PHOSPHORUS BIOAVAILABILITY IN RELATION TO SUBMERGED MACROPHYTE SPECIES AND BIOMASS IN FOURTEEN TEMPERATE LAKES, CHINA

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ABSTRACT

Submerged macrophyte composition and biomass, as well as bioavailable phosphorus in surface water and sediment were studied in 14 temperate lakes in southwestern China. Correlation analysis indicated that macrophyte biomass and species declined with the increase of soluble reactive phosphorus (SRP) in surface water. Sediment bioavailable phosphorus (BAP) and total phosphorus (TP) in investigated lakes changed along trophic gradient, and the sediment BAP concentration tended to decrease with the increase of macrophytes biomass and species. The correlation analysis between surface water SRP and sediment BAP with macrophytes indicates that the bioavailable phosphorus in water and sediment is coupled with the macrophytes biomass and species. Based on the study, it was suggested that increasing surface water SRP and sediment BAP could cause submerged macrophytes disappearing or decreasing in shallow lake ecosystem. Consequently, the restoration practice for submerged vegetation will favor to succeed when surface water SRP is below 5 µg/L and sediment BAP is below 60 µg/g.

KEYWORDS: Phosphorus bioavailability; Sediment bioavailable phosphorus; Submerged macrophytes; Soluble reactive phosphorus; Shallow lakes

INTRODUCTION

Submerged macrophytes can be the major components of primary production and may play an important role in maintaining nutrient cycling and system stability of aquatic ecosystem in shallow lakes, which lead to a clear-water state with vegetation instead of a turbid one with algal blooms [1-3]. So the environmental controls of macrophytes biomass and richness, as well as its spatial and temporal variability have been a topic of considerable interest in lakes ecology for decades. Compared to water depth, light limitation, transparency and wind wave, water chemistry has long been recognized as one of the most important factors to limit the occurrence of submerged macrophytes [1]. Of the many nutrients that are required for the growth of macrophytes, nitrogen and phosphorus are mostly the limiting factors which control the growth and species composition [1, 4].

Although nitrogen concentrations are important in explaining macrophytes species richness [5, 6], a great deal of researchers proved that the occurrence and vanish of submerged macrophytes even more corresponded to the increase of phosphorus levels [7-10]. High phosphorus loading could lead to a higher primary production of phytoplankton and lower seepage depth which result in the decreasing of macrophyte biomass and species. According to the long terms investigations in Danish lakes, Jeppesen et al. [11] suggested that macrophytes would dominate the shallow lakes only when TP concentration was reduced to below 80-150 µg/L in water body. In addition, as the growth substratum of macrophytes, sediment phosphorus also influences its biomass and species richness. It has been reported that the biomass of aquatic macrophytes is decreasing when sediment phosphorus exceeded 0.7 mg/g [12]. Based on those studies, submerged macrophytes restoration in shallow lakes should pay attention to control phosphorus, but not nitrogen [13, 14].

It has long been recognized that only part of the phosphorus in aquatic ecosystem is available for organism growth and that the total phosphorus content is of little or no value as a predictor of available phosphorus [15-17]. In aquatic ecosystem, available phosphorus often is a very small portion of the total phosphorus. Available phosphorus usually is taken up immediately by aquatic organism, which is the one reason why phosphorus often limits plant growth. Therefore, the total pool of phosphorus in surface water and
sediment is less important than the amount of its bioavailability fraction [7, 8, 18]. Several studies were conducted with one or two taxonomic groups and have indicated that macrophyte biomass and species richness will decrease with the increase of bioavailable phosphorus.

In this study we evaluate the relation between water and sediment phosphorus bioavailability with submerged macrophyte species and biomass, comparing the results from fourteen investigated temperate lakes in southwestern China (Yungui Plateau). The studies provide information to evaluate the hypothesis that the disappearing or decreasing of submerged macrophytes is initially because of the increase in bioavailable phosphorus from surface water and in the sediment.

