

# Effects of Different Primary Producers (Cyanobacteria and Macrophyte) on the Spatio-Temporal Distribution of Phosphorus Forms and Concentrations in a Lake

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## Abstract

Lake eutrophication is concerning because of its harmful effects on water ecosystems. The field samplings were collected to investigate various forms of phosphorus in the water columns, clarifying the relationship between phosphorus levels and types of primary producers (cyanobacteria and macrophytes) in the different regions of Lake Taihu in China. High phosphorus levels were observed in Meiliang Bay suffering from cyanobacterial bloom, while phosphorus concentrations were relative lower in Xukou Bay and East Lake Taihu, where many macrophytes grow. Thus, cyanobacteria and macrophytes could significantly affect phosphorus forms and contents in the different lake regions. In Meiliang Bay, aqueous total phosphorus ( $TP_{\text{aqueous}}$ ) concentrations ( $0.312 \pm 0.158 \text{ mg} \cdot \text{L}^{-1}$ ), total dissolved phosphorus concentrations ( $0.108 \pm 0.072 \text{ mg} \cdot \text{L}^{-1}$ ), and dissolved inorganic phosphorus concentrations ( $0.018 \pm 0.022 \text{ mg} \cdot \text{L}^{-1}$ ) were much higher in July under the action of cyanobacteria than in any other period. Aqueous phosphorus concentrations in Xukou Bay and East Lake Taihu were much lower in July due to macrophyte growth. However, macrophyte decomposition made  $TP_{\text{aqueous}}$  concentrations in Xukou Bay extremely high in December. Furthermore, Exchangeable phosphorus (Ex-P), Al-combined phosphorus (Al-P), Fe-combined phosphorus (Fe-P), Autogenetic calcium phosphorus (ACa-P), detritus calcium phosphorus (De-P), and organic phosphorus (Or-P) in Meiliang Bay were much lower in July due to the action of cyanobacteria. However, only Ex-P, ACa-P, and Or-P contents in the sediments of macrophyte-dominated lake regions were much lower in July due to the growth of macrophytes. Therefore, interactions between phosphorus contents and types of primary producers were simultaneously observed in a single lake.

**Keywords:** Lake Taihu, phosphorus, eutrophication, cyanobacteria, macrophytes, sediment

## Introduction

Eutrophication of freshwater bodies such as lakes, reservoirs, and rivers has become a worldwide environmental problem, and is of great concern to increasing amounts of researchers [1-8]. However, most emphasis has been put on the cyanobacteria-dominated eutrophication due to the harmful effects of nuisance, toxic algal blooms, and their induced algal toxins to the freshwater ecosystems [4, 6]. Relative little attention has been paid to macrophyte-dominated eutrophication, which is usually ignored as if there are no harmful effects in these ecosystems. In fact, macrophyte-dominated eutrophication, which can also induce swamp status in a lake [9], is also worthy of being concerned since it was as crucial to ecological health as the cyanobacteria-dominated eutrophication.

Both types of eutrophication were mainly caused by an excessive input of nitrogen (N) and phosphorus (P) nutrients [10-17]. Phosphorus is a critical element in both cyanobacteria-dominated and macrophyte-dominated lakes because it is an essential macronutrient to living organisms in freshwater ecosystems [10, 18-19]. High historical P levels, high P inputs, P distributions, and its occurrence forms can generally influence its transportation and transfer in lake ecosystems, and thus affect the biogeochemical cycle of phosphorus in entire lake systems [11, 20-25]. Therefore, phosphorus levels in lake ecosystems determine the producer type and biomass in different lakes. However, the fact that different lake ecotypes inversely affected phosphorus forms and concentrations in lake ecosystems was usually ignored by researchers. It is known to all that a large amount of phosphorus in lake water is transferred into the sediment by settling or adsorption if phosphorus concentrations increased within a certain period [11, 24, 26]. Conversely, at high levels, internal phosphorus loading may postpone improvements in lake water quality following a reduction in external loading [21, 24]. Phosphorus fractions in the sediment have been widely investigated [20, 25, 27]. Zhu et al. reported that seven fractions of phosphorus were sequentially extracted from sediment by the modified Ruttenberg's method, suggesting that less than 10% of the total extracted phosphorus was bioavailable in the sediment [22]. Søndergaard et al. supposed that some forms of phosphorus, which might be bound to redox-sensitive iron compounds or fixed in more or less labile organic forms, would be prone to release from sediment to lake water due to the actions of many factors, especially biological factors [21]. Therefore, how the two types of primary producers (cyanobacteria and macrophytes) in different eutrophic lake regions affect the spatio-temporal distribution of phosphorus forms and concentrations was one of the focuses of our work.

Lake Taihu, with an area of 2,338 km<sup>2</sup>, is the third largest freshwater lake in China and is located in the southern Yangtze River Delta [9]. With the rapid industrial and agricultural development, population growth as well as urbanization, a large amount of wastewater containing excessive nutrients (N and P) has been discharged into the lake directly or indirectly, leading to eutrophication over the

past three decades [12, 15, 28]. Meiliang Bay has been suffering from cyanobacterial bloom, and is always drawing the attention of most researchers and the public [6, 9, 16, 29-30]. However, Xukou Bay and East Lake Taihu, which also have been experiencing eutrophication in recent years because of increasing nutrient levels and high macrophyte biomass [9, 14, 31], are often ignored because there are no direct harmful effects on the aquatic organisms and water environment in summer. Thus, the aims of our work are to study the relationships between P-levels and ecotype in three different lake regions of Lake Taihu (Meiliang Bay, Xukou Bay, and East Lake Taihu), and then to discuss how the primary producers (cyanobacteria and macrophytes) affect the phosphorus forms and concentrations in the water columns.

