2 years, with a maximum Chl *a* of 0.05 mg/L and 0.12 mg/L, respectively. In the third year, phosphorus fertilization ceased but carbon and nitrogen addition stayed constant. Blooms ceased and Chl *a* recovered to the level before the fertilization.

The experiment in Lake 226 lasted at least 14 years (1973–1986) [17,18]. The lake has a ‘figure of 8’ shape and was divided into two approximately equal portions (the north region and the south region) using a plastic divider curtain. In the south lake region, 6.05 g/m² carbon and 3.16 g/m² nitrogen were added to the lake each year. The total phytoplankton biomass stayed constant and Chl *a* remained at about 0.01 mg/L. In the north lake region, not only identical areal rates of carbon and nitrogen addition were used to those in the south region, but 0.59 g/m² phosphorus was added each year for the first 10 years. Cyanobacteria bloomed frequently. After the tenth year, no phosphorus was added and algae blooms ceased immediately with Chl *a* below 0.01 mg/L. In comparison with the first experiment, the second experiment set a control and lasted longer. However, the same outcomes were obtained. This sufficiently proves that the key factor causing lake eutrophication is neither carbon nor nitrogen but phosphorus; phosphorus abatement alone can effectively recover eutrophic lakes.

4.2. Practices of lake restoration indicate that focus on phosphorus can mitigate eutrophication effectively

Lake restoration practices in Europe and America also prove that the focus on phosphorus can effectively mitigate eutrophication [19–21]. The most representative case is the recovery of Lake Washington in Seattle, USA [19,22]. It is the second largest natural lake in the state of Washington, with an area of 87.6 km². During the 1930s, sewage entering the lake caused a rapid increase in phosphorus of lake water and severe eutrophication. Blooms of cyanobacteria occurred continuously from 1955 to 1976. Since 1936, sewage diversion focusing on phosphorus removal has been put into practice. All sewage inputs into the lake ended before 1968. After the sewage diversion, total phosphorus decreased significantly, being 0.07 mg/L, 0.03 mg/L and 0.02 mg/L in 1963, 1968 and 1979, respectively. There was less variation of nitrogen. Nitrate concentrations were 0.44 mg/L, 0.37 mg/L and 0.30 mg/L and total Kjeldahl nitrogen concentrations were 0.29 mg/L, 0.31 mg/L and 0.20 mg/L in 1963, 1968 and 1979, respectively. Simultaneously, total phytoplankton biomass decreased significantly. Chl *a* in the summers of 1963, 1968 and 1979 was 0.03 mg/L, 0.01 mg/L and 0.002 mg/L, respectively. The dominance of cyanobacteria also decreased, changing from levels above 90% during 1962–1968 to levels below 20% during 1976–1978. Therefore, phosphorus abatement is the main reason to explain the recovery of Lake Washington from eutrophication.

In China, the Diversion Project of Lake Xihu is an experiment succeeding in eutrophication mitigation, in which only phosphorus was controlled.¹ The project has

¹ Water Administration Office of Lake Xihu, Hangzhou. Assessment on the Benefit of the Diversion Project of Lake Xihu, 2006.

been put into practice since 2003. Water from the Qiantangjiang River was diverted to the various regions of Lake Xihu after preliminary treatment. Nutrients from river water before the preliminary treatment were high, with TN and TP of 3.08 mg/L and 0.13 mg/L, respectively, in 2005. In the process of preliminary treatment, only flocculation and precipitation were performed. Nitrogen was not removed effectively in the process. Concentrations of TN and TP in the water diverted into the region of Xiaonanhu in 2005 were 2.07 mg/L and 0.04 mg/L, respectively. However, phytoplankton biomass in the lake was still low. After diversion (2005–2006), Chl *a* of various regions decreased 11–82% in comparison to the levels before diversion (2002–2003). Further correlations indicate that the changes of Chl *a* were largely determined by the changes of TP ($r = 0.93$, $n = 5$, $p < 0.001$), but independent of the changes of TN ($r = -0.46$, $n = 5$, $p = 0.44$). This indicates that focus on phosphorus abatement can effectively control the phytoplankton in Chinese lakes.