MATERIALS AND METHODS

Study area

Study sites are located in Yunnan Province of Yungui Plateau within southwestern China (Fig. 1). The Yungui Plateau lies within Yunnan, Sichuan, and Guizhou provinces, and this region has about 60 temperate lakes. The majority of the lakes are concentrated in Yunnan Province. Studied lakes were selected to encompass nutrient status, submerged macrophyte, and sediment geochemistry. Basic limnological characteristics on the lakes are given in Table 1. Conductivity and secchi depth were measured in situ with the portable multi parameter probe YSI 63-10 pH & conductivity meter (YSI, America) and secchi disc. Field investigations were conducted in the period of July 2007 and 2008. Sampling sites were designed on a depth transect to get representative regions of submerged macrophyte and recorded by a GPS system. Four to six samples were collected for each lake. The submerged macrophyte survey included location, species identification, and quantity. Submerged macrophytes were harvested using a filter net with 0.16 m² areas, and five to ten replicate were randomly collected in each site. After swashing for several times to dislodge loose attachment, the collected plants were separated by species and determined the fresh weight respectively. Species identity was according to local flora. Meanwhile, surface sediment and water samples were collected from each site accordingly.

![Figures](image)

**FIGURE 1 - Location of research lakes in Yunnan Province, China:**

- a. Yunnan Province located in the southwest of China; b. Distribution of research lakes in Yunnan Province.

**TABLE 1 - Limnological characteristics of the 14 temperate lakes in Yungui Plateau, China.**

<table>
<thead>
<tr>
<th>Lake</th>
<th>Elevation (m)</th>
<th>Area (km²)</th>
<th>z_max (m)</th>
<th>z_min (m)</th>
<th>Volume (10⁶ m³)</th>
<th>Secchi depth (m)</th>
<th>Conductivity (μS/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cibi Lake</td>
<td>2097</td>
<td>8</td>
<td>30</td>
<td>32</td>
<td>0.93</td>
<td>2.5</td>
<td>322</td>
</tr>
<tr>
<td>Xiba Lake</td>
<td>1975</td>
<td>3.3</td>
<td>1.8</td>
<td>3.3</td>
<td>0.1</td>
<td>2.7</td>
<td>329</td>
</tr>
<tr>
<td>Erhai Lake</td>
<td>1974</td>
<td>246</td>
<td>10.6</td>
<td>21.3</td>
<td>28.8</td>
<td>1.9</td>
<td>363</td>
</tr>
<tr>
<td>Lashi Hai</td>
<td>2429</td>
<td>9</td>
<td>3.9</td>
<td>9</td>
<td>0.2</td>
<td>2.3</td>
<td>202</td>
</tr>
<tr>
<td>Cheng Hai</td>
<td>1503</td>
<td>74.6</td>
<td>25.7</td>
<td>35</td>
<td>19.8</td>
<td>2.5</td>
<td>1112</td>
</tr>
<tr>
<td>Jianhai Lake</td>
<td>2184</td>
<td>6.2</td>
<td>2.7</td>
<td>6</td>
<td>0.32</td>
<td>1.4</td>
<td>231</td>
</tr>
<tr>
<td>Changgiao Hai</td>
<td>1295</td>
<td>13.3</td>
<td>1.3</td>
<td>2.5</td>
<td>0.4</td>
<td>1.2</td>
<td>569</td>
</tr>
<tr>
<td>Yilong Lake</td>
<td>1414</td>
<td>42</td>
<td>4</td>
<td>15</td>
<td>2.2</td>
<td>1.0</td>
<td>371</td>
</tr>
<tr>
<td>Datan Hai</td>
<td>1284</td>
<td>18</td>
<td>1.3</td>
<td>2.7</td>
<td>0.4</td>
<td>0.5</td>
<td>704</td>
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<tr>
<td>Oliu Lake</td>
<td>1790</td>
<td>42</td>
<td>4</td>
<td>15</td>
<td>0.17</td>
<td>1.2</td>
<td>570</td>
</tr>
<tr>
<td>Yangzong Hai</td>
<td>1768</td>
<td>30.6</td>
<td>20</td>
<td>30</td>
<td>6.04</td>
<td>2.2</td>
<td>331</td>
</tr>
<tr>
<td>Xingxian Lake</td>
<td>1722</td>
<td>38.6</td>
<td>5.6</td>
<td>12</td>
<td>1.84</td>
<td>1.1</td>
<td>893</td>
</tr>
<tr>
<td>Dianchi Lake</td>
<td>1887</td>
<td>309</td>
<td>5.3</td>
<td>10.4</td>
<td>12.9</td>
<td>0.6</td>
<td>1134</td>
</tr>
<tr>
<td>Qingzhibai Hai</td>
<td>2188</td>
<td>7</td>
<td>20</td>
<td>30</td>
<td>1.17</td>
<td>3.1</td>
<td>104</td>
</tr>
</tbody>
</table>


In laboratory, the hydrochemical parameters of water samples were assayed with the methods of SEPAC [19]. Total phosphorus (TP) was determined with ammonium molybdate spectrophotometric method after being digested with K$_2$S$_2$O$_3$ solution; soluble reactive phosphorus (SRP) was determined directly with the ammonium molybdate spectrophotometric method. For sediment samples, bioavailable phosphorus (BAP) are extracted using the method proposed by Zhou et al. [20] and SRP was analyzed with the ammonium molybdate spectrophotometric method [19].