## Materials and Methods

### Study Areas and Sampling

Lake Taihu, a large shallow lake (mean water depth is 1.89 m), has different types of primary producers in different regions. Meiliang Bay is a typical cyanobacteria-dominated lake region with an area of 124 km<sup>2</sup> that is located in northern Lake Taihu [9, 32, 33]. Three rivers (the Liangxi, Zhihu Port, and Wujin Port) flow into Meiliang Bay (Fig. 1. M<sub>3</sub>, M<sub>5</sub>, and M<sub>6</sub>). Among them, Zhihu Port River is the most important river for phosphorus input from watercraft discharge, domestic sewage, and industrial wastewater [6, 16]. Wujin Port River has been receiving large amounts of treated and untreated wastewater from a rural area and factories in this area. Liangxi River passes through Wuxi City, an industrialized city in Jiangsu Province, and large amounts of domestic sewage enter it, too [6, 9]. Therefore, the water quality in Meiliang Bay has deteriorated in the past few years, with frequent outbreaks of algae blooms [32, 33]. It has been reported that cyanobacteria, especially *Microcystis* spp., are the dominant species of algae blooms [6].

Xukou Bay and East Lake Taihu are two typical macrophyte-dominated lake regions, with areas of 120 km<sup>2</sup> and 172.4 km<sup>2</sup>, respectively [6, 9]. The major nutrient salts come from a tourism near site X1 (Fig. 1) in Xukou Bay. *Potamogeton malaianus*, *Potamogeton maackianus*, *Vallisneria spiralis*, *Hydrilla verticillata*, *Limnanthemum nymphoides*, and other macrophytes were observed in Xukou Bay, and the highest coverage of macrophytes was 50-60% in Xukou Bay in summer [34]. East Lake Taihu is the water output region of Lake Taihu. Pollutants mainly come from domestic sewage, agricultural non-point source, and pisciculture wastewater [9]. The dominant macrophyte species were *Ceratophyllum demersum*, *Myriophyllum spicatum*, and *Elodea nuttallii* in the aquaculture areas and *Potamogeton malaianus* and *Vallisneria spiralis* in the waterway and open water regions of East Lake Taihu [14]. The highest coverage of macrophytes in East Lake Taihu was 91.9% in summer.

The water samples (50 cm under the water surface) and the surface sediment samples (0-10 cm of sediment) were collected in Meiliang Bay (13 sites), Xukou Bay (8 sites), and East Lake Taihu (5 sites) in March, July, and December of 2009, (Fig. 1 and Table 1). Two replicate samples were taken from each site for error analysis.

### Analysis Method

Physiochemical parameters of water quality in Lake Taihu, such as temperature (T), electrical conductivity (EC), salinity, pH, turbidity, and dissolved oxygen (DO) were directly measured by a multi-parameter water quality instrument YSI6600V2. Secchi disk transparency was detected in the field by a Secchi plate. For Chl-a analysis, 20 ml aliquots were collected from every sampling site and refrigerated. These samples were filtered, ground, extracted with 90% acetone, and centrifuged before the absorbance was then measured with a UV-Vis spectrophotometer [35]. For total phosphorus (TP) and total dissolved phosphorus (TDP) analyses, water samples were digested with potassium persulphate in a high-pressure sterilization pot at 121°C, and then their concentrations were determined by molybdenum-antimony-ascorbic acid colorimetry with a Shimadzu UV 2450 spectrophotometer [32]. Other 10 ml aliquots filtered using a 0.45  $\mu\text{m}$  mixed-fiber membrane were sent to Nanjing Institute of Geography and Limnology for dissolved inorganic phosphorus (DIP) analysis detected with the skalar flow-injection analyzer. Error estimates

were determined as the differences between the detective values and the average value of triplicates at each site.

To determine the contents of active-Al and active-Fe in the sediment with ICP-AES, the sediments were air-dried, sieved with a standard 100-mesh sieve, and then sent to the Center of Modern Analysis of Nanjing University after they were extracted with ammonium oxalate-oxalic acid (pH=3) in shaken conditions [36]. Organic matter contents were measured according to the method for determination of soil organic matter (GB9834-88, China). Different forms of phosphorus in the sediment, such as exchangeable phosphorus (Ex-P), aluminum-bound phosphorus (Al-P), iron-bound phosphorus (Fe-P), occluded state phosphorus (Oc-P), autogenetic calcium phosphorus (ACa-P), detritus calcium phosphorus (De-P), and organic phosphorus (Or-P), were determined using chemical sequential extractions that have been widely used [37-41] and revised by Zhu et al. [22]. Furthermore, the active phosphorus (including Ex-P, Al-P, and Fe-P) contents were calculated since they were crucial to understand the P biogeochemical cycles in different lake ecosystems [6, 22]. For all the sediment samples, triplicates were analyzed for each of the two parallels and the data were reported as the average in this study.

### Statistical Analysis

Standard deviation of various parameters in all three lake regions (n=26 in Meiliang Bay, n=16 in Xukou Bay, and n=10 in East Lake Taihu) were calculated using Microsoft

