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Improvement of water quality by sediment capping and re-vegetation with *Vallisneria natans* L.: A short-term investigation using an *in situ* enclosure experiment in Lake Erhai, China

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A B S T R A C T

This study evaluated the effects of sediment capping with local unpolluted soil and re-vegetation with *Vallisneria natans* on the water quality in a two-month *in situ* experiment in a mesotrophic lake. Water quality was improved substantially by sediment capping whether alone or along with re-vegetating using *V. natans*, although varied greatly with time. Sediment capping was an effective technique to reduce nitrogen (N) and phosphorus (P) release from fertile sediment, which thus inhibited phytoplankton growth in the water column. Re-vegetation using *V. natans* helped to improve water quality slightly more. Sediment capping alone or along with re-vegetating also changed interactions of the water quality parameters substantially. Compared to the control, sediment capping alone enforced the relationships between *Chl-a* and both SD and *K*, but along with re-vegetation weakened the relationships. In addition, sediment capping alone enforced the relationship between *Chl-a* and $N\text{-}NH_4$, but with or without along with the re-vegetation the relationships between *Chl-a* and both TN and $N\text{-}NO_3$ decreased.

1. Introduction

Sediment can be a sink or source for nutrients in the water column, depending on sediment fertility and other characteristics (Søndergaard et al., 2003, 2013). Release of nitrogen (N) and phosphorus (P) from sediments into the water column plays a critical role in the nutrient dynamics of shallow lakes (Beutel, 2006; Granéli, 1999; Scharf, 1999). Overloading of nutrients into lakes leads to deterioration of the ecosystem and excessive accumulation of N and P in the sediment. Excess nutrients in the sediment, in turn release into the water column and support the growth of phytoplankton, which then impedes the recovery of submerged vegetation and delays water quality improvement for decades, even when external nutrient loading has stopped (Søndergaard et al., 2003, 2013). Therefore, reducing nutrient release from sediments and re-vegetation of submerged macrophytes are proposed as a management technique for shallow eutrophic lakes (Scheffer et al., 1993; Smith and Schindler, 2009).

Many approaches including hydraulic flushing (Turner et al., 1983; Beutel, 2006), chemical injection (Wauer et al., 2005), precipitation of phosphorus by metal salts (Reitzel et al., 2006), sediment dredging (Zhong et al., 2008) and sediment capping (Gibbs and Özkundakci, 2011; Lin et al., 2011) have been employed to control N and P release from sediments in specific lakes worldwide. Among these approaches, sediment capping was considered as an effective technique that used Phoslock^{TM} (Robb et al., 2003), iron-, aluminum- and calcium-based chemicals (Cooke et al., 1993; Wauer et al., 2005) to create an inactive barrier between the sediment and the overlying water. Sediment capping not only blocks nutrient flux but also reduces resuspension of soft sediment and alters the physico-chemical properties of sediment–water interface, thus retraining nutrients in the sediment (Kim et al., 2007; Simpson et al., 2002).

However, a variety of negative effects of chemical sediment capping have been observed, such as an increase in pH value, a reduction in oxygen, and toxic effects to some aquatic

Abbreviations: $N\text{-}NO_3$, nitrate nitrogen; $N\text{-}NH_4$, ammonium nitrogen; TN, total nitrogen; DIN, total dissolved nitrogen; TP, total phosphorus; SRP, soluble reactive phosphorus; *Chl-a*, chlorophyll a; SD, Secchi-depth; *K*, light attenuation coefficient; *T*, temperature; DO, oxygen concentration; PAR, underwater photosynthetic active radiation.

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animals (Vopel et al., 2008). In pristine areas, soil particles erode from unvegetated land and are transported to lakes by rain and floods. They bury organic matter, reverse anoxic condition and retain nutrients in the sediment, an important mechanism for maintaining water quality in natural water systems. Therefore, local unpolluted soil, which is more economically and ecologically friendly, may be a potential alternative to chemicals for sediment capping (Pan et al., 2011).

Submerged macrophytes play a key role in maintaining a clear water state of eutrophic shallow lakes. They improve the water quality by ways of absorbing nutrients, stabilizing sediment, sheltering algae-filtering zooplanktons and competing with phytoplankton for light and nutrients (Scheffer et al., 1993; Qiu et al., 2001). Rooted submerged macrophytes absorb nutrients by both shoots and roots, but the relative importance of sediment *versus* overlying water as N and P sources for the plants varies among species and depends on nutrients concentrations in the water and sediment (Madsen and Cedergreen, 2002; Xie et al., 2005; Cao et al., 2011). The submerged macrophyte *Vallisneria natans* is a perennial species with a large amount of roots, that prefers mesotrophic to eutrophic water. It can absorb significant amounts of nutrients from the sediment by roots, and thus has potential for use in re-vegetation efforts in degraded lakes.

In this study, we conducted an *in situ* enclosure experiment in a littoral zone with fertile sediments, using local unpolluted soil as a sediment cap, with or without re-vegetation using of *V. natans* in order to control nutrient release from sediments and thus improve the water quality. Specifically, two hypotheses were tested: (1) sediment capping can help to improve the water quality by the inhibition of N and P release; (2) re-vegetation of *V. natans* could improve the water quality further due to its water cleaning effects.

