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Opinion

Submerged Macrophyte Restoration in Enclosure: A Proper Way for Ecological Remediation of Shallow Lakes?

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Abstract: Degradation of lake ecosystem is a common problem existing in many countries. Remediation of degraded lake is urgently needed in order to maintain water safety and lake ecosystem health. Restoration of submerged macrophyte is considered as an important measure of ecological remediation of shallow lakes after pollution loading get effectively controlled. Nowadays, enclosures resembling those used in aquaculture historically are widely used for submerged macrophyte restoration. Although submerged macrophyte can be successfully restored in enclosure, it's contribution to the whole lake ecological remediation is limited. Fish manipulation, which reduces fish stock and adjusts fish community structure, was found able to improve water quality and promote submerged macrophyte restoration in many lakes. However, the role of fish in ecological restoration do not receive enough attention in many ecological remediation projects. Future studies are required to better understand the role of fish in lake nutrient cycle and the influence on submerged macrophyte to help develop theory that better guide the fish manipulation for the ecological remediation in shallow lakes. In the end, we want to point out that manipulation of fish community structure following by natural restoration and/or artificial planting of submerged macrophyte could be an effective strategy for whole lake ecological remediation of shallow lakes, and suggest that fish manipulation measure should be tested in more ecological remediation projects of shallow lakes worldwide.

Keywords: lake; ecological restoration; enclosure; submerged macrophyte; biomanipulation

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1. Introduction

Enclosure aquaculture refers to a method of aquaculture that uses a fixed enclosure in large areas of lakes, reservoirs, and shallow sea. Such aquaculture method originated in Japan around the 1920s, and spread to many other countries gradually [1]. This mode was introduced into China in the 1950s, and had become the main aquaculture mode in many lakes since 1980s [2]. However, the unregulated development led to the rapid increase of the scale and density of enclosure aquaculture in inland waters, which had caused serious degradation of the water quality and adversely affected the structure and functions of the aquatic ecosystem [3,4]. Therefore, enclosure aquaculture in China was banned gradually in natural lakes since 2000s and replaced by more environmental friendly aquaculture modes [5]. However, cumulative impacts from enclosure aquaculture and other human activities on lakes are difficult to recover in a short period of time [6,7].

In the last few decades, pollution lead to increasing of lake eutrophication in China as well as in many other countries [8], which leads to loss of biodiversity and occurrence of harmful algal blooms [9]. For the protection of ecosystem health and water safety, remediation of degraded waters is on increasing demand [10]. Lake remediation usually

involves reducing of external and internal nutrient loading, oxygenation, biomanipulation, and aquatic macrophytes restoration [11]. Many efforts have been made to reduce external nutrient input, but limited improvement was observed in many lakes due to difficulty in internal loading control and homeostatic effects of the aquatic ecosystem [12].

Additionally, restoration of submerged macrophytes is usually required for shallow lakes to maintain a long-term clear water state [13]. Submerged macrophytes are key components of the lake ecosystem and provide important ecosystem services [14]. However, loss of macrophyte is becoming a serious issue in many lakes due to eutrophication and other human interference worldwide [15,16]. As a result, many shallow lakes turn from submerged macrophyte-dominated clear state to algae-dominated turbid state [17]. Restoration of submerged macrophyte is considered as an effective way of improving water quality and control harmful algal bloom [18]. However, how to restore submerged macrophyte successfully and maintain stable communities is still challenging in practice, especially in large lakes. Enclosure is increasingly used for submerged macrophyte restoration in lake remediation, but the effectiveness is on debate. In the following we will discuss the advantages and disadvantages of enclosure submerged macrophyte restoration and propose suggestions on measures of the whole lake remediation.

2. Enclosure for Submerged Macrophyte Restoration

Restoration of submerged macrophyte usually involves increasing water clarity, reducing nutrient levels, fish stock reduction, water level regulation, and natural or artificial development of macrophyte [19,20]. Light is vitally important for submerged macrophytes restoration, macrophytes usually fail to survive or reestablish at water depths where light is below ~1% of the surface value [21]. Additionally, grazing by herbivorous fishes, snails, and waterfowl also limit the growth of submerged macrophyte [22]. Poor light conditions and grazing pressure from herbivores are major factors that restrict submerged macrophyte development in shallow lakes.

To overcome those issues, enclosures build with pile-net and confining cloth are often constructed to help the restoration of submerged macrophyte in large lakes (Figure 1), which is similar to those used in aquaculture [23–25]. Enclosure provides several benefits for submerged macrophyte restoration such as reducing the disturbance of wind and waves, preventing the interference from lake area outside, and facilitating the implementation of other measures. Water clarity within the enclosure can be improved with or without using flocculants. Fish reduction can be performed within enclosure to reduce fish disturbance and grazing on plants. After improving water clarity and fish stock reduction, submerged macrophyte restoration can be performed subsequently [26].