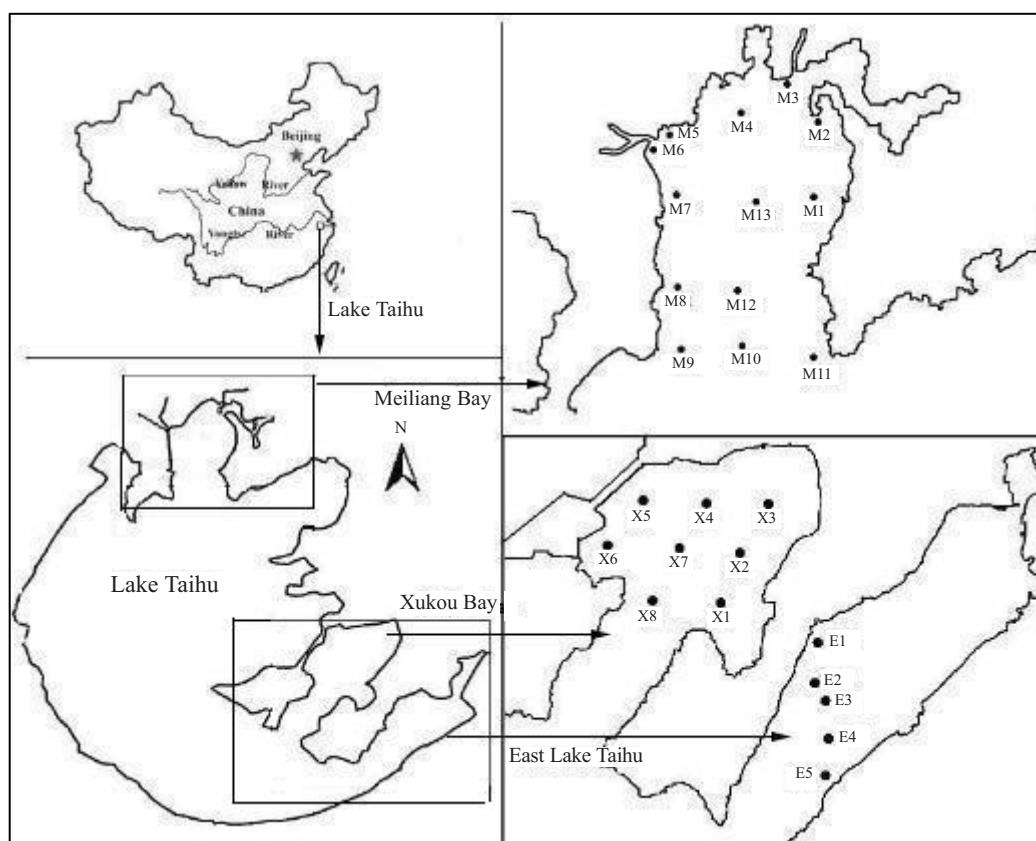


Fig. 1. Sampling sites in Meiliang Bay, Xukou Bay, and East Lake Taihu of Lake Taihu.

Table 1. The locations of different sampling sites and the characteristics of lake water qualities.

ID	GPS	Secchi Disk (m)		
		March	July	December
M <sub>1</sub>	N31°29'14" E120°12'41"	0.58	—	0.32
M <sub>2</sub>	N31°31'14" E120°12'41"	0.46	—	0.45
M <sub>3</sub>	N31°32'19" E120°11'40"	—	—	
M <sub>4</sub>	N31°31'14" E120°10'41"	0.36	—	0.36
M <sub>5</sub>	N31°30'23" E120°07'31"	0.26	—	0.22
M <sub>6</sub>	N31°30'06" E120°07'22"	0.3	—	0.17
M <sub>7</sub>	N31°29'14" E120°08'41"	—	—	0.28
M <sub>8</sub>	N31°27'14" E120°08'41"	0.52	—	0.23
M <sub>9</sub>	N31°25'14" E120°08'41"	0.43	—	0.31
M <sub>10</sub>	N31°25'14" E120°10'41"	—	—	0.32
M <sub>11</sub>	N31°24'46" E120°12'20"	0.6	—	0.25
M <sub>12</sub>	N31°27'07" E120°10'30"	—	0.27	0.20
M <sub>13</sub>	N31°29'14" E120°11'11"	0.24	0.22	0.40
X <sub>1</sub>	N31°07'36" E120°24'29"	0.23	—	0.18
X <sub>2</sub>	N31°09'36" E120°25'29"	0.14	1.32	0.15
X <sub>3</sub>	N31°11'36" E120°26'59"	0.18	1.00	0.25
X <sub>4</sub>	N31°11'36" E120°24'59"	0.24	1.26	0.23
X <sub>5</sub>	N31°11'36" E120°22'54"	0.13	1.06	0.11
X <sub>6</sub>	N31°09'36" E120°21'29"	0.18	0.50	0.11
X <sub>7</sub>	N31°09'36" E120°23'29"	0.17	0.43	0.11
X <sub>8</sub>	N31°07'36" E120°21'59"	0.23	0.78	0.13
D <sub>1</sub>	N31°05'26" E120°28'23"	0.39	0.48	0.65
D <sub>2</sub>	N31°03'37" E120°28'13"	0.2	0.44	0.27
D <sub>4</sub>	N31°01'53" E120°28'51"	0.14	0.58	0.25
T <sub>1</sub>	N31°00'47" E120°28'28"	0.13	0.65	0.18

Excel 2007. The differences in phosphorus contents among the lake regions and different sampling sites within the lake region were analyzed with correlation analysis by SPSS 17.0. The Principal components of aquatic environment variations for different types of primary producers in different lake regions were analyzed using SPSS17.0.

## Results

### Phosphorus Forms and Concentrations in Different Lake Regions with Different Types of Primary Producers

Different primary producers can affect phosphorus forms and concentrations in lake ecosystems. In Meiliang Bay (a typical cyanobacteria-dominated lake region of Lake Taihu), the aqueous TP concentrations were always high throughout the study period, and the average aqueous TP concentration was  $0.256 \pm 0.146 \text{ mg} \cdot \text{L}^{-1}$  in 2009. The highest aqueous TP concentration ( $0.312 \pm 0.158 \text{ mg} \cdot \text{L}^{-1}$ ) and the highest aqueous dissolved phosphorus concentrations (TDP  $0.108 \pm 0.072 \text{ mg} \cdot \text{L}^{-1}$  and DIP  $0.018 \pm 0.022 \text{ mg} \cdot \text{L}^{-1}$ , respectively) were observed in Meiliang Bay during the outbreak of a cyanobacterial bloom in July 2009 (Fig. 2). In addition,

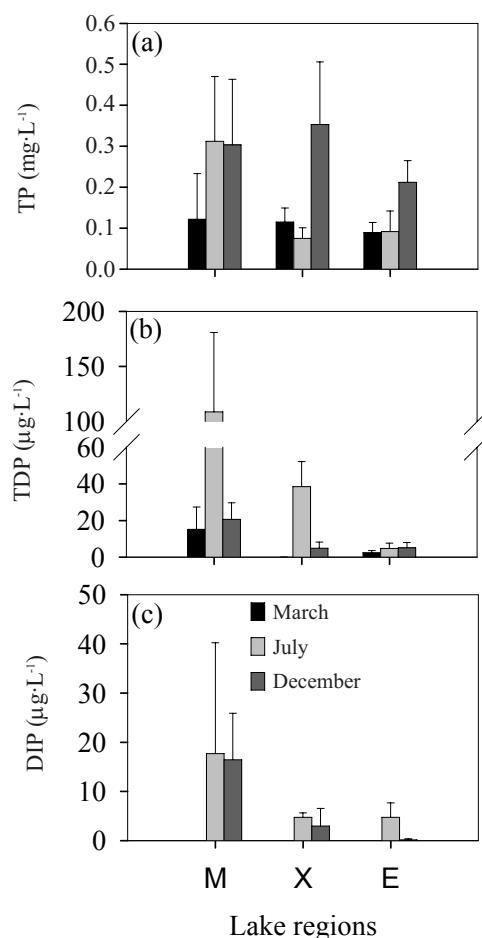


Fig. 2. Variations of aqueous TP (a), TDP (b), and DIP (c) concentrations in Meiliang Bay (M), Xukou Bay (X), and East Lake Taihu (E), respectively, in 2009.

