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RESEARCH ARTICLE

Fenced cultivation of water hyacinth for cyanobacterial bloom control

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Abstract To achieve the goals of harmful cyanobacterial bloom control and nutrient removal, an eco-engineering project with water hyacinth planted in large-scale enclosures was conducted based on meteorological and hydrographical conditions in Lake Dianchi. Water quality, cyanobacteria distribution, and nutrient (TN, TP) bioaccumulation were investigated. Elevated concentrations of N and P and low Secchi depth (SD) were relevant to large amount of cyanobacteria trapped in regions with water hyacinth, where biomass of the dominant cyanobacteria *Microcystis* (4.95×10^{10} cells L^{-1}) was more than 30-fold compared with values of the control. A dramatic increase of TN and TP contents in the plants was found throughout the sampling period. Results from the present study confirmed the great potential to use water hyacinth for cyanobacterial bloom control and nutrient removal in algal lakes such as Lake Dianchi.

Keywords Bloom control · Water hyacinth · Nutrient removal · Harmful cyanobacteria · Water restoration · Eutrophication

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Hongjie Qin and Zhiyong Zhang contributed equally to this work.

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Introduction

In recent years, harmful cyanobacterial blooms, especially *Microcystis* blooms, have been considered to be a common environmental issue (Zhang et al. 2014) and have received worldwide attention as they can produce and release toxins that greatly harm aquatic ecosystems and cause potential hazard to human health to exist (Ou et al. 2012).

To inactivate or remove cyanobacterial blooms, many methods and technologies have been explored. Mechanical algae removal (Conklin et al. 2008) and ultrasonic treatment (Wu et al. 2012) are the main physical methods as emergent measures for bloom control, while they consume a great deal of energy and do not efficiently inactivate algal cells (Wang et al. 2012b). The chemical algicidal agents such as chlorination (Daly et al. 2007) and H_2O_2 (Barrington et al. 2013) may result in secondary effects on other aquatic organisms (Zhang et al. 2014) and were not suitable for in situ application in large-scale waters. Biological methods were recognized as safe and reliable, such as using filter-feeding fish to graze algae (Xie and Liu 2001) and planting macrophytes to inhibit algal growth by excreting allelochemicals (Gross 2003); however, due to low transparency and low dissolved oxygen together with high concentrations of ammonia in the regions with dense cyanobacterial blooms, the survival rates of fish and transplanted macrophytes were so low that the effect of bloom control was not remarkable. The basic and effective way to control cyanobacterial blooms was to reduce problematic nutrient contents in the water, especially N and P which were two key limited elements for controlling blooms (Conley et al. 2009), though it is a long process (Wang et al. 2012b). So, it is an urgent need to develop effective, cost-saving, safe, and eco-friendly integration technology to remove and control the growth of algae and to decrease N and P concentrations as well as to reduce adverse impacts of cyanobacterial blooms on other aquatic organisms, which is the key step and precondition in the recovery and protection of aquatic ecosystems (Li et al. 2007b).

Water hyacinth (*Eichhornia crassipes* (Mart.) Solms), a free-floating perennial aquatic macrophyte native to tropical South America (Tipping et al. 2011), is a member of the monocotyledonous family Pontederiaceae (Patel 2012) with long and dense hairy root system which was conducive to absorbing nutrients and was a medium for the filtering out and attachment of particulate matter including cyanobacteria (Kim and Kim 2000). It is notorious as one of the world's worst noxious invasive weed due to its tremendously vigorous growth rate (Mishra and Tripathi 2009) and depends on its peculiar physiological characteristics and nutrient absorption efficiency (Paganetto et al. 2001). However, these just were the reasons for using it in phytoremediation technology on nutrient removal (Fox et al. 2008; Chavan and Dhulap 2012). On the one hand, uncontrolled dense water hyacinth mats over water surface were considered as a nuisance for obstructing navigation, irrigation, and fishing and causing blockage of drainage systems as well as hampering recreational activities (Khaket et al. 2012), causing significant ecological and socioeconomic impacts in areas of introduction (Fan et al. 2013). However, on the other hand, as it generally grows well even in heavily polluted waters (Hu et al. 2007), together with its wide tolerance to environmental conditions (De Casabianca and Laugier 1995; Rommens et al. 2003), as a scavenger of nutrients (Fang et al. 2007), heavy metals (Hadad et al. 2011), and toxic organics (Ebel et al. 2007), it has been wildly used and has gained increasing attention in recent years for phytoremediation of many waters. If exploited properly, green and environment-friendly technologies based on water hyacinth could address many prevailing issues; however, as notorious weed causes it to fail to lure entrepreneurs, it hinders capital investment and application (Patel 2012). Previous studies mostly were conducted in laboratories under static water conditions or in ponds and other small-scale waters; therefore, it was difficult to accurately reflect phytoremediation effects of the actual liquidity conditions especially for large lakes disturbed by perennial storm water. In addition, eco-engineering with water hyacinth acted as a biological wave dissipation belt, which could provide a calm condition for phytoremediation in the north lakeshore of Waihai (AVRA, Fig. 1). Moreover, there are fewer researches on the integrated technology with functions of *E. crassipes* for cyanobacterial bloom control, particularly for large-scale (1.33 km^2) application in the field.

Dianchi Lake is in a hypertrophic status, where serious cyanobacterial blooms dominated by *Microcystis* occur every summer during the past decades (Wang et al. 2010). Blooms of *Microcystis* break out yearly, with high density of cells, on a large scale, and lasting for a long time period. So, it was too difficult to restore the vegetation, especially at the lakeshore where it accumulated a large number of *Microcystis* blooms, one of the main carriers of nitrogen (N) and phosphorus (P) in the lake, due to the wind and lake current. Many projects have been executed in Dianchi Lake for nutrient removal and cyanobacterial bloom control such as sediment dredging, external sewage interception, ecological restoration and reconstruction, and outer basin water transfer; however, nutrient (N and P) level still stays at an unacceptable level with cyanobacterial blooms occurring every year.

