Environmental Science and Pollution Research (2019) 26:12975–12984
https://doi.org/10.1007/s11356-019-04469-8

RESEARCH ARTICLE

Phosphorus removal from the hyper-eutrophic Lake Caohai (China) with large-scale water hyacinth cultivation

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Received: 28 September 2017 / Accepted: 4 February 2019 / Published online: 20 March 2019

Abstract

A phytoremediation project involving the large-scale cultivation of water hyacinths (*Eichhornia crassipes* (Mart.) Solms) was conducted in Lake Caohai (China) from May to November during 2011–2013 to remove pollutants and decrease eutrophication. Water hyacinths were cultivated in two areas of Lake Caohai, Neicaohai, and Waicaohai, which are connected and function as a relatively independent water body. The areas for macrophyte growth varied in size from 4.30 km^2 in 2011 to 0.85 km^2 (2012) and 1.15 km^2 (2013). Compared with historical data from 2007, the concentrations of total phosphorus decreased significantly, while dissolved oxygen concentrations increased slightly. After plant cultivation in 2011, the average concentrations of total phosphorus, total dissolved phosphorus, and phosphate anions decreased from 0.54, 0.35, and 0.23 mg L^{-1} upstream (river estuaries) to 0.15, 0.13, and 0.08 mg L^{-1} downstream (Xiyuan Channel), respectively. The amount of phosphorus assimilated by the macrophytes (44.31 t) was more than 100% of the total removed phosphorus (40.93 t) from lake water when water hyacinths covered 40.9% of the area, which could indicate sedimentary phosphorus release. Our study showed the great potential of utilizing water hyacinth phytoremediation to remove phosphorus in eutrophic waters.

Keywords Nutrient removal · Water restoration · *Eichhornia crassipes* · Phosphorus · Eutrophication

Introduction

Eutrophication is the most widespread global water quality issue (Schindler 2012; Sinha et al. 2017). In China, among the 19 lakes distributed in the middle and lower reaches of the Yangtze River, 47% are eutrophic and 53% are mesotrophic (Qin et al. 2013). Eutrophication results from an excess in nutrient delivery into natural water bodies (Schindler et al. 2016; Sinha et al. 2017). Common symptoms of eutrophication include decreased water clarity, dense algal blooms (Lapointe et al. 2015), and anoxia in deeper parts of the water column that result in fish kills and noxious odors. One of the most objectionable symptoms is the appearance of algae blooms, such as *Microcystis aeruginosa* (Zhou et al. 2014), which can produce hepatotoxic and neurotoxic compounds that harm aquatic ecosystems and human health (Funari and Testai 2008).

Phosphorus (P) control can combat eutrophication and inhibit the growth and reproduction of cyanobacteria in freshwater (Schindler et al. 2016). Chapra and Dobson (1981) have introduced a trophic classification scheme based on total phosphorus (TP) and chlorophyll *a* (Chl *a*). Dove and Chapra (2015) determined that the two variables of Chl *a* and TP are well related, and the significance of the relationship is that extreme P-limitation is implicated in reducing lake productivity. A study of lakes along the Yangtze River in China also indicated that P is the primary factor regulating cyanobacteria growth (Wang and Wang 2009). Therefore, P control should be an essential step for the mitigation of eutrophication in freshwater bodies, such as lakes, rivers, and reservoirs.

The point source of P from sewage treatment facilities is a significant risk for eutrophication, particularly sewage effluent discharging into ecologically sensitive tributaries (Stutter et al. 2010; Bowes et al. 2010). Weekly surveys of the Thames River (United Kingdom) and its tributaries between 1997 and 2007

Responsible editor: Elena Maestri

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showed that the decline of P concentrations in the water resulted from soluble reactive phosphorus (SRP) reduction in the sewage effluent (Neal et al. 2010). When aquatic ecosystems accept P from sewage effluent, both biotic and abiotic components maintain a long 'memory' of the input in terms of P storage after loading (Stutter et al. 2010). That implied the point source of P from sewage treatment facilities continue to threaten aquatic ecosystems with nutrient loading. Thus, it is necessary to decrease P concentrations in sewage effluent before its discharge into natural waters (Lapointe et al. 2015).

In situ phytoremediation is a solar-driven ecological measure to combat eutrophication; it has the advantages of low cost, high efficiency, and environmental friendliness (Batty and Dolan 2013; Xu et al. 2018). Water hyacinth (*Eichhornia crassipes* (Mart.) Solms) is a useful plant for phytoremediation. This macrophyte is notorious as an invasive species in China for its tremendously vigorous growth (Yan and Guo 2017). However, water hyacinth has advantages of high biomass accumulation, an extensive root system, easy adaptation to various habitats, high tolerance, and the ability to accumulate pollutants (Rodríguez et al. 2012; Wang et al. 2013; Yan and Guo 2017). Therefore, water hyacinths have gained increasing attention recently and have been widely utilized in the phytoremediation of various polluted water bodies (Rezania et al. 2016; Zheng et al. 2016; Ting et al. 2018).

From 2011 to 2013, a phytoremediation project involving the large-scale cultivation of water hyacinths was conducted in Lake Caohai, which is an open hyper-eutrophic water body that primarily receives discharging effluent from the 1st and 3rd sewage treatment facilities of Kunming City (Yunnan Province, China). Our previous research showed that N in the lake was removed through assimilation by the macrophyte and nitrification/denitrification in the water (Wang et al. 2013). However, less has been reported on P removal by large-scale water hyacinth cultivation in natural waters that primarily received sewage effluent. In the present study, we assumed that water hyacinths could effectively decrease the P concentrations in Lake Caohai, and that the removal of P in the water was mainly from assimilation by the macrophytes. The study aims were (1) to evaluate changes in P concentrations in Lake Caohai associated with the confined growth of water hyacinths, (2) to assess how the P mass balance is influenced by water hyacinths, and (3) to discuss the management of phytoremediation projects that use cultivated water hyacinths.