five fractions of phosphorus, including Ex-P, Fe-P, Aca-P, De-P, and Or-P, were much lower in the sediment for the outbreak of cyanobacterial bloom in July than that in the other two periods ( $p < 0.05$ ), and their contents decreased 62.22%, 95.17%, 61.16%, 68.10%, and 56.34%, respectively, in July compared with other periods. There were no significant differences in Al-P and Oc-P in sediments of Meiliang Bay.

However, in Xukou Bay and East Lake Taihu (macrophytes-dominated lake regions of Lake Taihu), the highest aqueous TP concentrations ( $0.353 \pm 0.153 \text{ mg}\cdot\text{L}^{-1}$  in Xukou Bay and  $0.209 \pm 0.053 \text{ mg}\cdot\text{L}^{-1}$  in East Lake Taihu) were observed in December and the lowest aqueous TP concentrations ( $0.075 \pm 0.026 \text{ mg}\cdot\text{L}^{-1}$  in Xukou Bay and  $0.091 \pm 0.050 \text{ mg}\cdot\text{L}^{-1}$  in East Lake Taihu) were observed in July (Fig. 2). Aqueous TDP concentrations in July ( $0.038 \pm 0.014 \text{ mg}\cdot\text{L}^{-1}$  in Xukou Bay, and  $0.005 \pm 0.003 \text{ mg}\cdot\text{L}^{-1}$  in East Lake Taihu) were also higher than that in March ( $0.0001 \pm 0.0003 \text{ mg}\cdot\text{L}^{-1}$  in Xukou Bay and  $0.002 \pm 0.003 \text{ mg}\cdot\text{L}^{-1}$  in East Lake Taihu) and in December ( $0.005 \pm 0.003 \text{ mg}\cdot\text{L}^{-1}$  in Xukou Bay and

$0.005 \pm 0.003 \text{ mg}\cdot\text{L}^{-1}$  in East Lake Taihu). There were no significant differences in DIP in these two lake regions throughout the year ( $p > 0.05$ ). Meanwhile, Ex-P, Aca-P, and Or-P in the sediment of the two lake regions were significantly lower in July than in December and March ( $p < 0.05$ ). No significant differences ( $p > 0.05$ ) were observed for Al-P, Fe-P, Oc-P, and De-P contents in the sediment of the two lake regions (Fig. 3).

In general, the aqueous total levels of various phosphorus forms in July were higher in Meiliang Bay than that in Xukou Bay and East Lake Taihu. However, the aqueous TP concentrations were extremely high in Xukou Bay and East Lake Taihu in December, especially in Xukou Bay, where the aqueous TP concentrations were even higher in December than that in Meiliang Bay in July. The TP contents in the sediment of Meiliang Bay ( $0.950 \pm 0.390 \text{ mg}\cdot\text{g}^{-1}$ ) was much higher than that in the sediment of Xukou Bay ( $0.538 \pm 0.068 \text{ mg}\cdot\text{g}^{-1}$ ) and East Lake Taihu ( $0.684 \pm 0.082 \text{ mg}\cdot\text{g}^{-1}$ ). The active phosphorus, including Ex-P, Al-P, and Fe-P, were higher in the sediment of Meiliang Bay than that from the other two lake regions, too.