Submerged macrophyte restoration can be achieved by natural restoration and artificial planting depending on the existence of seed bank in lake sediment. Sediment containing rich viable propagules can be used for submerged macrophyte once the required propagation conditions are provided [27]. Artificial planting is usually adopted to overcome seed bank lacking and to accelerate the restoration process in lakes [19]. Artificial planting can be carried out by seeding, sinking, and cutting [28]. Local and stress-tolerant species are usually selected for restoration initially to increase the chance of successful restoration, and combined use of various plant species was also suggested [29,30].

Enclosure has been demonstrated successfully for restoring submerged macrophyte in many cases. Three perennial submerged species *Potomageton maackianus*, *Elodea nutalli* and *Myriophyllum spicatum* survived in enclosures established in different sub-lake areas of East Lake in Wuhan, China, except the one in Shuiguohu due to the development of dense filamentous algae [31]. In a large-scale in situ enclosure at Gonghu Bay of Taihu Lake, China, *Vallisneria natans*, *Potamogeton crispus*, *Myriophyllum spicatum*, and *Hydrilla verticillata* were planted and grew well, which resulted in an improvement of water quality [32]. In Baima Lake Huai'an, China, *Myriophyllum verticillatum* was restored by planting in PVC net beds fixed by bamboo stakes in a 200,000 m^2 enclosure, which improved water quality and decreased phytoplankton abundance [23].

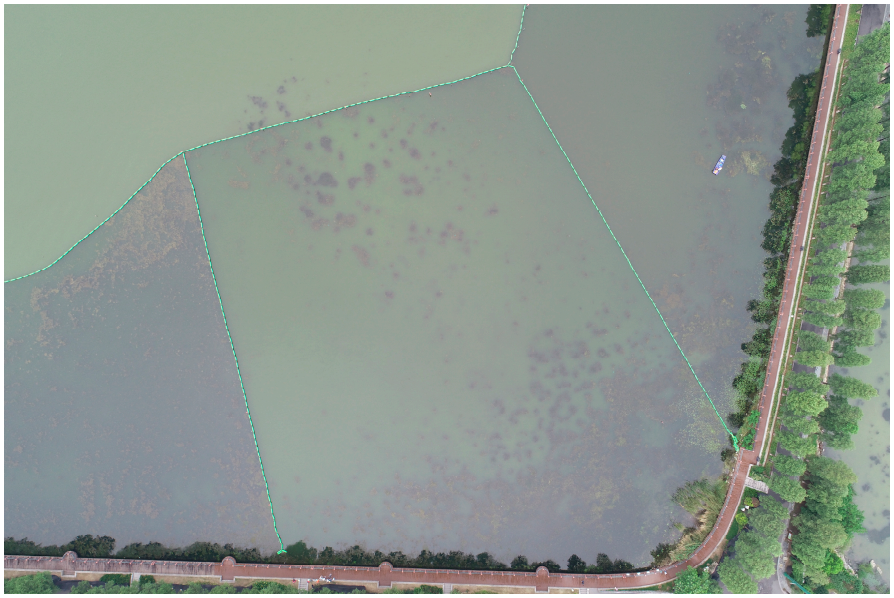

Figure 1. Enclosure used for the restoration of submerged macrophyte in East Lake, Wuhan, China.

Although restoration of submerged macrophyte has been proved to be feasible using enclosures build in lakes, it's contribution to whole lake ecological remediation is still on debate. Firstly, enclosures are separated from the main lake and thus hinder the water exchange with the main lake area. Secondly, restored submerged macrophyte in enclosures could be difficult to expand naturally to the main lake, so it is helpless for the restoration of the main lake. Thirdly, enclosures affect the natural landscape and lead to fragmentation of the lake ecosystem. Finally, submerged plants in enclosure need intensive maintenance to prevent excessive plant growth and the impact of plant withering in cold seasons. The disadvantage of enclosures is particularly prominent in large lakes, and limits their application in whole lake restoration.

3. Strategies for Whole Lake Ecological Remediation

Whole lake ecological remediation is still a challenge, especially for large lakes. In China, large lakes such as Taihu, Caohu, and Dianchi still suffer eutrophication and cyanobacterial bloom after decades of pollution control and restoration [33,34]. The main difficulties include: (1) External pollution especially non-point source pollution is difficult to control effectively; (2) The release of endogenous pollution from sediment are long lasting; (3) Physical and chemical measures are expensive and difficult to be applied on a large scale; (4) Biological measures have slow effect and are susceptible to the influence from the environment. Therefore, whole lake remediation often requires more comprehensive measures, a long restoration period, and continuous management.

Fishes are important parts of the lake ecosystem and play an important role in nutrient cycling [35]. Fish can affect the water nutrient cycle directly through ingestion, excretion, and disturbance, and indirectly by affecting the community structure of other aquatic organisms. Compared with other measures, fish manipulation is easier to implement, and thus it is usually used as an important measure for lake restoration and management [36]. Biomanipulation are proposed based on reduce planktivorous fish and thus increase large zooplankton to reduce algal biomass [37]. Control of benthivorous and herbivorous fish biomass can reduce disturbance to the sediment and grazing on submerged macrophyte [38]. Increased stocking of filter-feeding fish was found to be able to control cyanobacterial bloom in hypereutrophic lakes [39].

