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Effects of harvest management of *Trapa bispinosa* on an aquatic macrophyte community and water quality in a eutrophic lake

Weiwei Xu[a,b], Weiping Hu[a,*], Jiancai Deng[a], Jinge Zhu[a], Qinqin Li[a,b]

[a] *State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, China*

[b] *Graduate School of the Chinese Academy of Sciences, Beijing 100039, China*

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ABSTRACT

We examined how the harvest intensity of *Trapa bispinosa* affects the aquatic macrophyte community and water quality in a eutrophic lake using an *in situ* experimental system in the aquatic vegetation restoration zone 200 m from the west coast of Dongtaihu Bay. The experimental system was composed of 15 subzones of 10 m × 10 m that were subjected to nearly identical environmental conditions and were separated by bamboo and net. All subzones were evenly divided into five sets, numbered COV100, COV75, COV50, COV25 and COV0. *T. bispinosa* in set COV100 was not harvested, and was harvested three times by hand and rake in COV75, COV50, COV25 and COV0, by leaving 75%, 50%, 25% and 0% floating-leaved plant cover on the water surface. The harvests took place on 13 June, 3 July (at 20 days), and 6 August (at 54 days). Even the relatively heavy COV25 harvesting allowed sufficient regrowth and recovery potential of *T. bispinosa.* The increase in number of rosettes is the dominant response of *T. bispinosa* as the harvesting intensity increases. Harvesting can postpone the decline phase of *T. bispinosa* and extend its life cycle. Every *T. bispinosa* harvest had a positive impact on *Myriophyllum spicatum*, especially the COV50, COV25 and COV0 harvests that increased *M. spicatum* biomass, which played an important role in improving the water transparency. However, TP was higher when all *T. bispinosa* was harvested in the open experimental system. COV25 harvesting is recommended as the optimal strategy of repeated harvest to both control eutrophication and restore *M. spicatum* when coverage of *T. bispinosa* nears 100% in the macrophyte communities of eutrophic lakes.

1. Introduction

Many shallow lakes have become eutrophic as a result of anthropogenic influences. Eutrophication can decrease water transparency and subsequently reduce the abundance of submerged macrophytes (Hu et al., 2008; Reisinger et al., 2008; Scheren et al., 2000). At the same time, residential development on the lake shore can alter lake ecosystems because of tight linkages between the riparian and littoral zones (Schindler and Scheuerell, 2002; Steffenhagen et al., 2011). To cope with the continued decline in the water quality of lakes, many researchers have been focusing on the ecological restoration of the lakes that serve as sources of drinking water (Asgher and Bhatti, 2012; Hu et al., 2010b; Rybicki and Landwehr, 2007; Ye et al., 2009).

In shallow lakes, aquatic plants are important to primary production and environmental protection. Recovering lacustrine ecosystems, especially the submersed macrophytes, is extremely important because macrophytes have multiple ecological functions such as improving the self-purification capacity of a lake ecosystem (Hu et al., 2010a; Knight et al., 2003; Porrello et al., 2003; Soana et al., 2012; Tanner and Headley, 2011), stabilising sediments, preventing sediments from re-suspending and improving the general environmental conditions (Chen et al., 2012; Hu et al., 2010a; Mitsch et al., 2005). Macrophytes are usually considered in framing management measures to improve the water quality of aquatic ecosystems. Some restoration programmes focus not only on reducing of external nutrient loads but also on additional measures concerning macrophytes, such as biomanipulation to reinstate macrophytes and clear water conditions (Dai et al., 2012; Jeppesen et al., 1997; van Donk and Gulati, 1995; Zhu et al., 2012). Promoting native macrophytes is an important step in the

* Corresponding author. Current address: Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, 73 East Beijing Road, Nanjing 210008, Jiangsu, China. Tel.: +86 25 86882180; fax: +86 25 55714759.
E-mail addresses: 409000498@qq.com (W. Xu), wphu@niglas.ac.cn (W. Hu).

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ecological remediation of shallow eutrophic lakes (van Nes et al., 2002). In particular, the restoration of submerged macrophytes has been proposed as an important ecological measure for improving the water quality in shallow eutrophic lakes.

However, in some cases macrophytes can cause silting by adding large amount of plant material to the lake bottom and release pollutants to the lake water when they die and decay, thus limiting the discharge capacity of downstream lowlands (Vereecken et al., 2006). An engineering approach has become a common method for the restoration of shallow eutrophic lakes where aquatic plant communities are important components. Harvesting can help to alleviate eutrophication because nutrients contained in the plant tissues are removed from the ecosystem (Evans and Wilkie, 2010; Vymazal et al., 2010). However, the influence of harvest on the recovery of a lake from eutrophication should be carefully considered because of the strong interactions between macrophytes and their environment (Galanti et al., 1990). Although the principle of selective removal of components of the community is very important (Johnston et al., 1983), little attention has been paid to differentiate between species in management regimes. Usually, such harvesting methods simply remove the maximum possible biomass on a regular basis, regardless of species (Schwarz and Snelder, 1999), but increased harvest in a vegetated lake may result in the collapse of the vegetation biomass, and settle to a stable state with zero biomass. Even "careful" harvesting protocols may cause complete loss of vegetation in eutrophic lakes. Johnston et al. (1983) showed that even a management strategy aimed at removing moderate plant biomass might not be feasible for ecological reasons. If the ecosystem has alternative stable states, harvesting becomes risky because the vegetation may collapse entirely below a certain level of biomass, which is unknown in practice (van Nes et al., 2002). Such a decrease in macrophyte coverage as a consequence of unreasonable harvesting would lead to fewer sites for spawning and young fish and ultimately a reduction in overall ecosystem productivity (Carpenter and Lodge, 1986). The critical biomass at which macrophytes become beneficial for conservation will vary considerably for different lakes and depend on the growth forms of the predominant plant species (van Nes et al., 2002). However, integrated management programmes are rarely formulated because there is no mechanism to evaluate the relative benefits and drawbacks to the plants in relation to their perceived values (Johnstone, 1986).