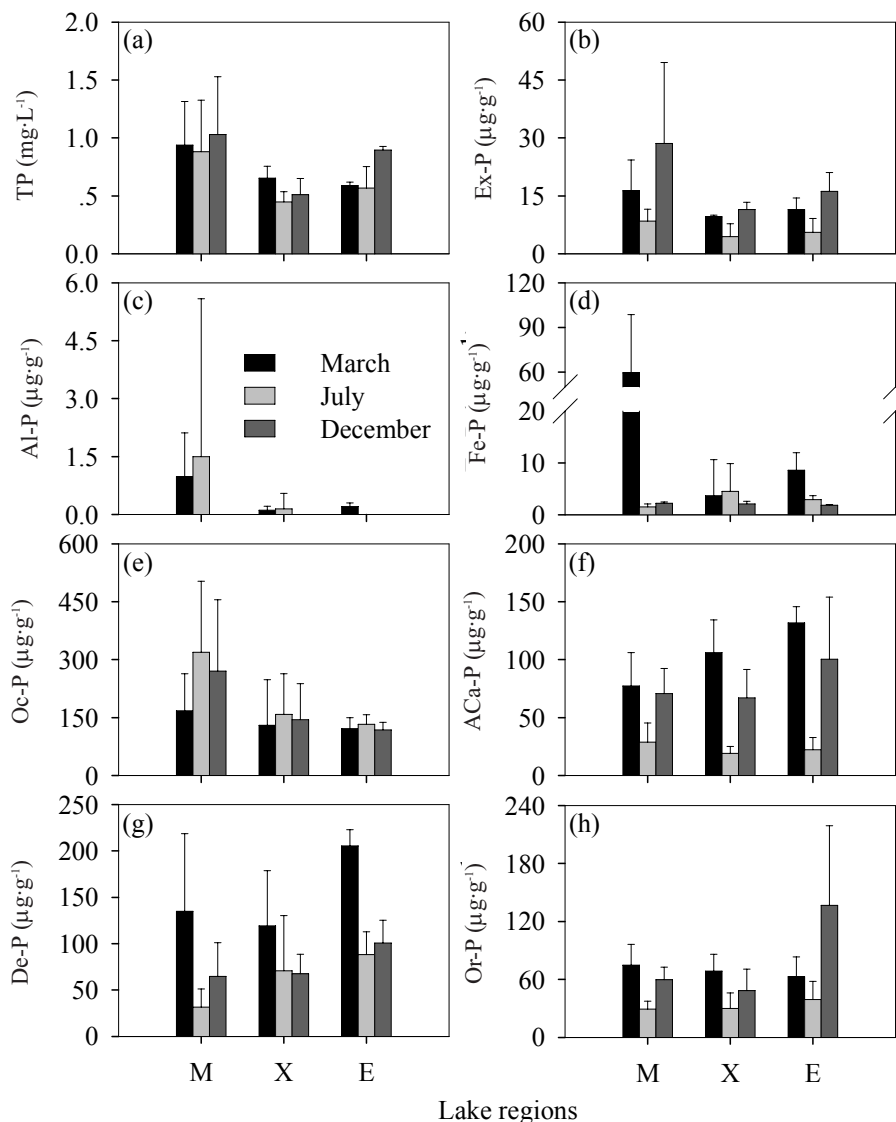


Fig. 3. Phosphorus fractions of TP (a), Ex-P (b), Al-P (c), Fe-P (d), Oc-P (e), Aca-P (f), De-P (g), and Or-P (h) in the sediments of Meiliang Bay (M), Xukou Bay (X), and East Lake Taihu (E), respectively, in 2009.

### Effect of Different Primary Producers on the Aqueous Physicochemical Parameters in Lake Taihu

The various water quality parameters showed significant differences between the two types of lake regions by principal component analysis. In Meiliang Bay, the cyanobacteria-dominated lake region, cyanobacteria affected the aqueous physicochemical parameters significantly. Cyanobacterial

bloom affected EC, salinity, and Chl-a significantly other than TP and TDP in Meiliang Bay according to the principal analysis (Fig. 4). The Chl-a content ( $39.7 \mu\text{g}\cdot\text{L}^{-1}$ ) was much higher during the outbreak of cyanobacterial bloom in July than that in December ( $21.41 \mu\text{g}\cdot\text{L}^{-1}$ ) and in March ( $6.108 \mu\text{g}\cdot\text{L}^{-1}$ ), which caused salinity and EC to increase significantly in July ( $p < 0.05$ ). In Xukou Bay and East Lake Taihu, the macrophyte-dominated lake regions, the macrophytes also affected the aqueous physicochemical parameters sig-

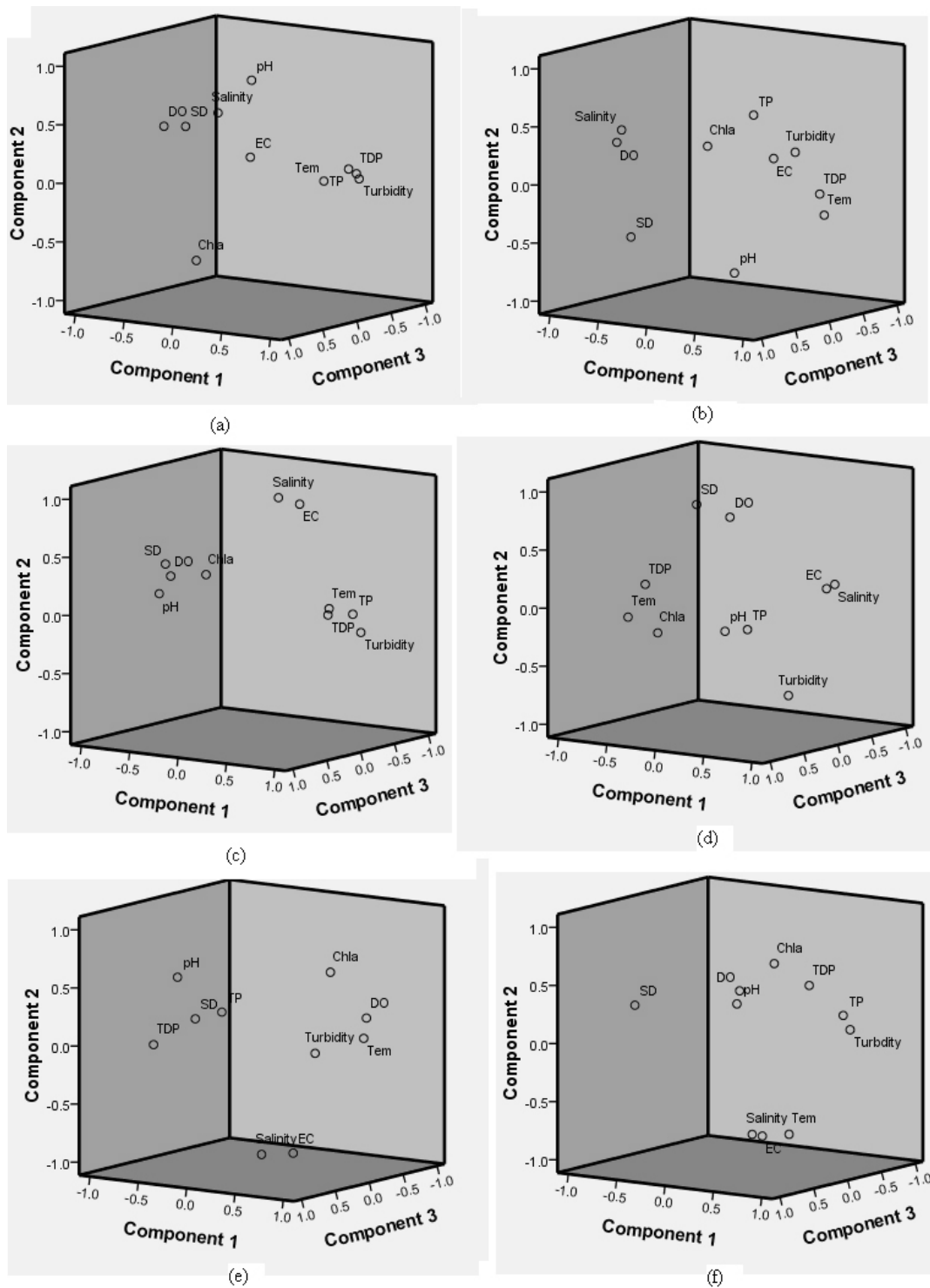


Fig. 4. PCA plots of the first three principal components of the aquatic environmental parameters in cyanobacteria-dominated lake regions (Meiliang Bay) in March (a), July (b), and December (c), and in macrophyte-dominated lake regions (Xukou Bay and East Lake Taihu) in March (d), July (e), and December (f).

nificantly. Since macrophytes grew ambitiously in July, TP, Turbidity, and Chl-a decreased significantly ( $p < 0.05$ ), while SD and DO increased significantly in the meanwhile. The influences of macrophytes on aqueous TP concentrations in December are mostly due to the macrophytes' decomposition (Fig. 4f). Although turbidity was not the most significant aquatic parameter in December, the high turbidity in Xukou Bay in December, with the average value of  $90.0 \pm 42.4$  NTU, made it one of the aquatic parameters in December that was in need of more attention.