Materials and methods

Study area

Lake Caohai (24°57′N to 25°1′N, 102°38′E to 102°40′E) has an area of 10.5 km^2 and a mean water depth of 2.5 m. It is the northern part of Lake Dianchi, which is separated into two regions (Lake Caohai and Lake Waihai) by a man-made dike. Lake Caohai is composed of four areas: Neicaohai (1.8 km^2), Dongfengba (2.4 km^2), Waicaohai (5.8 km^2), and Laoganyutang (0.5 km^2) (Fig. 1). Dongfengba and Laoganyutang are ponds, which are separated from the main body of Lake Caohai by dikes. Neicaohai (25°0′49.36″N, 102°39′30.40″E) and Waicaohai (24°58′49.02″N, 102°38′28.61″E) are connected and treated as a relatively independent water body and were the pilot areas used in this study. Six river estuaries are to the northeast of Lake Caohai, and downstream to the southwest is the Xiyuan Channel (Fig. 1); the lake water thus flows from the northeast to the southwest. Sewage effluent from the 1st and 3rd sewage treatment facilities of Kunming flows into Neicaohai and Waicaohai through the rivers and is discharged from the Xiyuan Channel. On average, from 2010 to 2013, $117.50 \times 10^6 \pm 4.38 \times 10^6$ m^3 of sewage was discharged into the lake. In addition to being surrounded by sewage treatment facilities, the primary activity at Lake Caohai is recreational tourism. Furthermore, the natural wetlands around the lake offer habitats for wintering water birds from Siberia and other aquatic animals. Thus, it is very important for local residents and aquatic life to improve the water quality and optimize the environment of Lake Caohai.

Phytoremediation project

The water hyacinth phytoremediation project in Lake Caohai was conducted by Kunming Dianchi Investment Corp. Ltd. The water hyacinth seedlings were cultivated in a fence made of galvanized pipe, plastic foam, and mesh by the end of April, and the macrophytes were harvested by boat until mid-November; this took place each year from 2011 to 2013. The April 2011 water hyacinth plantation in Lake Caohai was 0.3 km^2 (~ 9.0 kt), which grew to the final area of 4.3 km^2 (~ 211.0 kt) by November 2011 (Fig. 2). After harvesting in 2011, the macrophyte planting areas in man-made fence were reduced by the Kunming Dianchi Investment Corp. Ltd., so the final areas in 2012 and 2013 were 0.85 km^2 (~ 45.9 kt) and 1.15 km^2 (~ 62.8 kt), respectively, during harvest time (Fig. 2).

Field experiments

The water sampling sites were selected along the direction of water flow. Sites R1 to R6 were situated in the six river estuaries, sites C5 and C4 were in Neicaohai, sites C3 and C2 were in Waicaohai, and site C1 was in downstream of the Xiyuan Channel (Fig. 1). During project implementation, water samples were collected up to twice per month at the sampling sites (R1–R6 and C1–C5). Water was collected from three depth ranges (0–0.5 m, 1–1.5 m, and 0.5 m above the lake bottom) by a cylinder sampler and mixed in a plastic bucket; 1 L of