Statistical analyses, including means, correlations and variance analysis, were performed using Statistical Analysis System (SPSS Institute, Inc. 1995) procedures [21].

RESULTS

Macrophyte species and biomass

Investigated lakes showed considerable variations in macrophyte species and biomass (Fig. 2a). A total of 13 submerged macrophyte taxa were recorded in the investigated lakes, but sample sites were typically dominated by 2-3 species of plants. Of all genera, the Potamogeton L. contributed the highest number of species with 5 records. The submerged plants Potamogeton pectinatus L., Myriophyllum spicatum, Potamogeton malaianus and Vallisneria L., associated with mesotropic and eutrophic conditions, were the most frequent species in the fourteen studied lakes. The species number was highest in Cibi Lake with 8 species and least in Dafun Hai without any macrophytes. Chara spp. and Potamogeton lucens were scarce species, and only appeared in two clear lakes (Cibi Lake and Lashihai).

At all sampling sites, total fresh weight of submerged macrophyte biomass varied between 112 and 7349 g/m$^2$ (Fig. 2a). Mean fresh weight was highest in Yangzong Hai (4190 g/m$^2$), and the lowest in Dianchi Lake (954 g/m$^2$). In Dianchi Lake, macrophyte biomass varied between 237 g/m$^2$ and 829 g/m$^2$ and consisted of Potamogeton maackianus A. Benn. and Myriophyllum spicatum. In particular, no submerged macrophytes were found in Dafun Hai. On average over all sites, biomass of Potamogeton maackianus A. Benn was greatest with about 773 g/m$^2$ fresh weight. In the next place, Myriophyllum spicatum and Potamogeton malaianus biomass were 577 g/m$^2$ and 761 g/m$^2$ fresh weight respectively. Moreover, the biomasses of other species, including Hydrilla verticillata, Chara spp., Potamogeton crispus Linn., were less than 50 g/m$^2$ fresh weight. Species number of macrophytes decreased significantly with fresh weight biomass of the macrophytes ($r=0.71$, $P<0.001$) (Fig. 2b).

Surface water SRP in relation to submerged macrophyte

The SRP and TP concentrations in surface water of the 14 investigated lakes showed significant variations (Fig. 3). SRP ranged from 1 μg/L to 32 μg/L, and TP ranged from 4 μg/L to 192 μg/L. On average concentration, Cibi Lake had minimum SRP (about 2 μg/L) and TP (about 5 μg/L) and Dafun Hai had maximum SRP (about 25 μg/L) and TP (about 161 μg/L). Moreover, SRP and TP concentrations in Dafun Hai were double or treble higher than other lakes ($P<0.001$). Proportion of SRP accounting for TP was varied between 10% and 20%, and significantly correlated with TP ($R^2=0.68$, $P<0.001$).
Macrophyte biomass and species numbers were negatively related to SRP (Fig. 4 a and b). The linear regressions were significant for each individual site ($R^2=0.44, P<0.0001$) as well for each lake ($R^2=0.48, P<0.0001$). The relationship of biomass and species of submerged macrophyte with TP showed a similar pattern as that with SRP (Fig. 4c and d), but correlation coefficient was inferior to the later.

**Sediment BAP in relation to submerged macrophyte**

The sediment BAP differed significantly with concentrations ranging from 13 µg/g to 141 µg/g dry weight (DW) (ANOVA, $P<0.001$) (Fig. 5). TP was range from 102 µg/g to 2825 µg/g. The proportion of sedimentary BAP on TP was significantly different among the investigated lakes (ANOVA, $P<0.001$). Multiple linear regression of sediment BAP and submerged macrophyte indicated that

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**FIGURE 4** - Correlations between surface water SRP and the biomass and species numbers of macrophytes (Fig. 4a and b), as well as the correlation between TP and macrophytes (Fig. 4c and d).

**FIGURE 5** - Plot of sediment TP and BAP differences 14 temperate lakes. Error bars represent standard deviations of samples of each lake.
was also negatively related to biomass ($R^2=0.47, P<0.0001$) and species ($R^2=0.55, P<0.0001$) (Fig. 6a and b). Datum Hai had extremely high sediment BAP concentrations and no macrophyte existed. In contrast, sediment TP concentration and macrophyte biomass ($R^2=0.15$) and species numbers ($R^2=0.07$) had no statistical significance (Fig. 6c and d).