#### Effects of Different Primary Producers on Sediment Properties in Lake Taihu

Sediment properties in the different lake regions are shown in Fig. 5. Significant temporal and spatial differences in organic matter (OM) were observed in the three lake regions throughout 2009 (Fig. 5a). On a spatial scale, sediment OM content was highest in East Lake Taihu ( $3.506 \pm 0.590$   $\text{mg}\cdot\text{g}^{-1}$ ), followed by the contents in Meiliang

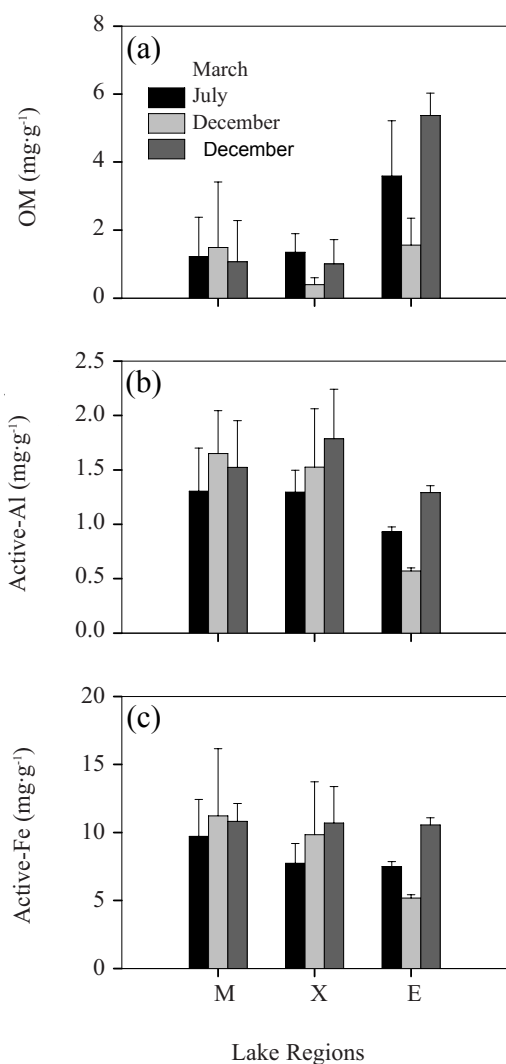


Fig. 5. The contents of OM (a), Active-Al (b), and Active-Fe (c) in sediment of Meiliang Bay (M), Xukou Bay (X), and East Lake Taihu (E), respectively, in 2009.

Bay ( $1.261 \pm 1.100$   $\text{mg}\cdot\text{g}^{-1}$ ) and Xukou Bay ( $0.918 \pm 0.370$   $\text{mg}\cdot\text{g}^{-1}$ ). The OM content in the sediment of Meiliang Bay was higher in July than that in any other period. The lowest OM contents in Xukou Bay and East Lake Taihu were observed in March 2009. The active-Al contents of sediment were much higher in Meiliang Bay and in Xukou Bay than in East Lake Taihu (Fig. 5b). On a temporal scale, the active-Al contents in sediment of Meiliang Bay were the highest in July ( $1.650 \pm 0.395$   $\text{mg}\cdot\text{g}^{-1}$ ) and lowest in March ( $1.305 \pm 0.396$   $\text{mg}\cdot\text{g}^{-1}$ ). In Xukou Bay, the active-Al content reached its highest in December ( $1.786 \pm 0.457$   $\text{mg}\cdot\text{g}^{-1}$ ) and lowest in March ( $1.296 \pm 0.201$   $\text{mg}\cdot\text{g}^{-1}$ ), with a medium level in July ( $1.526 \pm 0.535$   $\text{mg}\cdot\text{g}^{-1}$ ). In East Lake Taihu, the highest active-Al content in sediment was observed in March and the lowest was observed in July. The active-Fe contents displayed a similar trend to active-Al in the three lake regions of Lake Taihu in 2009 (Fig. 5c).

## Discussion

### The Influences of Different Primary Producers on the Aqueous Phosphorus Forms and Concentrations in Lake Taihu

Lake Taihu has been suffering eutrophication or hypertrophication in the past few years [6, 9, 12, 15, 28, 29]. Nutrient (nitrogen and phosphorus) concentrations increased dramatically from the early 1980s to the middle 1990s (i.e., the highest TP concentration was  $0.133$   $\text{mg}\cdot\text{L}^{-1}$  in 1995, Fig. 6). The Chinese government has tried to control lake eutrophication by a series of actions such as controlling external nutrition, dredging, and transferring water from the Yangtze River into Lake Taihu [9, 42-43]. Although these efforts have led to a recent decrease in annual phosphorus concentrations, eutrophication remains a serious problem in Meiliang Bay and East Lake Taihu [9, 16, 29, 32] because phosphorus concentrations in these two lake regions have still shown high levels in the past few years (Fig. 6).