The aims of the current study were to obtain an integrated technology of the eco-engineering with water hyacinth planted in large-scale enclosures nearby the shore of Dianchi Lake where a large number of cyanobacterial blooms accumulated and to evaluate the hypothesis on two main functions of the integrated technology. The first states that water hyacinth could grow well in the fenced area without escape and plays an outstanding role as a physical barrier as well as a bloom-trap and helps to inactivate or remove cyanobacterial blooms; the second states that it has been found that cyanobacteria may improve the N accumulation ability of water hyacinth based on our previous findings via laboratory experiment, so we hypothesize that water hyacinth can act as a scavenger with high efficiency of N and P bioaccumulation (g kg^{-1} fresh weight) and removal even under abominable conditions with thick harmful cyanobacterial scum where many other aquatic macrophytes could not survive. Therefore, final results on blocking the migration of nutrients and the dynamics of nitrogen and phosphorus cycle in lakes can be achieved.

Materials and methods

Study area

Dianchi Lake, the famous plateau freshwater lake (elevation of 1886 m) as well as the biggest inland lake (area of 320 km^2) (Wang et al. 2013), is located in the Central Yunnan Plateau of southwestern China (24° 29 –25° 28 N, 102° 29 –103° 01 E, Fig. 1). The lake was bisected by an artificial causeway, the northern lake called Caohai (about 3 % of the total volume) and the southern lake called Waihai (Liu et al. 2013). The water exchange between Caohai and Waihai was controlled by a ship lock as shown in Fig. 1. With a capacity of 1.179×10^9 m^3, the average and maximum water depths are 4.4 and 10.4 m, respectively (Wang et al. 2013). Wind-generated water current with a cyclonic swirl field in the center and several eddies in some regions near the shore was the major site of surface current in Waihai of Dianchi as shown in Fig. S1 (imitate Wang et al. 1986). It had been named the bright pearl in the Yungui Plateau of southwest China and was the major water source of human drinking water, industry, and agriculture in Kunming city, Yunnan Province, while

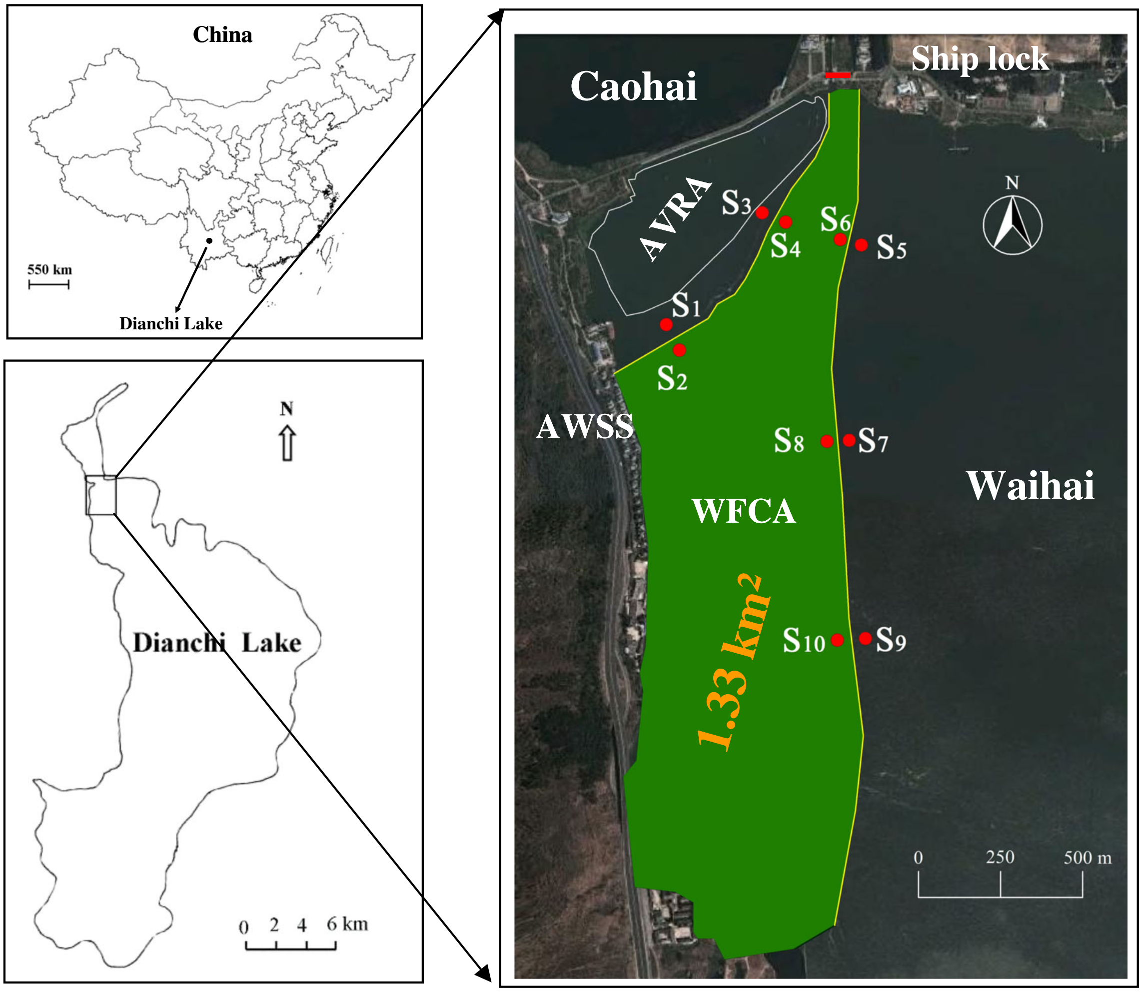


Fig. 1 The location of fenced cultivation of water hyacinth and the distribution of sampling sites in Waihai of Dianchi Lake. *WFCA* water hyacinth fenced cultivation area. *AWSS* algae-water separation station. *AVRA* aquatic vegetation restoration area, where different types of aquatic plants with different niches such as submerged, emerged, and floating-leaved macrophyte were planted in different water layers

water quality of Dianchi Lake has deteriorated over recent decades (Ni et al. 2011) as it is the pond to receive sewage from irrational distribution of the industry with the rapid increase in the local population (Liu and Zhang 1996).