4.3. Logical reasoning indicates that only one element needs to be controlled to mitigate eutrophication

To promote growth of living organisms, every essential element should be provided. However, to limit their growth, only one essential element needs to be controlled. These two processes are often confused. For the growth of phytoplankton, both nitrogen and phosphorus are the essential macronutrients. To mitigate eutrophication, only one element needs to be controlled. Because phosphorus is relatively easy to control, it should be focused upon to mitigate eutrophication.

4.4. Focus on phosphorus abatement can greatly decrease the cost of wastewater treatment

If we focus on phosphorus abatement in wastewater treatment plants, the cost can be greatly decreased. First, nitrogen removal needs prolonged processing involving microorganisms to carry out nitrification and denitrification steps. Therefore, the cost is relatively high. In comparison, the process of phosphorus removal is easier, with a lower cost. Through flocculation and filtration, the removal rates of phosphorus in wastewater can reach 80–95%, meeting directly the first class A discharge standard for a wastewater treatment plant. Second, the needs for nitrogen and phosphorus removal contradict each other in the process of wastewater treatment. Therefore, focus on both nitrogen and phosphorus will definitely decrease the efficiency and hence increase the costs. The process of efficient nitrogen removal needs low F/M (organic loading rate) and high SRT (sludge retention time in the system), while the process of efficient phosphorus removal needs high F/M and low SRT. If only phosphorus removal is needed, the removal rate can approach 80% when SRT is set shorter than 6 days. While in the anaerobic–anoxic–oxic (A/A/O) process, where both nitrogen and phosphorus are

focused, the SRT should be set between 8 and 15 days and the removal rate will be decreased to 50% [23].

5. Suggestions on loosening or cancelling nitrogen control and abatement of lake eutrophication

To accelerate the solving of the eutrophication crisis, four suggestions are proposed as follows according to the above-mentioned reviews and relevant research.

5.1. Perform pilotscale experiments as quickly as possible: loosen or cancel nitrogen control in wastewater treatment

In China, the problems of lake eutrophication and cyanobacteria bloom are becoming more and more severe. The most fundamental restoration measure is pollutant control. However, many wastewater treatment plants do not run regularly due to the high costs. The complex process of nitrogen removal is the main reason. It is better to try to remove phosphorus only and not to remove nitrogen or remove less nitrogen than to leave these treatment plants unused. It is suggested to perform pilotscale experiments in the wastewater treatment plants in various regions of our country to loosen nitrogen control, monitor the development of eutrophication and cyanobacteria bloom to test the efficiency of water treatment and generalize the experiences throughout the country. The costs of wastewater treatment are expected to be greatly reduced.

There may still be someone who disagrees with our viewpoint of “no need for nitrogen control to mitigate eutrophication”. In this case, we may follow the principle of “No Argument” proposed by Mr. Xiaoping Deng and perform pilotscale experiments as quickly as possible to reduce or cancel nitrogen control to test this method as a practical restoration on a larger scale.

5.2. Revise discharging standard of pollutants and quality standards for surface water to delete nitrogen limits

When considering only the control on phytoplankton, there is no need to control nitrogen for relevant water quality standards. However, the limits on nitrogen set by the present standards of our country are too strict. The limits of Discharging Standards of Pollutants for Municipal Wastewater Treatment Plant (GB 18918-2002) and Environmental Quality Standards for Surface Water (GB 3838-2002) on total nitrogen are 15–20 mg/L (standards of First Class A and B) and 0.2–1.0 mg/L (Classes I–III), while the limit of Standards For Drinking Water Quality (GB 5749-2006) on nitrate is 10–20 mg/L. Obviously, the various limits on nitrogen can be greatly loosened or cancelled to set economic and practical management targets. However, some forms of nitrogen are toxic to human beings and aquatic organisms when the concentrations are high enough [24]. Unionized ammonium is very toxic to aquatic animals, particularly to fish by causing asphyxiation, inhibition of ATP production, and repression of the

immune system. Nitrite may cause fish and crayfish hypoxia and ultimately death by converting oxygen-carrying pigments to forms that are incapable of carrying oxygen. Therefore, before loosening or cancelling the limits on nitrogen, it is quite necessary to explore the effects of high nitrogen on the lake ecosystem and determine the maximum allowable concentration. It is suggested to fund some relevant institutions to perform regional comparative limnological researches and whole-lake experiments to explore the approaches and intensity of the effects of high nitrogen on aquatic organisms and the integrity and resilience of the lake ecosystem. In combination with the above pilot works, it is suggested to revise discharging standards and water quality standards according to the functions of different waters.