As a general rule, the eutrophication of shallow lakes often leads to a shift in the macrophyte community from dominance of submerged plants to dominance of floating-leaved plants (Egertson et al., 2004). The mechanism behind the shift is the formation of a dense canopy that has key role in interspecific competition among several morphologically similar macrophytes (Hofstra et al., 1999). Such a shift occurred in the littoral zone of Lago di Candia, which is occupied by a homogeneous community of the floating-leaved water chestnut (*Trapa natans* L.). Many other lakes have also suffered from increased biomass of floating-leaved aquatic macrophytes and massive fish mortality (Glibert et al., 2002; Li et al., 2009). Hence, managing aquatic macrophytes in eutrophic lakes is important both as a technique and as a research topic.

Trapa bispinosa is one common floating-leaved macrophyte occupying transitional areas between the shore and the open water (Wu et al., 2007). In the spring, the plants emerge as rosettes from seeds that may remain viable in shallow water for up to 12 years and cover the water surface with dense foliage, often becoming the dominant species (Kunii, 1988). They often develop into monospecific stands of plants that are rooted in the sediment with petioles holding leaves that float on the surface. More than 40% of the total plant biomass may be concentrated in the top 30 cm during the growing season from late May until September, and few submerged macrophytes can grow at the edges or under the *Trapa* leaf canopy (Galanti et al., 1990).

The objectives of this study are to assess the effects of harvesting on macrophyte growth and the water quality in a eutrophic lake. Specifically, our goals are (1) to ensure sufficient regrowth and recovery of the macrophytes to maintain an optimal vegetative coverage, (2) to examine the role of submerged macrophytes on improving water quality under the repeated harvest of floating-leaved macrophytes, and (3) to offer guidelines for the management of aquatic plant communities in restored eutrophic lakes.

2. Materials and methods

2.1. In situ field experiment system and design

Dongtaihu Bay, which is located at the southeast part of Lake Taihu, is a macrophyte-dominated zone with a surface area of 131 km^2 and a mean water depth of 1.2 m. It is a primary supply of water to Shanghai, Suzhou and Zhejiang Provinces, but the water quality has deteriorated over the past three decades (Qin et al., 2007). The unwanted growth of some aquatic vegetation has become a considerable problem because of the excess detritus it produces in the bay (Hu et al., 2008; Qin et al., 2007). Therefore, we selected the bay as the experiment site (Fig. 1). An experimental system was established in the aquatic vegetation restoration zone 200 m from the west coast of the bay on June 13, 2011. Beforehand, the zone was covered by a *T. bispinosa*–*Myriophyllum spicatum* L. community with a water depth of 90 cm, and transparency of 76 cm. Fifteen subzones, each with an area of 10 m × 10 m and with similar environmental conditions such as vegetation density and 100% coverage by *T. bispinosa*, were separated by bamboo and netting (2 cm mesh size). The 15 subzones were evenly divided into five sets, numbered COV100, COV75, COV50, COV25 and COV0. *T. bispinosa* in set COV100 was not harvested, and COV75, COV50, COV25 and COV0 were harvested repeatedly to result in a remaining cover of 75%, 50%, 25% and 0% of the water surface, respectively. The harvest was carried out by hand and rake on 13 June, 3 July, and 6 August. Environmental parameters were measured before each harvest. The residual biomasses (wet wt.) of *T. bispinosa* after the first harvest in COV100, COV75, COV50, COV25 and COV0 were 1.65 ± 0.39 kg/m^2, 1.24 ± 0.29 kg/m^2, 0.83 ± 0.20 kg/m^2, 0.41 ± 0.10 kg/m^2 and 0 kg/m^2, respectively. The original, evenly distributed biomass (wet wt.) of *M. spicatum* was 0.91 ± 0.19 kg/m^2.

2.2. Environmental parameters and definitions of variables

We measured various aspects of the water quality and macrophyte community at each harvest and on September 15 in four divided subsections (5 m × 5 m) of each subzone. The *T. bispinosa* coverage was estimated before each harvest. Because *M. spicatum* grow under the *T. bispinosa* leaf canopy, it is very inaccuracy for estimating the coverage of *M. spicatum* on different harvest days. Water transparency and depth were measured by means of a Secchi disc, and 500 ml water samples were collected in plastic bottles from one of the divided subsections (5 m × 5 m), and immediately transported to a laboratory. Total phosphorus (TP) and total nitrogen (TN) were determined in the original water samples following the standard water sample analytical programmes issued by the Chinese National Environmental Monitoring Centre. Dongtaihu Bay is macrophyte-dominated area and the concentration of *Chl*.a is very low, so the *Chl*.a concentration was not taken into account in the experiment design. Wooden-frame quadrats (0.5 m × 0.5 m) were placed randomly on the water surface in the subsections