The ecological engineering area with large-scale confined growth of water hyacinth, named water hyacinth-fenced cultivation area (WFCA) in Fig. 1, with a fenced area of 1.33 km^2, was located in the northwest of Waihai (24° 57 N, 102° 38 E), where a large number of cyanobacterial blooms most of the time every year due to southerly wind (blowing to north) and lake current are usually gathered, as shown in Fig. S1. The aquatic vegetation restoration area (AVRA) was half-surrounded by the fenced water hyacinth from its southern edge, and it is a region where different types of aquatic plants with different niches such as submerged, emerged, and floating-leaved macrophyte were planted in different water layers. We hypothesize that water hyacinth can act as a wave dissipation belt, and one of the main aims of the ecological engineering in this study was to provide a good survival environment for the aquatic vegetation in AVRA. In the north of AVRA, there was a sightseeing road named "Hubin road," where many tourists traveled on the road for sightseeing every day. A large number of accumulated cyanobacterial blooms, owing to wind and current of the lake, released a smelly odor by dead cyanobacteria, especially during the summer days (June to September). The landscape effects nearby Dianchi Lake were severely affected by the hateful cyanobacteria every year. It is worth emphasizing that the adverse effects mentioned above were not reappeared again after the 1.33 km^2 eco-engineering with water hyacinth was completed. An algae-water separation station (AWSS) was located in the northwest corner of the ecological engineering area (on the shore of lake). The role of AWSS was to transfer cyanobacteria intercepted by the ecological engineering to the shore, especially when water hyacinth was harvested.

In order to prevent the floating macrophyte from escaping, a safe control mode called "double-row steel pipe and nylon mesh" was developed in this study. The detailed description of this mode was provided as the supplementary material (Fig. S2) and has been uploaded with the manuscript. The control mode has been applied for a patent in China named "A device for safety control of floating macrophytes suitable to open waters with heavy waves (China, ZL 2015 20097706.4.)." It could confine water hyacinth to grow in a designated area, and it has been rarely reported in previous studies. The fence was mainly composed by steel pipe, nylon rope, and nylon net, and its structural diagram and scene diagram were shown in Fig. S2a, b, respectively. In order to facilitate sample collection in the areas of water hyacinth planted, five trestles (1 m width, 10 m length) were constructed from the edge of the fence (located at the even sampling sites as described below).

Sampling sites

The wind direction in the ecological engineering area is southerly, which means that the wind always blows northward. The surface current in the designated area for water hyacinth growth (Fig. S1) has also been taken into account on sampling site selection, because algae distribution in water was closely related to wind and current of lakes. Ten sampling sites were chosen around the fenced area (Fig. 1), where the odd sites, free of water hyacinths (S_1, S_3 at the downwind and S_5, S_7, S_9 at the upwind) located outside the macrophyte mats, were indicated as CK-Down and CK-Up, respectively. The even sites, covered with water hyacinths, (S_2, S_4 at the downwind and S_6, S_8, S_{10} at the upwind) located inside the macrophyte mats were indicated as downwind and upwind, respectively. Upwind sites (S_1, S_2, S_3, S_4) and downwind sites (S_5, S_6, S_7, S_8, S_9, S_{10}) were evenly distributed at the confined area of water hyacinth.

Water sample collection and analysis

Water samples were collected monthly from June 2013 to October 2013 on a sunny day from 9:00 a.m. to 11:00 a.m. at the ten sites during the main growth periods of water hyacinth as shown in Fig. 1. In order to ensure the accuracy of samples, 0.5-L sub-samples were harvested from 15-L mixed water samples which were vertically collected from three layers (surface layer, 0~0.5 m; middle layer, 1~1.5 m, and bottom layer, 0.5 m above the bottom) of the water column using a 5-L cylinder sampler at each sampling site and stored in 500-mL polyethylene bottles. Water temperature (WT), dissolved oxygen (DO), and pH were determined with a portable temperature, dissolved oxygen, and pH meter (YSI 550A, YSI Inc., Yellow Springs, OH, USA), and secchi depth (SD) was measured with a 20-cm-diameter black and white Secchi disc in situ, respectively. The samples were transported to the field laboratory and analyzed as soon as possible. Chemical oxygen demand (COD_{Mn}), total phosphorus (TP), total dissolved phosphorus (TDP), total nitrogen (TN), total dissolved nitrogen (TDN), nitrate (NO_3^-), and ammonium (NH_4^+) were determined according to the standard methods (APHA 1995) for water quality analysis.

Phytoplankton sample collection and analysis

Sub-samples (0.5 L) were harvested from 15-L mixed water samples which were collected as described above and were immediately fixed with 1 % Lugol's solution then concentrated to 50 mL by siphon pipe after a 48-h sedimentation (Li and Li 2012). In order to count algal cells conveniently and accurately using the microscope, cells, particularly colonial *Microcystis*, were separated by sonication (LD-150N, Lede Technology Co., Ltd., Kunming, China) (Humphries and Widjaja 1979). The average cell numbers were counted by using a light microscope at ×4000 magnification (CX41, Olympus, Tokyo, Japan) with a plankton counting chamber and used to calculate the percent of the biomass. For each sample, three sub-samples were counted to ensure an accurate depiction of the community structure and algal biomass.

The viability of algae was determined in accordance to the methods provided by Li and Song (2007), which was based on the ability of viable cells to reduce the 3-[4,5-dimethylthiazol-2-yl]-2,5-diphenyl tetrazolium bromide (MTT) to formazan.

Water hyacinth harvest and analysis

Sub-samples of water hyacinth were selected randomly and harvested from sites Downwind and Upwind from June 2013 to October 2013 at monthly intervals and washed with running tap water to eliminate the adhering particle matters and then kept on a filter paper to remove water on root surface. The washed plants were oven-dried in an oven at 65 °C for at least 48 h to a constant weight after heat treatment under 105 °C for 30 min, and weighed up, then ground to fine powder with a high-speed universal disintegrator (FW100, Tianjin Taisite Instrument Co., Ltd., Tianjin, China) and sieved using an 80-mesh screen and kept in a dry place until used for TN and TP content analysis according to Bao (2000), which were expressed as grams per kilogram based on FW.