2. Materials and methods

2.1. Experimental site

The experiment was carried out in Haichao Bay in the northern part of Lake Erhai (25°52′ N, 100°06′ E) in the subtropic Yunnan Plateau, China (Fig. 1). The lake has a mesotrophic status, a moderate water depth (max. 20.5 m, mean. 10.5 m) and a total area of 249.8 km^2. Submerged vegetation once covered about 40% of the water surface in 1980s and sharply declined to less than 10% of the water surface in 2002–2003, causing the water clarity to become turbid (Fu et al., 2013). Lake Erhai has been fertilized by agricultural runoff and rural sewage in the past years, but the external nutrient input has not continued to increase due to changes in agricultural crops that consume less fertilizer. A National High Technology Research and Development Program of China has been implemented recently in Lake Erhai, which aims to reduce external nutrient loading as well as to improve the water quality by ecosystem management. The experimental area, Haichao Bay, had thick soft fertile sediment, which has a high potential to release nutrients into the water column by wind-induced sediment resuspension. Total nitrogen (TN) and phosphorus (TP) were 2354–6174 mg kg^{-1} and 418–1108 mg kg^{-1}, respectively, in the surface sediments (about 20 cm thick). Fe/Al-P was the main form of TP and inorganic-N was the main form of TN, consisting to 43% of TN (Zhao et al., 2013a, 2013b; Ni and Wang, 2015).

2.2. Experimental design

Twelve enclosures (3 m in diameter, 4 m in height) were constructed of water proof polyvinyl chloride (PVC) textile fastened to steel tubes, creating an enclosure volume of ~17.7 m^3 and were located 100 m offshore where water depth was ~2.5 m during the experimental period (Aug. 20–Oct. 22, 2013). The lower and upper parts of the enclosures were directly open to sediment and air, respectively, for free exchange of nutrients and air. Lower edges of the surrounding PVC textile were tied with cobblestone-filled net and buried 30 cm beneath the sediment surface, so as to isolate water inside the enclosures from their surrounding water (Fig. 1). Before the beginning of treatments, the PVC textile was dropped down to 50 cm beneath the water surface for free exchange between the internal and external water of the enclosures for 5 days, and all submerged macrophytes and fishes were removed from the enclosures.

There were three treatments (control, sediment capping [Treatment 1], sediment capping + re-vegetation with *V. natans* [Treatment 2]). At the beginning of the experimental treatments, the PVC textile of each enclosure was pulled up to 100 cm above water surface. For the sediment capping, local unpolluted soil was collected from the subsurface layer (30 cm beneath earth surface) of a red soil type found on a pristine hillside near Lake Erhai. The chemical composition of red soil consists of, mass %, Al_2O_3 = 10–13%, Fe_2O_3 = 6–8%, N = 0.05–0.07%, and P = 0.015–0.019% (Zhu et al., 2007). The soil was ground into small granules (diameter < 5 mm), air-dried for 2 weeks, and filled to cover the sediments to a ~5 cm thickness. For the re-vegetation treatment, seedlings (~40 cm in height) were collected from Lake Erhai and transplanted uniformly to sediments at a density of 600 seedlings per enclosure prior to the capping procedure.

2.3. Measurements of physico-chemical parameters of water in the enclosures

Measurements of physico-chemical parameters of water in the enclosures were done on Aug. 20, 2013, one day before the beginning of the treatments, not taken due to sedimentation of the capping soil for 2 weeks, on Sept. 3 and then at one-week intervals until Oct. 22, 2013. Water samples were collected by a Patalas-Schindler sampler; each sample was a mixture of subsamples collected from three layers (surface, middle and bottom). All water samples were stored on ice immediately and transported to the laboratory for analysis of *Chl-a*, TN, total dissolved nitrogen (DIN[1]), nitrate nitrogen (N-NO_3), ammonium nitrogen (N-NH_4), TP and soluble reactive phosphorus (SRP) according to methods described by Eaton et al. (1995). For the DIN measurement, water was filtered through a 0.45 μm Whatman GF/C glass fiber filter and analyzed using the same method for TN.

Secchi-depth (SD), temperature (T), pH, dissolved oxygen concentration (DO) and underwater photosynthetic active radiation (PAR) were measured *in situ* in water in the enclosures. SD was measured by a 30-cm diameter Secchi-disk. T, DO and pH were measured by a multifunctional YSI meter (Yellow Springs Instruments, Ohio, US). PAR was measured at water depths of 0, 0.5, 1.0, 1.5, and 2.0 m using an underwater radiation sensor (UWQ-8342) connected to a data logger (Li-1400; Li-Cor Company, Lincoln, NE, U.S.A). Light extinction coefficient of the water column (K) was calculated based on the equation: $K = -\ln (I_d/I_s)$, where I_d is PAR at water depth d and I_s is PAR at the water surface (Duarte et al., 1986).

2.4. Statistical analysis

Mean values and standard errors of water quality parameters were calculated from replicates within each treatment on one sampling time to understand differences between treatments.

[1] For DIN measurement, water was filtered through a 0.45 μm Whatman GF/C glass fiber filter; the filtered water was retained for total dissolved nitrogen analysis by the same method of TN measurement.