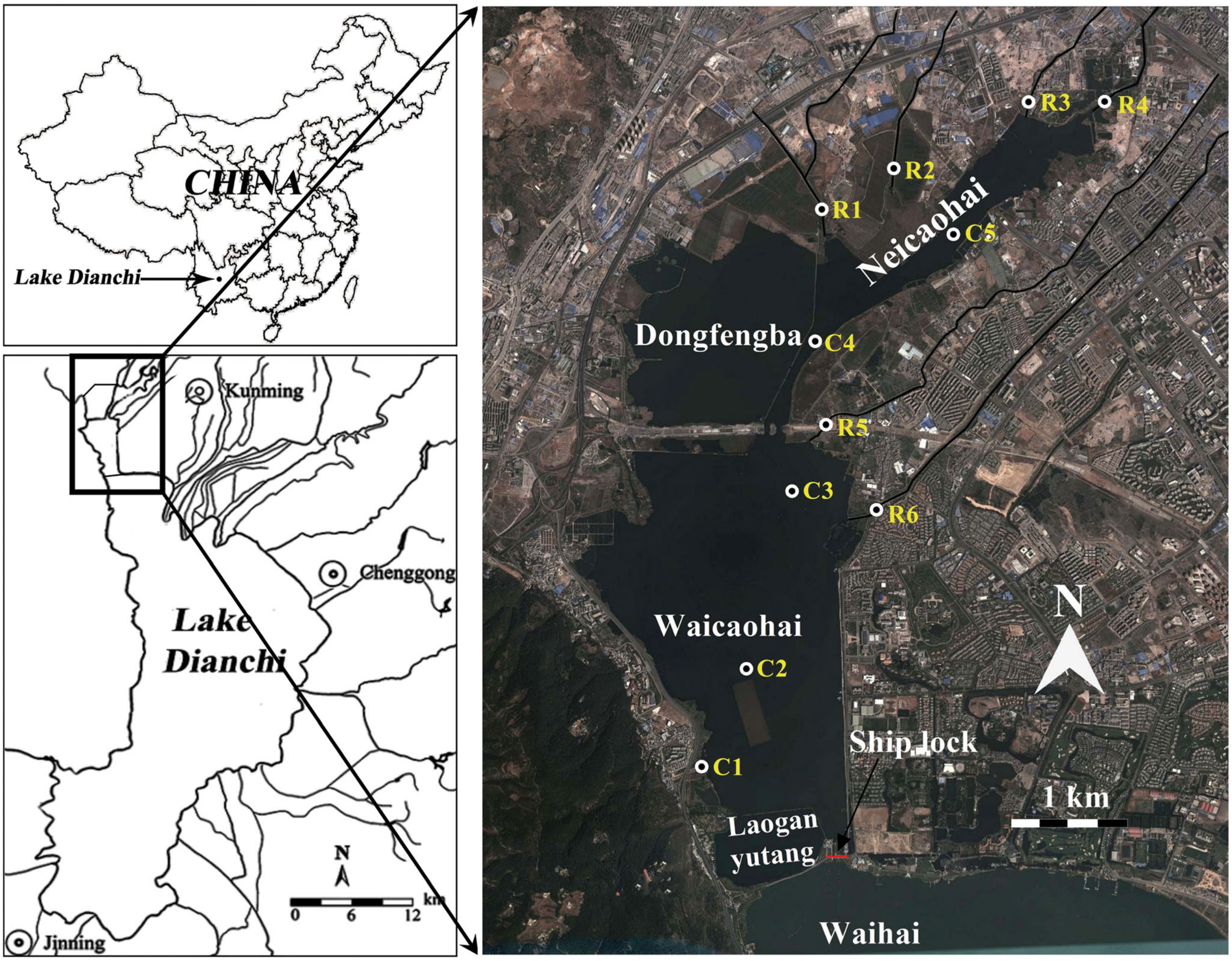

Fig. 1 Location of Lake Caohai and sampling sites in the lake. The pilot areas of this study are Neicaohai and Waicaohai. R1, R2, R3, R4, R5, R6, C5, C4, C3, C2, and C1 indicate the water sampling sites

mixed water was taken as the sample, preserved with 0.5 mL of chloroform, and kept in a refrigerator before chemical analysis. The water temperature, pH, and dissolved oxygen (DO) were measured in situ by a portable instrument (YSI Pro Plus, USA) at 0–0.5 m water depth. According to standard methods (APHA 1998), the physicochemical parameters assessed in the study included total P (TP), total dissolved P (TDP), and phosphate anions (PO_4^{3-}-P). Water hyacinth samples were collected in May (cultivation period) and November (harvest period) every year. The P content in the plant tissue was determined by H_2SO_4-H_2O_2 heating digestion and vanadate-molybdate (yellow) colorimetry (Bao 2000). The water hyacinth coverage in Lake Caohai was determined by satellite remote sensing technology. The remote sensing data were HJ-1B images received in 2011–2013. The HJ-1B satellite is the China's earth observation system launched in 6 September 2008, which is used for environment and disaster forecasting. The PSM of HJ-1B provides spectral resolution of 0.43–0.90 μm with four bands and spatial resolution of 30 m. The biomass of each unit area was measured by electronic balance in 1 m^2 quadrates at nine different sites. Then, the total macrophyte biomass was calculated from the average biomass of a unit area multiplied by the coverage area. All measurements were determined in triplicate.

Data acquisition and statistical analyses

Water quality data of Lake Caohai before May 2011 were provided by the Kunming Environment Monitoring Center, and effluent data from Lake Caohai were provided by the Management Center of Xiyuan Channel of Lake Caohai.

All statistical analyses were conducted with the SPSS 13.0 software (Chicago, USA). Data were presented as the mean ± standard deviation. Intergroup differences were assessed by one-way analysis of variance (ANOVA) with least significant difference (LSD). Temporal variances were performed by multivariate analysis of variance (MANOVA-repeated measure). The significance levels were set at $p < 0.05$.

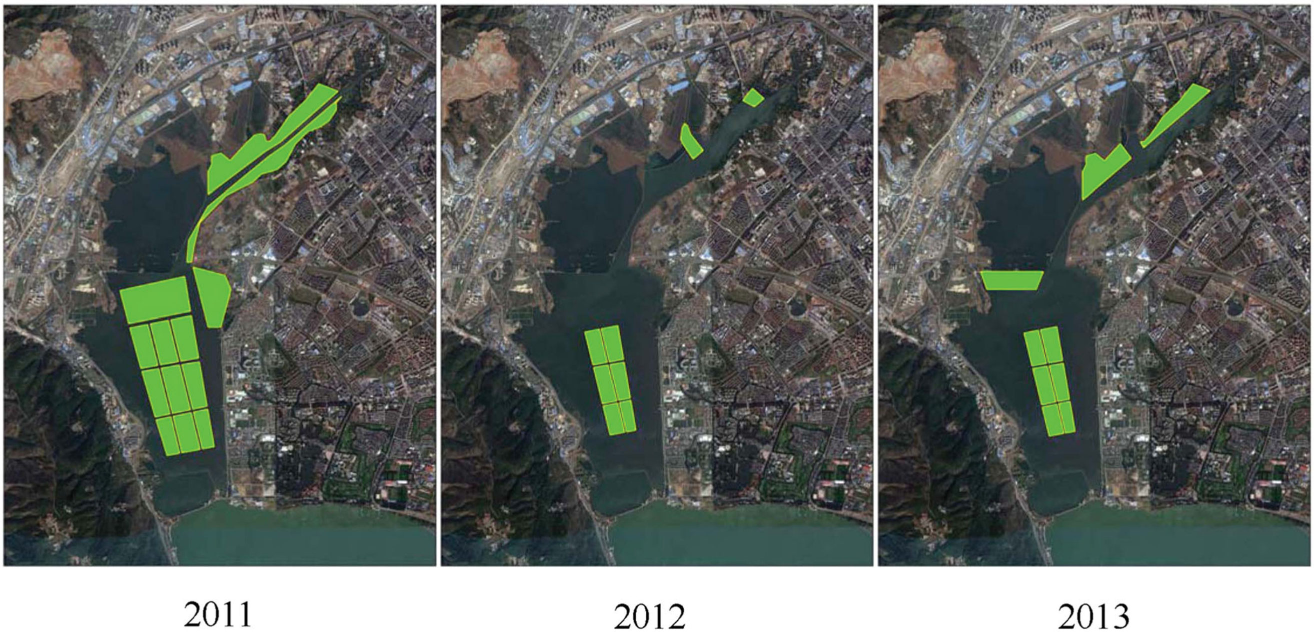

Fig. 2 Sketch map of water hyacinth coverage in Lake Caohai during the project (2011–2013). The green area indicates the water hyacinth cultivation area. The cultivation areas in 2011, 2012, and 2013 were 4.30 km^2, 0.85 km^2, and 1.15 km^2, respectively