For root volume, washed roots were put into a 1000-mL graduated cylinder containing 700 mL distilled water, and the increased volume in cylinder was indicated as the volume of roots.

Root total surface area (TSA) and active adsorption area (AAA) of fresh washed roots in different investigated plots were determined by methylene blue dyeing method described by Zhang et al. (1994).

In order to determine the amount of *Microcystis*, the dominant species adhering to the plant root systems, three water hyacinth coupons were randomly selected and their root mats were transferred to 1-L distilled water then carefully brushed with a soft brush. The distilled water containing *Microcystis* was fixed with 1 % Lugol's solution, and the cell numbers of the algae were counted as the method described above. The biomass of *Microcystis* adhered to the roots were indicated as cells per square meter of root.

Statistical analysis

Data between controls (CK-Up and CK-Down) and treatments (Upwind and Downwind) were statistically analyzed by performing one-way ANOVA followed by the least significant difference (LSD) post hoc test (SPSS, Chicago, IL, USA), at the 95 % confidence level. All data are presented as mean ± standard deviation (SD).

Results

Physicochemical properties of water samples

The physical and chemical properties of water samples taken from four different regions were analyzed in Figs. 2 and 3, where CK-Up, Upwind, CK-Down, and Downwind indicate the control of upwind (without *E. crassipes* grown), upwind sites, control of downwind (without *E. crassipes* grown), and downwind sites, respectively.

For water temperature (WT), no significant differences among the four survey sites were observed ($P > 0.05$) with maximum values of 24.33 ± 0.25 to 24.38 ± 0.35 °C in June and minimum values of 20.67 ± 0.15 to 20.82 ± 0.42 °C in October (Fig. 2a).

Though the concentrations of DO in Upwind sites were slightly lower than those of CK-Up sites (Fig. 2b), no significant differences were observed between Upwind and CK-Up from June to October ($P > 0.05$). In contrast, the levels of Downwind in July and October (4.10 ± 1.21 and 8.17 ± 1.05 mg L^{-1}) were significantly lower than those of CK-Down (9.85 ± 1.81 and 13.15 ± 0.07 mg L^{-1}) ($P < 0.05$).

As shown in Fig. 2c, there were no obvious differences of pH between Upwind and CK-Up throughout the sampling period, and a similar trend was observed between Downwind Upwind and CK-Down ($P > 0.05$).

Changes of COD_{Mn} were shown in Fig. 2d. No significant differences between CK-Up and Upwind were observed ($P > 0.05$). However, it is worth emphasizing that COD_{Mn} values of Downwind were markedly higher than those of the control CK-Down ($P < 0.05$), particularly values in August which were more than 20-fold compared with those of CK-Down.

Values of SD in Downwind were less than 0.1 m from June to October (Fig. 2e), which were significantly lower than those of CK-Down ($P < 0.05$).

Changes in concentrations of different forms of N and P among four different water samples were shown in Fig. 3. No significant differences between CK-Up and Upwind were observed from June to October, except NO_3^--N (CK-Up with 0.75 ± 0.14 mg L^{-1} and Upwind with 0.13 ± 0.06 mg L^{-1} in September). For the groups between CK-Down and Downwind, all concentrations of different forms of N except NO_3^--N (TN, TDN, and NH_4^+-N) and P (TP and TDP) in Downwind were significantly higher than those of the control CK-Down throughout the sampling period ($P < 0.05$) especially for parameters of TN and TP in September and October; however, NO_3^--N concentrations of Downwind were significantly lower than those of the control CK-Down except samples collected in June and August ($P < 0.05$).

Phytoplankton in water and attached on root mats

As shown in Fig. 4a, more than 90 % total biomass of phytoplankton was *Microcystis* except for August during the whole sampling periods. The accurate cell numbers of the dominant species—*Microcystis* of different sampling sites—were shown in Fig. 4b. A slightly increasing trend was observed in Upwind sites compared with the control CK-Up, and it was also worth emphasizing that the biomass in Upwind was markedly higher than that of the control for samples collected in August ($P < 0.05$). It was obvious that *Microcystis* biomass in Downwind were significantly higher than the values of CK-Down ($P < 0.05$); in particular, it was more than 30-fold (4.95×10^{10} cells L^{-1}) compared with the biomass of CK-Down (0.16×10^{10} cells L^{-1}) in October.

A fact that needs to be added is that *Microcystis* was still the dominant species attached on roots during the whole survey periods (data not shown). The changing trends of both Upwind and Downwind look like an "N" (decrease after increase then increase again). Cell numbers of samples collected from Downwind with maximum biomass of 1.55×10^{10} cells m^{-2} root were significantly higher than those collected from Upwind with maximum biomass of 0.38×10^{10} cells m^{-2} root in October ($P < 0.05$) (Fig. 4c).

It was the peak of cyanobacteria biomass in September during the outbreak of bloom every year in Lake Dianchi, with no exception for 2013 (Fig. 4b). Significant differences were observed between CK-Up and Upwind, Upwind and Up-root, CK-Down and Downwind, and Downwind and Down-root ($P < 0.05$). Viability of algae attached on root mats were the lowest among the investigated sites with A_{556} values of 0.33 ± 0.01 in Up-root and 0.32 ± 0.01 in Down-root, and the