**DISCUSSION**

Under low nutrient conditions an increase in the nutrition at first favors biological diversity to some extent; but then a further increase in water may lead to a decrease of overall biodiversity [22]. Bioavailable phosphorus is important for the variety of submerge plant communities. The disappearance of macrophyte communities is usually very sensitive to phosphorus such as *Chara spp.* and *Ceratophyllum demersum* [23]. In contrast, *Potamogeton pectinatus* and *Myriophyllum spicatum* are able to tolerate high trophic levels [24], and consist in almost all trophic lakes investigated. Our results from the fourteen investigated lakes also clearly showed a changing trend along phosphorus gradient in macrophytes productivity and species composition. Both biomass and species declined with the increasing of SRP concentration in lakes surface water and reached low levels when they exceeded 15 $\mu$g/L. These patterns were seen for every investigated sample and mean value in each lake. In addition, the macrophyte biomass decreased significantly with species number. The changes in plant community composition resulting from the SRP gradient in this study are somewhat consistent with conclusions of Van et al [25]. In shallow lake ecosystems, the macrophyte species of stain resistance and clean-type always coexist. Synchrony of phosphorus availability and phosphorus need for different plant species in aquatic ecosystem often affect competitive relationships among species with different adaptability [11]. In our finding, the macrophyte species numbers and biomass were negatively correlated to the SRP concentrations. Macrophyte species numbers and biomass showed the highest values in oligotrophic lakes, while they showed a decrease in more eutrophic lakes. The number of macrophytes species observed in the 14 investigated lakes was in the same order of magnitude as reported in many other studies [7, 26].

The macrophytes biomass was related with the TP concentration in surface water, but the correlation was not as good as for SRP. Such a relationship has also been observed in other studies, Carr et al. [27] showed only a weak but significant relationship between the biomass of macrophytes and total phosphorus concentrations in an analysis of data from 38 lakes. The findings of Królikowska and Sand-Jensen and Borum suggested that the total pool of nutrients was less important than the amount of its bioavailability fraction, which is also supported by our results [8, 18]. The dramatic decrease of macrophyte biomass at sites
where surface water SRP concentration was greater than 5 µg/L may be due to the interactive effects of physical chemical (pH and dissolved oxygen), and biological (tissue decay and competition) factors on macrophyte growth [28]. To take the biomass of different species into account, the submerged plants of Potamogeton lucens and Hydrilla verticillata (Linn. f.) Royle are associated with clear waters and with intermediated bioavailable nutrient conditions [26, 27]. Our results also showed that the biomass of Potamogeton lucens and Hydrilla verticillata decreased quickly with increasing SRP concentration, and less decreased in Potamogeton maackianus A. Benn. and Myriophyllum spicatum. This shows that the sensitivity of macrophytes community to varying SRP concentrations is different.

The distribution of different macrophyte species depends on the sediment characteristics [24, 29, 30]. At the same time, submerged macrophytes can modify the physico-chemical characteristics of sediment. Both implied a potential relationship between phosphorus bioavailability and macrophytes [31-33]. Among all of the study lakes, the decreases in sediment BAP and TP were correlated with the increases in the biomass of macrophytes. This connection may be produced by the fact that macrophytes root can amend sediment grain size and redox condition [32, 33].

The SRP concentrations in the water and the bioavailable phosphorus in the sediments are coupled with the macrophytes biomass and species number. As it is shown in Fig 7, an increasing sediment content of BAP correlates with an increasing concentration of SRP, and with a decrease of macrophyte biomass and number of species. When macrophytes are reduced, changes in BAP and SRP became apparent. This observation increases our understanding of the disappearing of submerged plant and the rehabilitation of vegetation in shallow lakes, and has important practical implications for lake management. Our results suggest that keeping surface water SRP below 5 µg/L and the sediment BAP below 60 µg/g is propitious to maintain macrophytes dominant in shallow lakes. In contrast, it is difficult to obtain a high macrophyte biomass and species number. The mechanism how the bioavailable phosphorus in the sediment is connected to macrophyte biomass and species richness needs further studies to clarify these interactions.

FIGURE 7 - Bubble chart on the relationship between surface water SRP, sediment BAP and macrophytes. The bubble size of (a) and (b) respectively represent macrophytes biomass and number of species.

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