Results

Changes in DO, pH, and TP from 2007 to 2013

Compared with 2007–2010, the DO concentrations increased significantly ($p < 0.05$) in 2011 despite water hyacinth mats covering 40.9% of the water surface (Fig. 3a). The DO concentrations in 2011 were significantly lower ($p < 0.01$) at the river estuaries (3.17 ± 1.09 mg L^{-1}) than at Neicaohai (6.60 ± 2.95 mg L^{-1}) and Waicaohai (7.14 ± 2.84 mg L^{-1}). The pH values in Lake Caohai decreased and approached neutral in 2010–2011 (Fig. 3b). The pH increased and the DO concentrations decreased in 2012–2013 owing to the change of inflow water quality and a large reduction in the macrophyte area.

The TP concentrations in water from 2007 to 2009 were not significantly different ($p > 0.05$) at the river estuaries (1.41–2.07 mg L^{-1}), Neicaohai (1.34–1.51 mg L^{-1}), and Waicaohai (1.15–1.39 mg L^{-1}). The TP concentrations in 2010 were significantly lower ($p < 0.01$) at the river estuaries (0.96 ± 0.31 mg L^{-1}), Neicaohai (0.63 ± 0.44 mg L^{-1}), and Waicaohai (0.58 ± 0.37 mg L^{-1}) than in 2009. The TP concentrations in 2011 were slightly lower at the river estuaries (0.78 ± 0.13 mg L^{-1}), but significantly lower ($p < 0.05$) at Neicaohai (0.24 ± 0.11 mg L^{-1}) and Waicaohai (0.24 ± 0.17 mg L^{-1}) than in 2010 (Fig. 3c). In 2011, with confined water hyacinth growth, the average concentration of TP in water decreased 18.7% at the river estuaries, whereas it decreased over 61.9% at Neicaohai and 58.6% at Waicaohai compared with 2010. Following the change in TP concentrations at the river estuaries and the reduction in macrophyte coverage, TP concentrations at Neicaohai and Waicaohai increased in 2012 and then decreased in 2013.

Effects of water hyacinth on P spatial distribution

The water hyacinth coverage in 2011 encompassed the largest area (4.30 km^2) during the project and covered 40.9% of the Lake Caohai water surface; therefore, the results in 2011 could show the influence of macrophytes on P spatial distribution.

The concentrations of TP, TDP, and PO_4^{3-}-P before water hyacinths were planted in 2011 showed an increase along the direction of water flow (Fig. 4a–c) from the river estuaries (R1–6) to Neicaohai (C5 and C4), Waicaohai (C3 and C2), and then on to the Xiyuan Channel (C1, water outflow). However, the average concentrations of TP, TDP, and PO_4^{3-}-P exhibited reductions of 72.2%, 62.8%, and 65.2% ($p < 0.05$), respectively, after water hyacinth cultivation in 2011 from the river estuaries (TP = 0.54 mg L^{-1}; TDP = 0.35 mg L^{-1}; PO_4^{3-}-P = 0.23 mg L^{-1}) to the Xiyuan Channel (TP = 0.15 mg L^{-1}; TDP = 0.13 mg L^{-1}; PO_4^{3-}-P = 0.08 mg L^{-1}) (Fig. 4a–c). Because of the large water hyacinth cultivation area, macrophyte assimilation was a primary factor affecting the concentrations of P in lake water. There were no significant differences between the average P concentrations from June to November in 2011 (after cultivation) among the different sampling sites except for sites R1–6.

Changes in P concentration during plant growth

The results from 2011 showed that the TP concentrations did not change significantly ($p > 0.05$) at sites R1–6, except for a

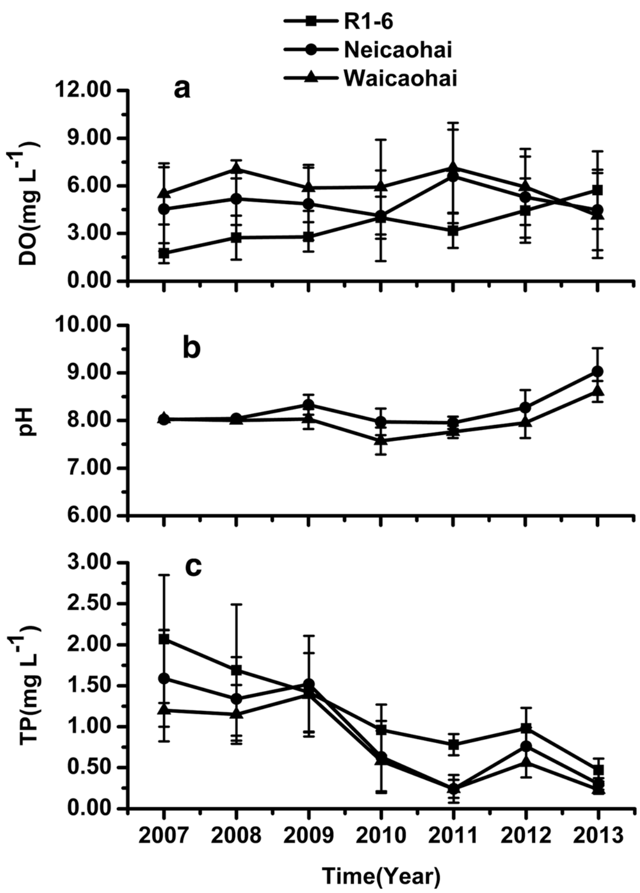

Fig. 3 **a** Dissolved oxygen (DO), **b** pH, and **c** total phosphorus (TP) of Neicaohai and Waicaohai from 2007 to 2013. Water quality data before May 2011 were provided by the Kunming Environment Monitoring Center. Data are presented as mean ± standard deviation. 2007, 2008, 2009, 2010, 2011, 2012, and 2013 indicate the average values of 11 or 12 months every year. R1–6 indicate the average values of the six river estuaries. Neicaohai indicates the average values of C5 and C4, and Waicaohai indicates the average values of C3 and C2