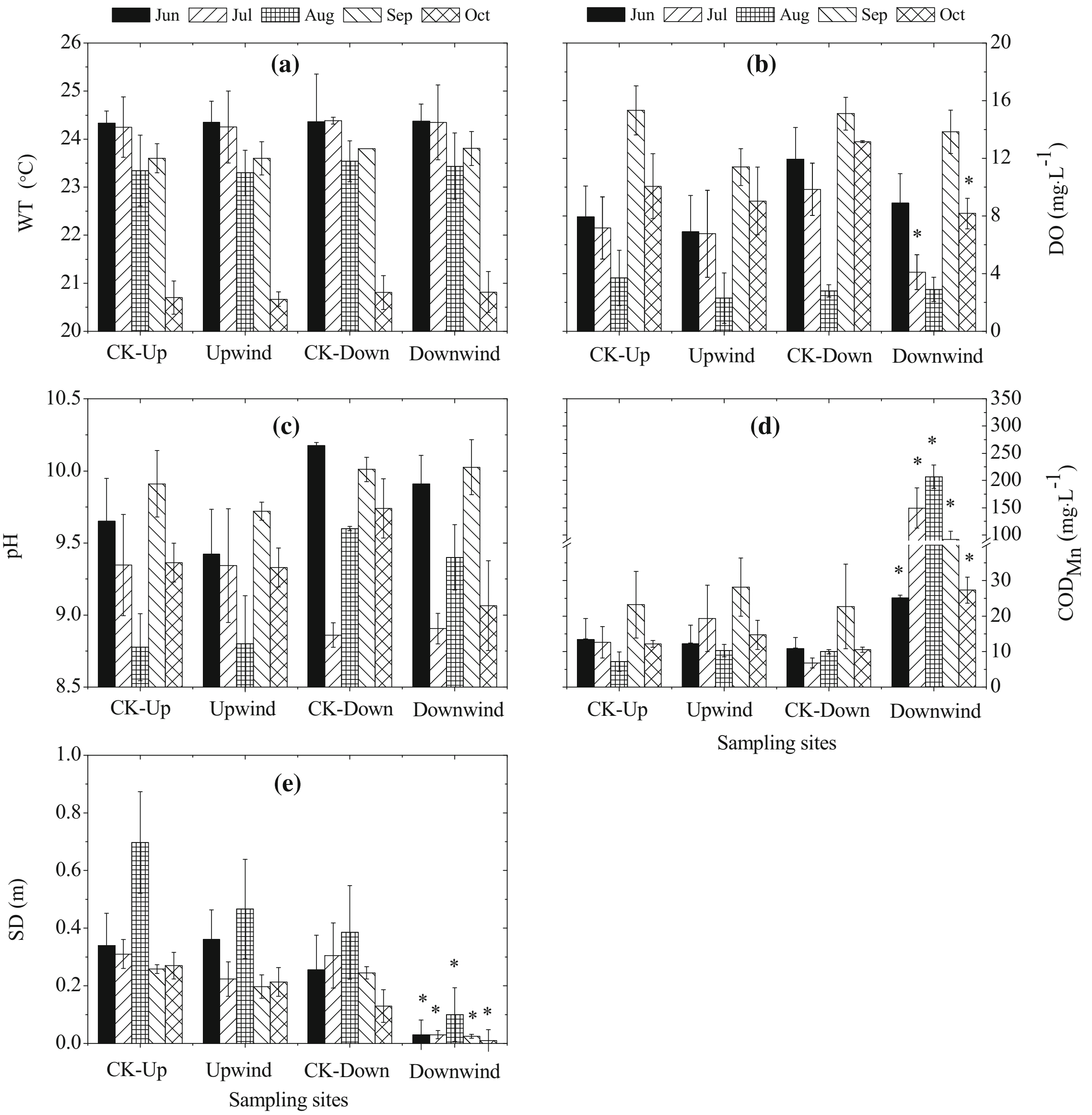


Fig. 2 Physicochemical parameters ((**a**) WT; (**b**) DO; (**c**) pH; (**d**) CODMn; (**e**) SD) of water samples in field of cultivation regions and regions without water hyacinth. *CK-Up*, *Upwind*, *CK-Down*, and *Downwind* indicate the control of upwind, upwind sites (without water hyacinth grown), control of downwind, and downwind sites (without *E. crassipes* grown), respectively. Data are presented in means ± standard deviation (SD). The levels of significant differences of parameters between CK-Up and Upwind and CK-Down and Downwind were indicated by an *asterisk* for $P < 0.05$ (the same for the following figures); panels "Jun, Jul, Aug, Sep, Oct" in figure indicate sampling time of "June, July, August, September, October", respectively (the same for the following figures)

values obtained from CK-Up and Upwind were 64.84 and 79.25 %, and 67.78 and 81.54 % for CK-Down and Downwind, respectively (Fig. 4d).

Water hyacinth

Root volume of water hyacinth planted in Downwind markedly decreased from July to October compared with the values of the plants growing in Upwind ($P < 0.05$), and it decreased to 24.00 ± 5.66 cm^{-3} plant^{-1}, only 20.81 % of Upwind in October (Fig. 5a).

The changing trends of root total surface area (TSA) and active adsorption area (AAA) was the same as those of root volume (Fig. 5b, c). TSA and AAA of plants growing in Downwind were significantly lower than those of plants in Upwind ($P < 0.05$). The ratios of AAA/TSA of plants in Downwind were also significantly lower than those growing in Upwind from August to October ($P < 0.05$) (Fig. 5d).

The TN contents of water hyacinth growing in Downwind were (2.52 ± 0.21 and 2.61 ± 0.21 g kg^{-1} FW in August and October) significantly higher than those in Upwind ($P < 0.05$), and a similar increasing trend of changes of TP contents was