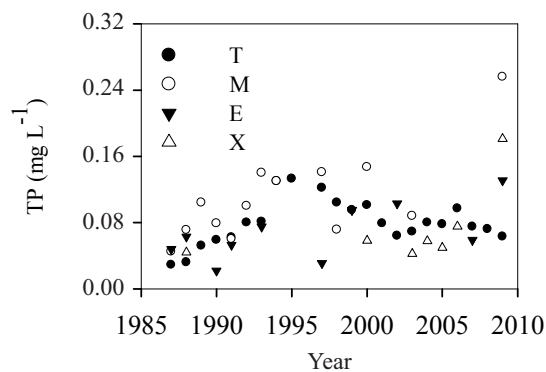


Fig. 6. Changing trends of TP concentrations in Lake Taihu (T), Meiliang Bay (M), East Lake Taihu (E), and Xukou Bay (X), respectively. (Cited from "Water resources quality status bulletin for water body in province boundaries of Lake Taihu Catchment and all the southeast rivers" on the Web: <http://www.tba.gov.cn/tba/content/TBA/lygb/sgnqstb/index.html>)

Because the aqueous TP concentration is high in Meiliang Bay (Fig. 6), a harmful cyanobacterial bloom dominated by *Microcystis* spp. has been occurring in the past few years [16, 29, 32]. Cyanobacteria was transported from other lake regions into Meiliang Bay by southeast monsoon in summer [44], which caused TP concentrations to remain at a relatively high level in Meiliang Bay [15, 44]. Cyanobacteria also can absorb phosphorus from sediments in Meiliang Bay. Higher concentrations of dissolved aqueous phosphorus were observed in Meiliang Bay when a serious cyanobacterial bloom broke out in summer. Of the average ratio of TDP/TP, 34.62% was induced mainly by a large amount of cyanobacteria in Meiliang Bay in summer, because Chl-a, one of the parameters that represented the biomass of cyanobacteria, was a significant discriminative significant parameter in summer (Fig. 4a, b, c). In addition, prior studies in our lab have indicated that the fast growth and metabolism of cyanobacteria allowed phosphorus to transform and transfer easily in water ecosystems [45-47], consistent with those reports by Cotner and Wetzel [48], Sudo et al. [49], and Baldia et al. [50]. Aqueous phosphorus was easily recycled with the occurrence of cyanobacterial bloom. Furthermore, bloom-cyanobacteria readily decomposed if its densities reached  $7.60 \times 10^8$  cell·L<sup>-1</sup> under high

temperature, weak illumination, and disturbance. More than 60% of aqueous TP was transferred into aqueous dissolved phosphorus in 6-7 days. In addition, through cyanobacterial growth and metabolism, cyanobacteria bloom also affected water quality parameters, such as a decrease of salinity and an increase of EC (Fig. 7). Thus, cyanobacteria, a primary producer, can influence phosphorus forms and concentrations, especially the dissolved phosphorus concentration, indirectly by assimilation and metabolism.

East Lake Taihu is a typical macrophytes-dominated lake region in Lake Taihu, and the biomass of macrophytes increased from 504 g·m<sup>-2</sup> in 1959 to 2,882 g·m<sup>-2</sup> in 2007 [9, 14, 31]. The annual TP concentrations in this lake region also have increased in the past few years (Fig. 6). An increase of annual TP concentration in recent years also was observed in Xukou Bay (Fig. 6). In Xukou Bay and East Lake Taihu, the levels of various phosphorus forms were extremely low in water body in summer since the macrophytes could assimilate various nutrients such as nitrogen, phosphorus, other ions, etc. [51, 52]. This could also explain why salinity and EC in these two lake regions were so low in July (Fig. 7). However, if macrophyte biomass increased too much in the lake ecosystem, the aquatic environment would switch to unsuitable conditions, i.e.

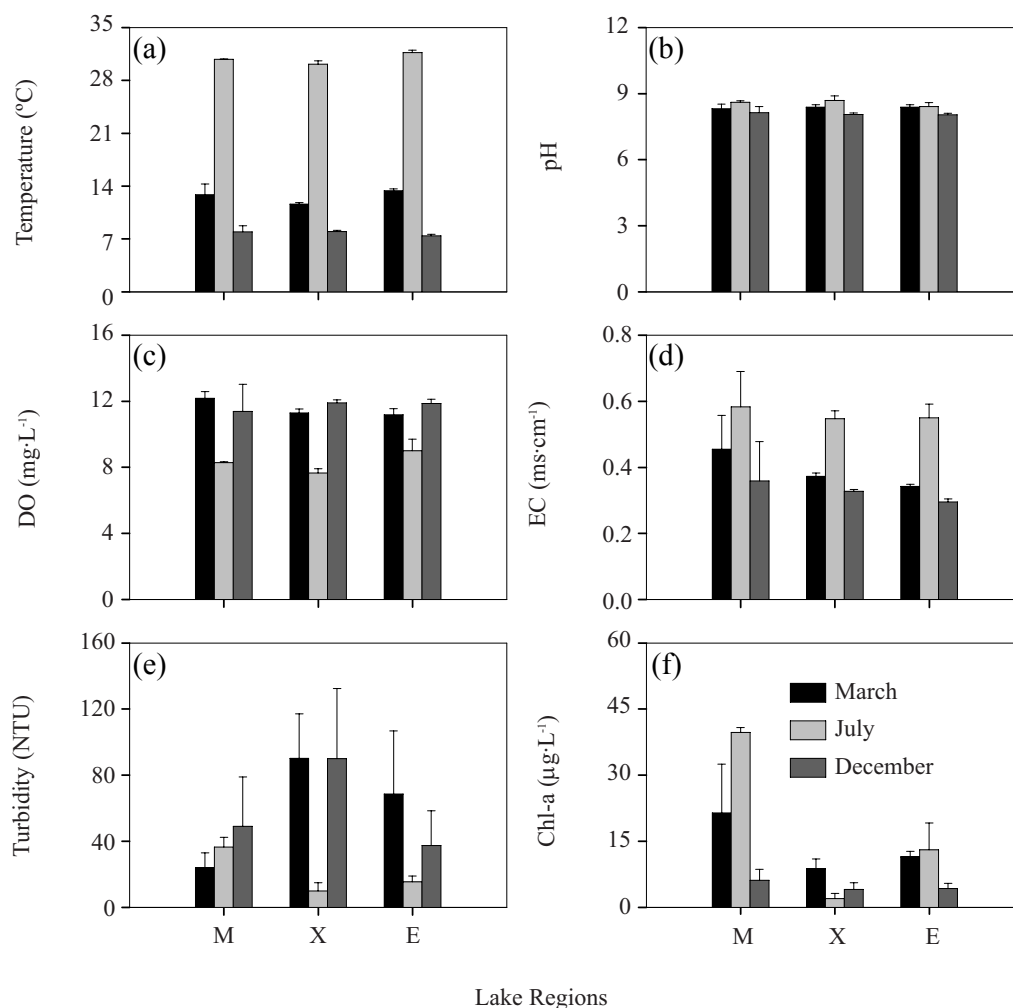


Fig. 7. Common parameters of temperature (a), pH (b), DO (c), EC (d), Turbidity (e), and Chl-a (f) in lake water of Meiliang Bay (M), Xukou Bay (X), and East Lake Taihu (E), respectively, in 2009.