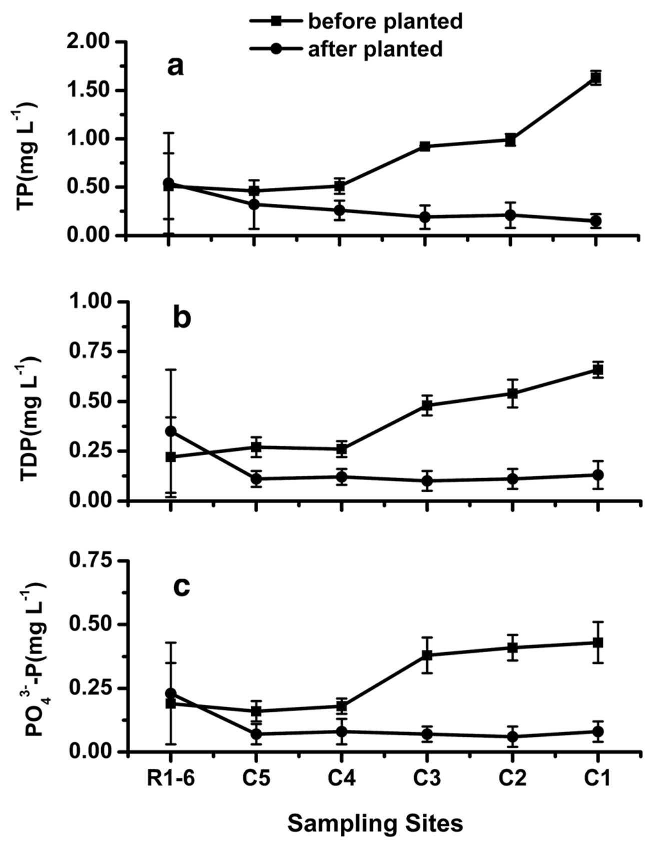

Fig. 4 **a** Total phosphorus (TP), **b** total dissolved phosphorus (TDP), and **c** PO_4^{3-}-P of the sampling sites before and after water hyacinths were cultivated in 2011. R1–6, C5, C4, C3, C2, and C1 indicate the water sampling sites following the direction of water flow. Data are presented as mean ± standard deviation. "Before planted" indicates May 2011, and "After planted" indicates the average values from July to November 2011

sudden increase ($p < 0.05$) in July. The TP concentrations at Neicaohai and Waicaohai decreased ($p < 0.05$) from June, increased at Neicaohai ($p < 0.05$) and Waicaohai ($p > 0.05$) in July, and then remained stable ($p > 0.05$) from August 2011 to January 2012 (Fig. 5a). The results from 2012 showed that the TP concentrations remained high from March to July and then decreased ($p < 0.05$) from August to December at sites R1–6. As a result of the reduced macrophyte area, TP concentrations at Neicaohai and Waicaohais showed the same trends as the river estuary sites. In 2011, the TDP concentrations increased gradually from May to December at sites R1–6. At Neicaohai and Waicaohai, the TDP concentrations decreased from May to August, increased slightly ($p > 0.05$) in September, and then remained stable ($p > 0.05$) from October to December (Fig. 5b). In 2012, as the macrophyte area was reduced, the main region was located in Waicaohai, so the TDP concentrations changed significantly ($p < 0.05$) at the river estuaries and Neicaohai, but remained stable ($p > 0.05$) at Waicaohai (Fig. 5b). In general, the PO_4^{3-} concentrations followed the same pattern as the TDP concentrations (Fig. 5c).

Effects of water hyacinth on P removal in 2011–2013

In Lake Caohai, sources of P came from the inflow of six rivers and the sediment, whereas the effluent pathways were the Xiyuan Channel, macrophyte assimilation, and sediment adsorption. With the exception of P flowing out from the Xiyuan Channel (Table 1), in 2011, 40.93 t of aqueous P was removed, according to a mass-balance estimation. The P removed by the plant harvest was 44.31 t and accounted for 108% of the TP loading (Table 2). In 2012, a total of 48.65 t P in water was removed, as well as 10.56 t removed by plant harvest, which accounted for 22% of the TP loading (Table 2). In 2013, TP concentrations from riverine inflow decreased as a result of river remediation; however, the TP concentrations in effluent water increased compared with 2011-2012 because of the reduced cultivation area and an earlier harvest in September. In 2013, a total of 25.81 t aqueous P was removed; the P removed by the plant harvest was 12.56 t, which accounted for 48% of the TP loading (Table 2).