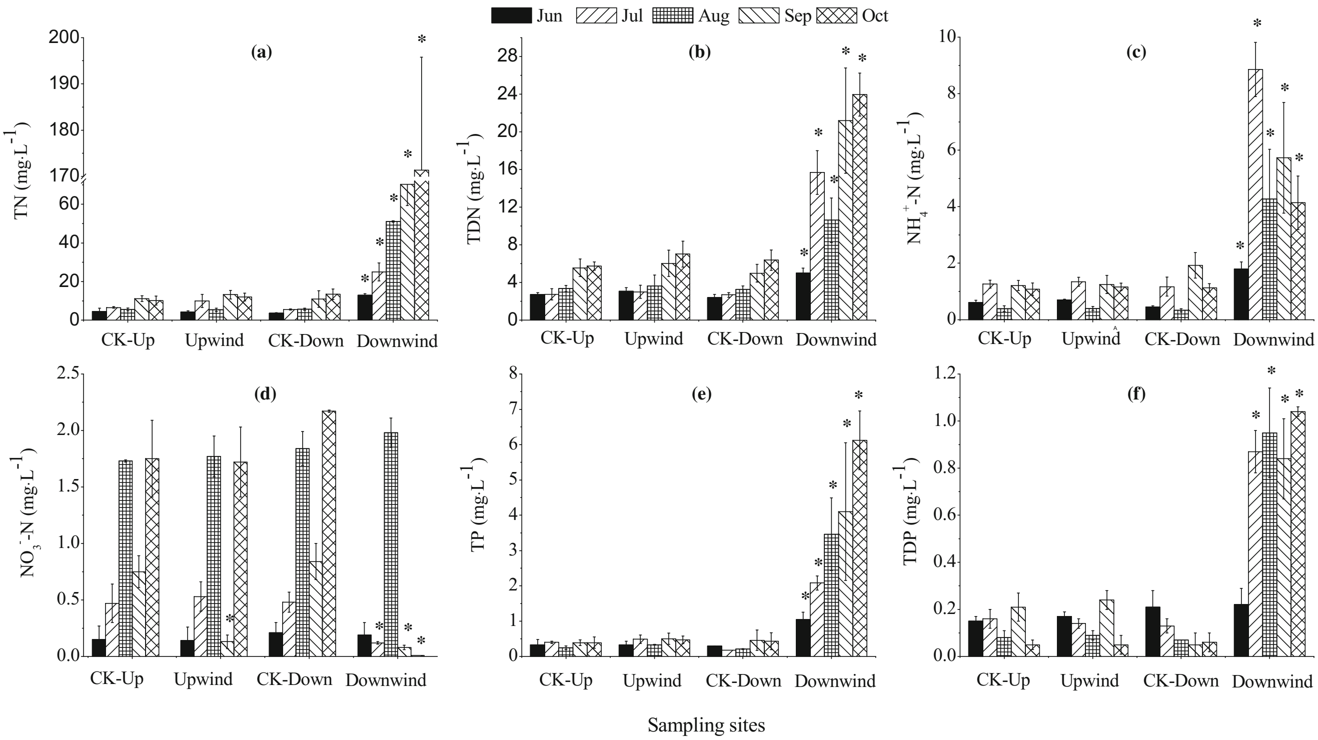


Fig. 3 Changes in concentrations of different forms of nitrogen (N) and phosphorus (P) ((**a**) TN; (**b**) TDN; (**c**) NH4+-N; (**d**) NO3–N; (**e**) TP; (**f**) TDP) among different water samples

observed. For samples collected from August and October, TP contents of Downwind were 2.65- and 3.46-fold compared with those of samples taken from Upwind (Fig. 6).

Discussion

Effects of the ecological engineering

Based on meteorological and hydrographical conditions, a bloom barrier and bloom trap as well as a wind dissipation device with fenced cultivation of *E. crassipes* (1.33 km^2) were constructed in the north in Waihai of Lake Dianchi. A large number of cyanobacteria accumulated around the root mats of water hyacinth (Fig. S2d), especially for these cyanobacteria growing at the downwind sites (Fig. 4b). *Microcystis* was the dominant species attached on the root of water hyacinth (Fig. 4c). It has been reported that the nylon-barrier enclosure played a role as *Microcystis* bloom trap (Li et al. 2012). The results from this study indicated that water hyacinth plays an outstanding role in cyanobacterial interception and plays roles as a barrier and trapper for cyanobacteria. The ecological engineering project with large-scale confined growth of water hyacinth resulted in changes in horizontal spatial distribution of cyanobacteria as well as changes of nutrition (especially TN and TP) in lake, both of which depended on the wind and wind-generated surface water current of Waihai Lake. The accumulated cyanobacteria would be efficiently transferred to the AWSS located in the northwest corner of the project (Fig. 1) so as to achieve the efficient bloom removal from the lake together with its high contents of nutrition, in particular during the harvesting season of water hyacinth.

Water quality

It has been widely reported that DO concentration could be decreased by *E. crassipes* (Villamagna and Murphy 2010). In this study, the survey results carried out in July and October in the Downwind sites suggested that *E. crassipes* might decrease DO concentration. The dense root system as well as large leaves of *E. crassipes* were able to cover the sunlight so as to prevent the transfer of oxygen from air to surface of water and block light necessary for photosynthesis by algae. In addition, large number of cyanobacteria in Downwind sites (4.95×10^{10} cells L^{-1} in October) floating on water surface forming an “algal scum” (Li et al. 2007a) which was unfavorable for oxygen release to water from algae. However, the phenomenon DO decreasing was not observed in the Upwind sites, where a certain amount of cyanobacteria (from 0.06×10^{10} to 0.25×10^{10} cells L^{-1}) were grown. The reasons may be that an appropriate amount of cyanobacteria in Upwind could release a large amount of oxygen through photosynthesis, which might meet the demand for oxygen of water hyacinth.

The randomly selected sites with *E. crassipes* in Lake Chivero, a highly eutrophic man-made reservoir, had lower pH than did sampling sites in the unvegetated area