5.3. Take discriminative measures for lakes of different states to mitigate eutrophication: perform mainly environmental engineering focusing on phosphorus abatement firstly in highly eutrophic lakes, while performing mainly ecological engineering in moderate-eutrophic lakes

In recent years, there occurs a misunderstanding in the eutrophication mitigation of our country, i.e., perform ecological engineering such as macrophyte planting disregarding the degree of pollution. According to one of our recent researches, the ecosystem of shallow lakes can only stay in a turbid-water stable state dominated by phytoplankton when TP exceeds 0.1 mg/L. The lake stays in a clear-water stable state dominated by submersed macrophytes when TP is less than 0.03 mg/L. The lake can be in either a turbid-water stable state or a clear-water stable state when TP ranges between 0.03 and 0.10 mg/L. Obviously, environmental engineering should be performed first to control point and non-point pollutants when phosphorus is overloaded; then, ecological engineering is performed to trigger the shift from a turbid-water state to a clear-water state after phosphorus is decreased enough. At present, 30% of the mid-lower Yangtze lakes have total phosphorus exceeding 0.10 mg/L. TP in the three most-watched lakes (Lake Taihu, Lake Chaohu and Lake Dianchi) reaches 0.20–0.40 mg/L. The efficiency of ecological engineering in these highly polluted lakes will be finite. This has been tested by many practices of recent years. Therefore, it is suggested to take discriminative measures for lakes of different states to mitigate eutrophication: perform mainly environmental engineering focusing on phosphorus abatement first in highly eutrophic lakes, while performing mainly ecological engineering in moderate-eutrophic lakes.

In China, ecological engineering concentrates mainly on artificial intervention in some local zones of lakes, such as macrophyte planting and fish stocking. Engineering like this usually needs great effort and energy. The system will not sustain itself without artificial maintenance. In fact, true ecological engineering is to create a necessary condition for the ecosystem to develop its self-organization func-

tion as much as possible and finally realize a sun-driven restoration of ecological integrity. Therefore, our ecological engineering should be designed to realize whole-lake ecological restoration based on self-organization of the system. In the mid-lower Yangtze Basin, regulation on water level should be considered first for ecological restoration, because periodic fluctuation of the water level is primarily important for the development of vegetation [25].

5.4. Establish Chinese Experimental Lakes Area to test mechanisms of cyanobacteria bloom and restoration measures

The success of eutrophication mitigation can only be realized based on the right understanding on objective rules. Although there have been many researches on the mechanisms of algae bloom in China and overseas, there are still few general rules that have received strict tests on a large scale. The reason is that most researches were carried out in the laboratory using small equipment and hence failed to simulate the complex process of real systems. For example, as one of the bases supporting the traditional view of nitrogen control, bottle bioassay experiments failed to simulate the process of nitrogen fixation due to their small scales in time and space, and hence resulted in incorrect conclusion. Besides regional comparative studies, manipulative experiments in real waters are necessary to explore the large-scale aquatic ecological principle.

There have been some large-scale limnological experimental platforms in the world. One of the most distinguished platforms is the Experimental Lakes Area (ELA) in Ontario, Canada. The ELA area was established more than 40 years ago. It includes 58 small lakes (1–84 ha in area) and their drainage and three river sections. Based on the agreement between the governments of Canada and Ontario, the area is set aside for scientific research. A series of whole-lake experiments have been carried out there by scientists from North America, and many key issues concerning eutrophication (as described previously), biomanipulation, ecological effects of reservoirs and acidification of waters have been solved there. Relevant achievement was published in *Science* [26].

Therefore, it is suggested to set aside dozens of lakes in the Yangtze Basin and somewhere else as the Experimental Lakes Area to establish a large-scale limnological experimental platform. On the platform, the macroecological mechanisms of eutrophication and the effectiveness of measuring mitigating cyanobacteria bloom and other environmental techniques on a whole-lake scale could be tested. These strategies will enable our country to formulate policy of aquatic environmental restoration on strong scientific bases.

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