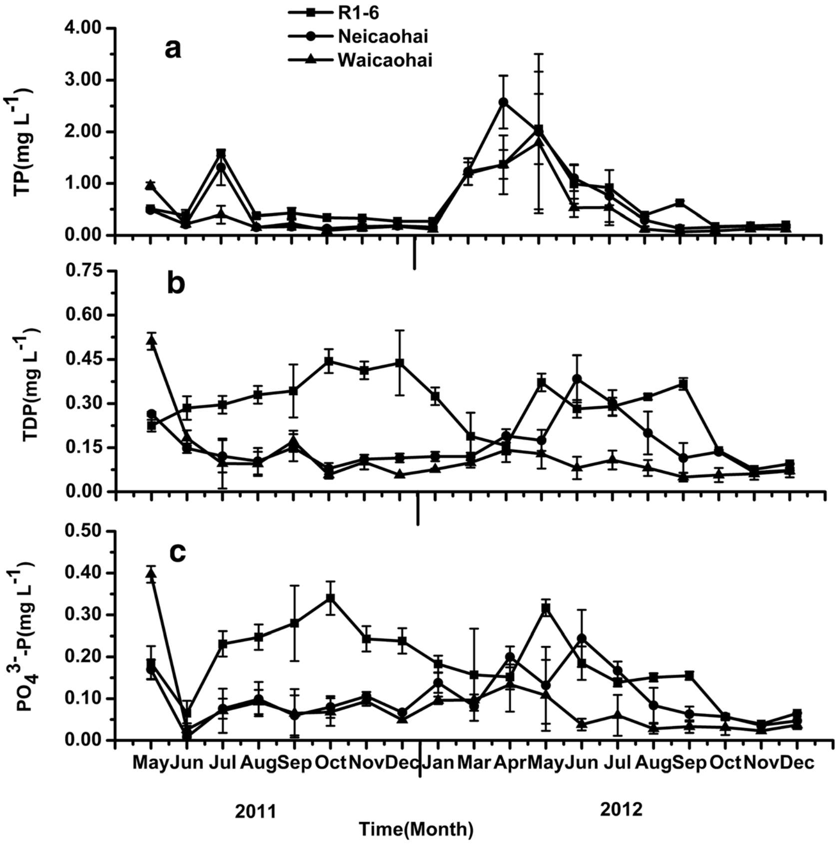

Fig. 5 Monthly variation in the **a** total phosphorus (TP), **b** total dissolved phosphorus (TDP), and **c** SRP of Neicaohai and Waicaohai during the project implementation. Data for TP, TDP, and SRP in February 2012, and TDP and SRP in 2013 were not obtained. Data are presented as mean ± standard deviation. R1–6 indicate the average values of six river estuaries. Neicaohai indicates the average values of C5 and C4, and Waicaohai indicates the average values of C3 and C2

Discussion

Effective removal of P by water hyacinth in Lake Caohai

The results of the phytoremediation project indicated that water hyacinths can effectively remove P from a hypereutrophic lake that receives large amounts of effluent from sewage treatment facilities. P removal through aquatic plant absorption in small-scale experiments has been intensively studied. The TP concentrations in ponds decreased from 1.89 to 0.30 mg L^{-1} after water hyacinth cultivation, 1.70 to 0.20 mg L^{-1} with water lettuce, and 1.80 to 0.35 mg L^{-1} with *Myriophyllum spicatum* after 20 days (Lu et al. 2018). A higher removal potential (56.6%) for aerated and water hyacinth cultures was recorded for PO_4^{3-}-P in municipal wastewater than the treatment with *Salvinia natans* (Kumari and Tripathi 2014). Water hyacinths also performed better than water lettuce in reducing the concentrations of nitrate-N and ortho-phosphates in domestic wastewater (Ismail et al. 2015). Some studies indicated that a large area of water hyacinths in natural lakes can improve water quality and decrease concentrations of TP and PO_4^{3-}-P around the plant mats, instead of beneath them, owing to the capture of algae and suspended solids by plant roots (Rodríguez et al. 2012; Wang et al. 2012).

Reduction of TP in aquatic ecosystems may result from plant uptake of soluble P, filtration of particulate matter through the roots and settling (Shah et al. 2014). Regarding PO_4^{3-}-P removal, cultivated plant species play a significant role along with precipitation and adsorption (Kumari and Tripathi 2014). Aquatic plant species tend to accumulate more nutrients than needed for growth when they are exposed to nutrient-rich effluent (Valipour et al. 2015). Vymazal (2007) reported that the standing stock of P for water hyacinths may be as high as 45 g P m^{-2}, and the annual amount of P taken up by a plant could be up to 126 g P m^{-2} per year because of its high productivity. Thus, this shows that the amount of P removed by plant assimilation can be huge; in our study, it reached 44.31 (t). Recent research indicated that water hyacinth roots are mainly involved in nutrient transportation, while the shoots accumulated more nutrients (N and P) in comparison to the roots (Valipour et al. 2015). In addition, the well-developed root system of water hyacinths provides a suitable environment for microorganism growth that is beneficial for organic pollutant degradation and P removal (Shah et al. 2014).

Influence of water hyacinths on pH and DO in aquatic environments

The pH in Lake Caohai approached neutral after the large-scale water hyacinth cultivation in 2011 (Fig. 3b). This finding

Table 1 Phosphorus fluxes carried by water flow in Lake Caohai from May to November in 2011–2013

Year	Month	Water effluent at Xi Yuan ($\times 10^6$ m^3)	TP concentration of effluent waters (mg L^{-1})	P flux out from lake[a] (t)	Averaged balance of evaporation and precipitation ($\times 10^6$ m^3)	Water inflow from rivers[b] ($\times 10^6$ m^3)	TP concentration of inflow waters (mg L^{-1})	P flux into lake [c] (t)
2011	5	12.104	0.34	4.12	0.251	12.355	0.51	6.30
	6	14.018	0.22	3.08	0.251	14.269	0.38	5.42
	7	11.135	0.17	1.89	0.251	11.386	1.59	18.10
	8	5.987	0.15	0.90	0.251	6.238	0.38	2.37
	9	14.168	0.23	3.26	0.251	14.419	0.43	6.20
	10	6.071	0.08	0.49	0.251	6.322	0.34	2.15
	11	5.192	0.11	0.57	0.251	5.443	0.33	1.80
	Total	68.674		14.31	1.757	70.431		42.34
2012	5	11.330	1.20	13.60	0.061	11.391	2.06	23.47
	6	10.800	0.52	5.62	0.061	10.861	0.99	10.75
	7	14.900	0.36	5.36	0.061	14.961	0.92	13.76
	8	14.070	0.07	0.98	0.061	14.131	0.39	5.51
	9	16.230	0.07	1.14	0.061	16.291	0.50	8.15
	10	7.280	0.05	0.36	0.061	7.341	0.17	1.25
	11	3.310	0.10	0.33	0.061	3.371	0.19	0.64
	Total	77.920		27.39	0.427	78.347		63.53
2013	5	14.557	0.19	2.77	0.038	14.595	0.54	7.88
	6	13.527	0.25	3.38	0.038	13.565	0.63	8.55
	7	17.890	0.43	7.69	0.038	17.934	0.59	10.58
	8	15.080	0.23	3.47	0.038	15.118	0.48	7.26
	9	9.264	0.15	1.39	0.038	9.302	0.45	4.19
	10	22.238	0.16	3.56	0.038	22.276	0.32	7.13
	11	24.687	0.18	4.44	0.038	24.725	0.28	6.92
	Total	117.243		26.70	0.266	117.515		52.51