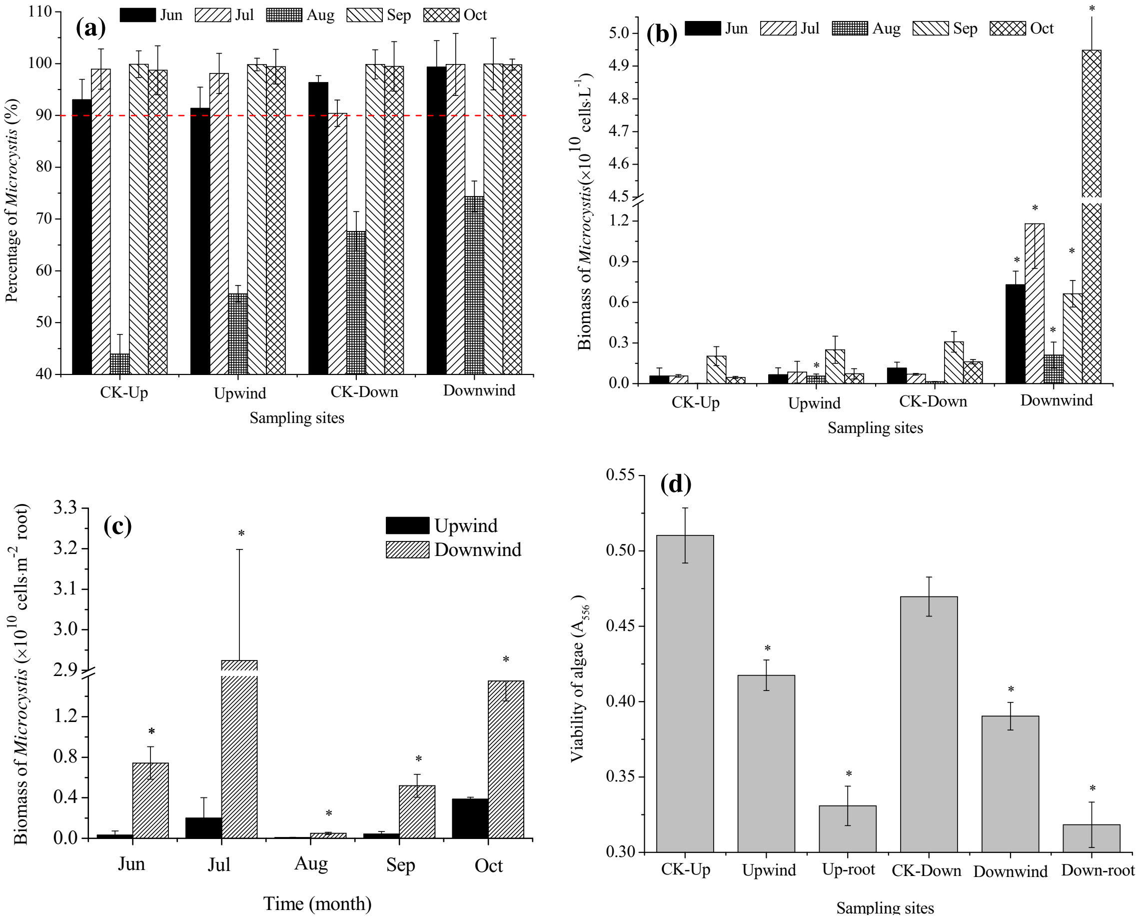
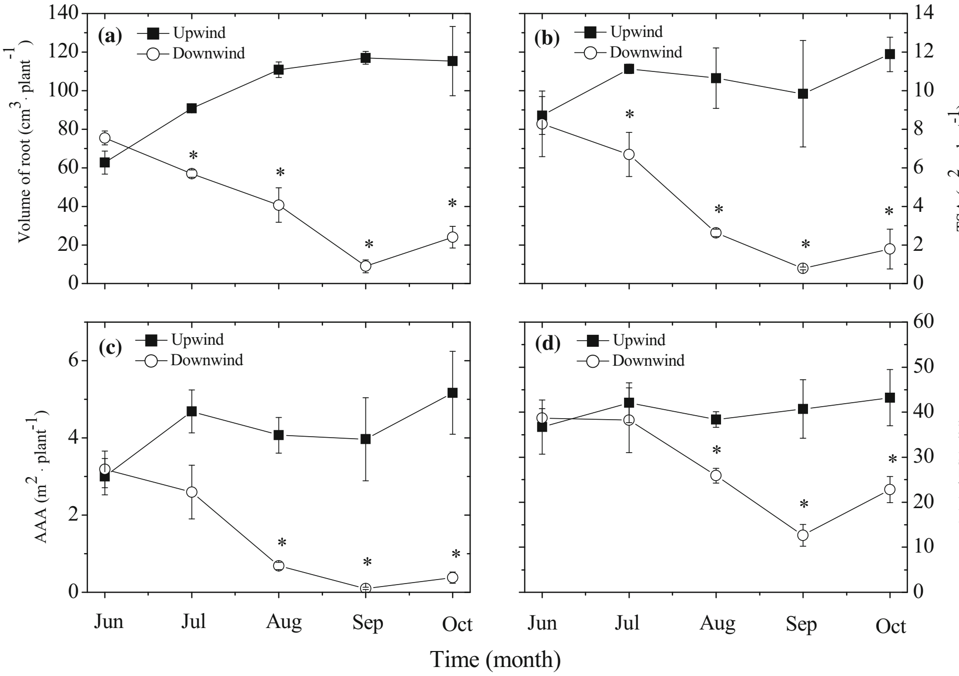


Fig. 4 Changes of algae in water and attached on roots. **a** Percentage of *Microcystis* abundance. **b** Changes of *Microcystis* biomass in water. **c** Comparison of biomass of *Microcystis* attached on root mats. **d** Viability of algae in water and attached on roots in September. *Up-root* algae attached on roots of water hyacinth growing at Upwind sites. *Down-root* algae attached on roots of water hyacinth growing at Downwind sites

Fig. 5 The comparison of volume (**a**), TSA (total root surface area, **b**), AAA (active absorption area, **c**), and AAA/TSA ratio (**d**) of roots in different investigated plots



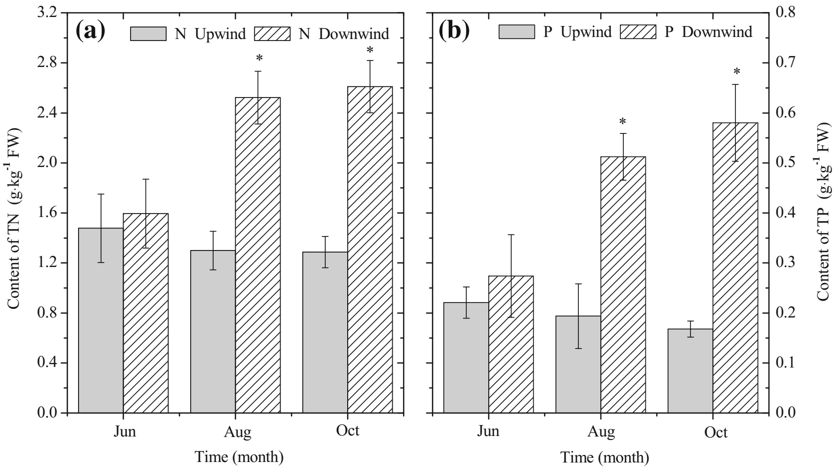


Fig. 6 The comparison of total nitrogen (TN, **a**) and total phosphorus (TP, **b**) contents of *E. crassipes* cultivated in different regions