high pH values in the daytime and low DO in the night, which would accelerate the decay of macrophytes in the aquatic environment. This decay would lead to further harmful effects, such as an increase of solid particle substances and turbidities, or a decrease of SD. All of these would aggravate macrophyte-dominated eutrophication, and this was confirmed by the high turbidity and high aqueous TP concentration in winter. The TP concentrations in Xukou Bay and East Lake Taihu were higher in winter than those in the cyanobacteria-dominated Meiliang Bay in summer. Thus, the different primary producers (cyanobacteria and macrophytes) can affect the P levels as well as the water parameters in different regions of Lake Taihu.

### The Influences of Cyanobacterial Bloom and Macrophytes on Phosphorus Forms and Contents in the Sediment

Sediment phosphorus contents would be improved with the enhancement of aqueous phosphorus concentrations in the lake water body through organic P decomposition, diagenesis, inorganic P adsorption and diffusion [23, 24, 53, 54]. For the cyanobacteria-dominated lake regions, anaerobic or anoxic conditions would be formed around the surface sediment as high cyanobacterial biomass greatly depleted a large amount of DO in the water columns during the outbreak of a cyanobacterial bloom [6], which would in turn provide suitable conditions for the growth of anaerobic bacteria [55-57]. Low Eh causes  $\text{Fe}^{3+}$  transforming to  $\text{Fe}^{2+}$ , then the Active-Fe and Ex-P increased significantly and Fe-P decreased significantly in sediments of a water bloom's lake regions. At the same time, cyanobacteria would assimilate a large amount of Ex-P, and then Ex-P released from the sediment to the water body. Therefore, Ex-P in the sediment decreased significantly, consistent with the results from Xie et al. [58]. Consequently, the active phosphorus in the sediment, which were easily released from surface sediments and then utilized by organisms in the overlying water [22, 58], were much lower in July ( $11.465 \pm 4.890 \mu\text{g}\cdot\text{g}^{-1}$ ) than in March ( $76.716 \pm 46.252 \mu\text{g}\cdot\text{g}^{-1}$ ) and December ( $30.749 \pm 26.161 \mu\text{g}\cdot\text{g}^{-1}$ ). This was confirmed by the finding that the active-Al and active-Fe in the surface sediment were the highest in July directly. In addition, several fractions of phosphorus, including TP, ACa-P, De-P, and Or-P, were lower in July than that in any other periods (Fig. 3a, f, g, h), which disagreed with Zhu et al. [22], who proposed that ACa-P, De-P, and Or-P were difficult to be utilized by organisms.

In macrophyte-dominated lake regions, no significant differences were observed for the active-P except that Ex-P in the sediment of Xukou Bay and East Lake Taihu was much lower in July than in other periods. The Ex-P would release from sediment to the overlying water if the aqueous phosphorus concentrations reduced significantly in summer due to the assimilation of macrophytes in the water ecosystems [23, 59]. In addition, ACa-P and Or-P in the sediment was much lower in the presence of macrophytes than that in the absence of macrophytes because some organic residues in the sediment could also be decomposed under high Eh conditions.

High phosphorus content, cyanobacterial bloom, and relatively high contents of active-Al/Fe in sediments caused active-P (Ex-P, Al-P, and Fe-P) to be much higher in the sediment of Meiliang Bay than that in the sediment of Xukou Bay and East Lake Taihu (Fig. 3). In addition, because sediment OM contents were much higher in East Lake Taihu than in Xukou Bay, and the natural adsorption of phosphorus on the sediment was positive correlation to OM contents, active-P was higher in East Lake Taihu than in Xukou Bay. Thus, changes of phosphorus forms and contents in sediments are driven by the type of primary producers. The different types of primary producers (cyanobacteria or macrophytes) not only affected the spatio-temporal distribution of phosphorus forms and concentrations in the aquatic environment, but also affected phosphorus forms and contents in the sediments of different lake regions in Lake Taihu in different seasons.

### Conclusion

We attempted to reveal that the effects of different types of primary producers (cyanobacteria or macrophytes) on the phosphorus forms and contents in different lake regions of Lake Taihu. High aqueous P levels appeared in the cyanobacteria-dominated lake region, and there were relatively low aqueous P levels in the macrophyte-dominated lake regions in July. The different primary producers could affect phosphorus forms and concentrations in the lake ecosystems. The high aqueous dissolved phosphorus in Meiliang Bay is related to the action of cyanobacteria, and the extremely low levels of various phosphorus forms in Xukou Bay and East Lake Taihu is related to the action of macrophyte growth. The outbreak of cyanobacterial bloom and the growth of macrophytes could also affect the phosphorus forms and contents in the sediment. For cyanobacteria-dominated lake regions, the active-P in the sediment was much lower in the presence of a large quantity of cyanobacteria than that in the absence of cyanobacteria in Meiliang Bay. In addition, ACa-P, De-P, and Or-P were much lower in July than in December and March.

For macrophyte-dominated lake regions, no significant differences were observed for the active-P in the sediment throughout the year, except that Ex-P was a little lower in July than that in March and December. The ACa-P and Or-P were also much lower in July than in other periods. Therefore, different types of primary producers can affect the spatio-temporal distribution of phosphorus forms and concentrations in different lake regions of one lake. Cyanobacteria can induce high aqueous P levels in summer. Macrophytes can induce the low aqueous P level in summer but high aqueous P level in winter. A high biomass of primary producers can also decrease the amounts of total phosphorus contents and influence the phosphorus forms in sediments in summer. The P levels appeared as inverse trends in different seasons due to the different primary producers in different regions of Lake Taihu. Thus, primary producers can affect the phosphorus forms and

concentrations not only in the water body but also in the sediment, though phosphorus concentrations determining the community structure is widely known in lake ecosystems.

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