[a] P flux out from lake = TP concentration of effluent waters × water effluent at Xi Yuan

[b] Water inflow from rivers = water effluent at Xi Yuan + averaged balance of evaporation and precipitation

[c] P flux into lake = TP concentration of inflow waters × water inflow from rivers

was in accordance with previous reports that water hyacinths growing in either acidic or alkaline water showed a tendency to alter pH towards neutral (Mironga et al. 2012; Moyo et al. 2013a). The pH of the water hyacinth-covered water was more constant than the water without the macrophytes (Giraldo and Garzón 2002). Generally, a pH range of 5.5–7.0 provides the

Table 2 Phosphorus removal in Lake Caohai and phosphorus assimilated by water hyacinth from May to November in 2011–2013

Year	P storage in water in May[a] (t)	P storage in water in November[b] (t)	Total P removed[c] (t)	Macrophyte assimilated and removed by harvest[d] (t)	Macrophyte assimilated percentage (%)
2011	15.98	3.08	40.93	44.31	108%
2012	15.40	2.89	48.65	10.56	22%
2013	5.39	5.20	26.00	12.56	48%

[a] P storage in water in May = TP concentration in water in May × water volume in the lake in May

[b] P storage in water in November = TP concentration in water in November × water volume in the lake in November

[c] Total P removed = (P flux into lake–P flux out from lake) (Table 1) + (P storage in water in May–P storage in water in November)

[d] Macrophyte assimilated and removed by harvest = TP concentration in organism at harvest time × macrophyte biomass by harvest. In 2011, 2012, and 2013, the average TP concentrations in the organism at harvest time were 0.21 kg t^{-1}, 0.23 kg t^{-1}, and 0.20 kg t^{-1}, respectively. The macrophyte biomass by harvest in 2011, 2012, and 2013 was 211.0 kt, 45.9 kt, and 62.8 kt, respectively

most satisfactory or balanced plant nutrient levels for most macrophytes. Overall, the characteristic of water hyacinths to adjust pH in water is beneficial for aquatic organisms.

A reduction in DO by water hyacinths beneath growing mats has been reported (Rodríguez et al. 2012). However, DO concentrations in our study increased after water hyacinths were cultivated, especially at Waicaohai where the average concentrations of DO reached 7.14 mg L^{-1} in 2011. Oxygen diffusion from the atmosphere into the water's surface among the water hyacinth mats is a relatively inefficient process because dense plant cover reduces surface gas exchange (Valipour et al. 2011). In contrast, the macrophytes play an important role in transferring atmospheric oxygen to their root system through aerenchyma and release the oxygen into the rhizosphere for aerobic microbial activity (Chunkao et al. 2012; Valipour et al. 2015). Rezania et al. (2016) showed that DO increased by 47% over 3 weeks in an experimental system with water hyacinths, which equaled a rise in DO from 2.1 to 3.1 mg L^{-1}. In this study, rising DO concentrations may be because of improvements to the inflowing water quality from river remediation, the oxygen transfer capacity of water hyacinths, and overall photosynthesis in surface waters without macrophytes.

Adaptive capacity of water hyacinths in different aquatic habitats

The primary removal of P from lake water is by channel outflow, macrophyte assimilation, and sediment absorption. In 2011, P removal by water hyacinth assimilation accounted for 108% of the TP loading (Table 2), which might result from macrophytes partially removing P from lake sediment. In 2012, the water hyacinth coverage decreased and the P removed by plant harvest accounted for only 22% of the TP loading (Table 2). This suggested that some species of P in water, especially particulate P, was deposited to the sediment. It also indicated that there was particulate P in lake water, which was shown by the much higher TP concentrations than TDP in 2012 (Fig. 5a, b).

When the available nutrients are sufficient, water hyacinths absorb N and P in excess of physiological requirements and store them in its tissues. Water hyacinths accumulate phosphate in plant tissue at concentrations eight times higher than their physiological needs (Reddy et al. 1990). To survive in various habitats, water hyacinths demonstrate adaptable morphology (Valipour et al. 2011; Rezania et al. 2015), especially with regard to their root properties. At very low nutrient concentrations (TP = 0.10 mg L^{-1}), the macrophytes can increase their root length to 2 m to enhance nutrient acquisition (Rodríguez et al. 2012). Xie and Yu (2003) examined the morphology of lateral water hyacinth roots in relation to P acquisition. The results indicated that the lateral roots were 2.43 times longer and 1.97 times denser under low-P supply treatments (0.6 g m^{-2} per year) than high-P supply treatments (4.8 g m^{-2} per year). As shown in Table 3, our observations from 2010 also indicated that water hyacinths in Lake Caohai had shorter roots, stronger aerial parts, and dark green leaves with sufficient nutrient supply. In contrast, macrophytes in Baishan Bay (Lake Waihai) had longer roots, slim aerial parts, and pale green leaves under lower concentrations of N and P (Zhang et al. 2011). Therefore, hyper-accumulation of nutrients (N and P) combined with adaptable morphology is the crucial biological characteristics of water hyacinths for phytoremediation.