(Rommens et al. 2003). However, our present study indicated no changes of pH in regions where water hyacinth was planted. These differences may be resulted from the fact that (1) water can be better exchanged between vegetated and unvegetated regions as small area of water hyacinth planted relative to the whole lake of Waihai and (2) CO_2 concentration in waters may be increased due to macrophyte root decomposition (Wang et al. 2012a), while it may be assimilated as photosynthesis of large amount of cyanobacteria surrounding the roots in this study.

Increase of different forms of N (except NO_3^--N), P, and COD_{Mn} concentrations along with low SD and low DO concentration in July and October in Downwind (Fig. 3) may suggest an accumulation of a large number of cyanobacteria in the regions of *E. crassipes* fenced cultivation, which played the roles as algae barrier and algae trap. The results were consistent with Kim and Kim (2000) that algae could be trapped in the root mats of the water hyacinths. It has been widely reported that low DO concentrations may promote the release of N and P from sediments (Jiang et al. 2006). Low levels of NO_3^--N in Downwind with "Algal scum" may result from the denitrification which was enhanced under anaerobic conditions.

It is worth mentioning that the dramatic changes in water quality in August (especially for sites of CK-Up and Upwind) were mainly due to heavy rains for about 20 successive days.

Water hyacinth

Roots as an integral part of plant play an important role in taking up nutrients (Yang et al. 2012), and their morphology and physiology are closely associated with regulating the growth and development of aboveground plants (Waines and Ehdaie 2007). Aquatic macrophytes can modify their root morphology in order to keep growing in polluted water bodies (Hadad et al. 2011), and the ability of absorbing contaminants from water depend on their morphological adaptive capacity. The parameters, such as volume, TSA (total root surface area), AAA (active absorption area), and AAA/TSA of roots were are considered to be crucial in root function (Yang et al. 2008). The present study provides clear experimental evidence which states that all the four parameters in Downwind sites were significantly lower than those values obtained in Upwind sites. These phenomena may be due to the following two reasons. Firstly, shading by the thick algal scum as well as the dense large leaves resulted in anoxic water. Secondly, a large number of *Microcystis* accumulated and attached to the roots, which may produce and release a great amount of microcystin especially in hypoxic and light-limited environment. Both of them may cause health hazards to the roots, leading to root decay and increasing root litter, and then result in the induction of parameter decrease as expressed previously. Changes in biomass of *Microcystis* attached on root mats were consistent with the predictions that the amount of *Microcystis* on roots may increase with the increase in their biomass in water column.

By contrast, even the volume, TSA, AAA, and AAA/TSA of roots reduced obviously; an exciting discovery of this research was that water hyacinth cultivated in Downwind water with higher nutrition (TN, TP) concentrations and large number of cyanobacteria than those of Upwind sites has a higher ability of nutrient accumulation such as TN and TP, and shown as a dramatic increase of TN and TP contents in the plants. The potential application of water hyacinth for nutrient removal from water was wildly reported (Jayaweera and Kasturiarachchi 2004; Wang et al. 2012a). There were few successful examples on nutrient accumulation under different nutrient levels and different biomass of toxic cyanobacteria in the large water body, though laboratory experiments have been carried out and suggested that TN and TP removal rates were increased with the increase of N and P concentrations in cultivated water (Zhang et al. 2009). On the one hand, water hyacinth growth was directly correlated with N and

P concentrations in water (Coetzee and Hill 2012); on the other hand, water hyacinth acted as "nutrition storehouse" based on their high nutrient absorption efficiency and also acted as an efficient "nutrition pump" due to their function on blocking cyanobacterial bloom which was the main nutrient carrier in Lake Dianchi and moved with wind-generated water current. Moreover, the water hyacinth contains high contents of nutrient (N and P) which would be associated with high utilization value when they were harvested in autumn and processed to produce biogas and biofertilizer (data not shown).

The results of previous studies suggested that *E. crassipes* could be a potential algaecide for controlling harmful algal blooms. The antialgal activity of the crude extract harvested from *E. crassipes* and its fractions were manifested against green microalgae and cyanobacteria (Shanab et al. 2010). Moreover, even the decaying water hyacinth litters could release some toxins which cause an acute toxicity to *Scenedesmus obliquus* (Sharma et al. 1996). A similar phenomenon was observed in this study which states that the viabilities of algae in regions with water hyacinth were significantly reduced, particularly for algae attached on root mats. In contrast, except for the allelopathic effects on algae, shading habitats caused by the large and dense leaves of water hyacinth as well as by algal scum would be detrimental to algae, reduced their vitalities, and then severely restricted algal growth. Moreover, it has been reported that there were no significant adverse effects on aquatic organisms such as macrozoobenthos and zooplanktons (cladocerans and copepods) which could have been used for ecological engineering with water hyacinth in Waihai of Lake Dianchi (Wang et al. 2012a).

Conclusions

In summary, outstanding roles of the large-scale fenced water hyacinth were confirmed, for instance, its roles as bloom barrier and bloom trap, its effect on cyanobacterial viability reduction, and its high N and P bio-accumulating ability even in waters with great amount of toxic cyanobacteria. Results presented in the present study confirmed the great potential to use water hyacinth for cyanobacterial bloom control and nutrient removal in Lake Dianchi. However, some areas still need to be further studied such as the mechanisms on high efficiency of nutrient absorption and bioaccumulation under extremely unfavorable conditions and that differential allelopathic effects of water hyacinth growing in environments contain different amounts of cyanobacteria.

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