Water hyacinth control and biomass utilization

Water hyacinths grow rapidly, doubling in population in 5–15 days, and have an average biomass accumulation of 100–140 t dry matter per hectare per year (Moyo et al. 2013b). Water hyacinths have been regarded as one of the most highly invasive species in the world because of the significant ecological impacts they have on the environment and the associated cascading socioeconomic effects (Pérez et al. 2015). Some studies investigated mechanical, chemical, and biological methods to eradicate water hyacinths, but all of these measures have been only partially successful (Moyo et al. 2013b; Koutika and Rainey 2015; Fraser et al. 2016). Jones et al. (2018) indicated biological control strongly affected plant size, biomass, and vigor, but did not affect plant cover. Therefore, if eradication of this notorious weed is not easy, then the feasibility of using this plant as an energy resource should be considered. Our study makes a case for integrated resource management to control water hyacinths while restoring water quality, improving aquatic environments, acting as resource, and generating energy. The phytoremediation project consisted of three procedures. First, water hyacinth seedlings were cultivated in a fence made of galvanized pipe,

Table 3 Comparison of nutrient concentrations and morphological characteristics of water hyacinth in Lake Caohai and Baishan Bay of Lake Waihai in 2010 (Zhang et al. 2011)

Location	Average concentrations of TN (mg L^{-1})	Average concentrations of TP (mg L^{-1})	Largest shoot length (m)	Largest root length (m)	Accumulated biomass in 6 months (kg m^{-2})
Caohai	6.38 ± 0.18	0.64 ± 0.03	85.50 ± 4.00	25.00 ± 0.50	85.37 ± 14.22
Baishan Bay	2.35 ± 0.16	0.23 ± 0.02	22.50 ± 2.65	69.50 ± 3.95	27.00 ± 3.60

plastic foam, and mesh. After a rapid growth phase, water hyacinths were harvested by specially designed boats. The harvested macrophyte biomass was crushed and squeezed; the squeezed slag was processed to make organic fertilizer or silage feed and the squeezed liquid was processed to manufacture biogas. When considered with other social benefits, our phytoremediation project has the potential to provide sustainable economic and environmental returns.

Management of water hyacinth phytoremediation project

The management of the phytoremediation project consisted of three steps: (1) where to cultivate water hyacinth, (2) when and how to harvest the macrophytes, and (3) utilization of water hyacinth biomass. Removal of exogenous P usually can be achieved by utilizing water hyacinths to treat sewage effluent or by cultivating the macrophytes at or near river estuaries with high nutrient loading (Yan and Guo 2017). Additionally, the removal of endogenous P can be achieved by cultivating water hyacinths at sites where populations of algae gather and decline, with released nutrients absorbed by the macrophytes (Zhou et al. 2014). Our results in 2011 showed that the concentrations of TP, TDP, and PO_4^{3-} decreased in June and lower levels were maintained after water hyacinths were planted. In November 2011, the concentrations of TP, TDP, and PO_4^{3-} increased slightly, which may have resulted from macrophyte decomposition and nutrient release. Therefore, water hyacinths must be harvested before November (Wang et al. 2013). To harvest large amounts of water hyacinth, two generations of mobile harvest vessels (35 t h^{-1}; US\$1.42 t^{-1}) were designed and manufactured as well as a stationary land-based harvester (75 t h^{-1}; US\$0.50 t^{-1}) (Yan and Guo 2017). High P concentrations (TP $\geq$ 1 mg L^{-1}) in eutrophic water and macrophytes in the early growth stages, harvested water hyacinth blades contained more P and might be more suitable for animal feed if other pollutants (e.g., heavy metals) are below safety limits. However, low P concentrations (TP $\leq$ 0.1 mg L^{-1}) in eutrophic water and macrophytes at mature growth stages, water hyacinths might be more suitable for methane and fertilizer fermentation owing to the low nutrient content in plant tissue.

Conclusions

In Lake Caohai, an open hyper-eutrophic plateau lake, water hyacinths showed a notably positive effect on improving water quality by removing P. Water hyacinths significantly decreased the concentrations of TP, TDP, and PO_4^{3-}-P in lake water. In 2011, P assimilated by the macrophytes principally came from the lake water and partially from the sediment. Water hyacinths showed a tendency to change the pH towards neutral, which is beneficial to aquatic organisms. In addition, DO concentrations in the lake water increased as a result of good management of the macrophytes. Hyper-accumulation of nutrients (N and P) with morphological plasticity are the crucial biological characteristics of water hyacinths for phytoremediation. Water hyacinths can be used to treat the effluent from sewage treatment facilities or they can be cultivated near river mouths to remove exogenous P. Additionally, the macrophytes can also be cultivated at sites with large concentrations of algae to help in the decline of assimilated nutrients and remove endogenous P. Considering the potential ecological risk, the management of phytoremediation projects should be strengthened, and water hyacinths in particular should be controlled.

Acknowledgments The authors would like to thank the support of Kunming Dianchi Investment Corporation Limited, Kunming Environment Monitoring Center and the Management Center of Xiyuan Channel of Lake Caohai. We thank Kara Bogus, PhD, from Liwen Bianji, Edanz Editing China (www.liwenbianji.cn/ac), for editing the English text of a draft of this manuscript.

Funding information This research was supported by the Jiangsu Agriculture Science and Technology Independent Innovation Funds (CX(16)1003-3), the National Science and Technology Major Project of Water Pollution Control and Treatment (2017ZX07202004-007), and the National Natural Science Foundation of China (NSFC41201533).

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