Many works demonstrate that manipulation of fish stocks and community could benefit whole lake ecological remediation without assistance of enclosures. In Denmark, biomanipulation through removing roach (*Rutilus rutilus*) and bream (*Abramis brama*) shifted

Lake Væng from a turbid, phytoplankton-dominated state to a clear, water macrophyte-dominated state [40]. In the USA, reducing carp density from 300 to 40 kg/ha resulted in an increase in vegetation density and an increase in springtime water clarity in Lake Susan [41]. This has been successful in other lakes too. In China, removing over 2/3 of the benthivorous and herbivorous fish biomass increased both species richness and spatial coverage of the submerged macrophytes in Lake Yanlong [42]. In China, fish removal and piscivores stocking combined with transplantation of submerged macrophytes showed significant effect on water quality improvement in West Lake in Huizhou [43].

Manipulation of fish community structure following by natural restoration and/or artificial planting of submerged macrophyte could be an effective strategy for whole lake ecological remediation. However, problems still exist for the application of fish manipulation. Firstly, fish community manipulation is laborious, and how many fish stock needs to be removed for the remediation is difficult to quantify. Secondly, many fish can breed rapidly in lakes, repeated fish removal is required to maintain the effects [44]. Thirdly, fish removal may affect the recovery of rare and protected fish. Finally, manipulation of fish community structure usually takes a longer time to achieve the expected effects. Therefore, adequate research and investigation are required before performing fish community manipulation in a lake, and monitoring and regular maintenance are required to ensure long-term stability of remediation effects. Other environmental issues such as protection of rare fish and biodiversity should also be considered in any specific fish manipulation measure.

The advantages and disadvantages are compared in Table 1. In general, enclosure is beneficial for the restoration of submerged macrophyte in a relatively short time. But the success of restoration could only be limited to the area within the enclosure and contribute little to the remediation of the whole lake, especially for large lakes. While, fish manipulation can improve the water clarity and reduce the fish disturbance on submerged macrophyte restoration and thus fish manipulation can be used for whole lake remediation. However, fish manipulation relies largely on experience and usually take longer to be effective. Fish manipulation can better improve the limiting environmental conditions for submerged macrophyte restoration in shallow lakes. While, enclosure can be effect in limited areas of the lake, and might only be suitable for the remediation of local lake area or as an early auxiliary measure for the preparation of submerged plant seedlings.

Table 1. Comparison of enclosure submerged macrophyte restoration and fish manipulation for lake remediation.

Measure	Advantages	Disadvantages
Enclosure for submerged macrophyte restoration	Facilitate submerged plant planting	Cause the fragmentation of the lake ecosystem and affect the landscape
	Protect the submerged macrophytes from the interference outside the enclosure	Restoration is limited within the enclosure and difficult to expand outside the enclosure
	Facilitate maintenance and management of the submerged macrophytes	High construction costs
	Submerged macrophytes can be restored in a short time	Removal of the enclosure is likely to result in the death of the submerged macrophytes in the enclosure
Fish manipulation for submerged macrophyte restoration	Improve the ecological and environmental quality of the whole lake rather than local areas	Take a longer time for the restoration of submerged macrophytes
	Lower cost with possible profit	Mainly relies on experiences and repeated fish removal is often required
	More conducive to the natural restoration of submerged macrophytes and reduce the effort of artificial planting	Usually need to be used in corporation with other measures
	Easy to maintain and manage	Potential influence on rare fish and biodiversity

4. Conclusions and Perspectives

Restoration of submerged macrophyte is a key measure for ecological remediation of shallow lakes. Nowadays, enclosure is widely used to assist the recovery of submerged macrophyte in many projects. Although restoration of submerged macrophyte with the enclosure prove to be successful in many cases, it's contribution to whole lake ecological remediation is limited. Manipulation of fish stocks and community can benefit water quality improvement and submerged macrophyte restoration. Manipulation of fish community structure following by natural restoration and/or artificial planting of submerged macrophyte could be an effective strategy for whole lake ecological remediation.

At present, lake ecological remediation pays more attention to the restoration of submerged macrophyte, but insufficient attention to fish manipulation. However, as an important component of lake ecosystem, impacts of fish on submerged macrophyte and water quality are non-negligible. Manipulation of fish community structure should be incorporated as an important measure together with other engineering measures for the successful ecological remediation of whole lakes.

Nevertheless, fish manipulation mainly relies on experiences, which can be difficult. It is required to investigate the current status of the fish stock and community structure in the lake thoroughly and then develop manipulation measure based on other environmental conditions. For a better remediation outcome, regular monitoring is suggested to evaluate and adjust the manipulation measure. Further research is needed to develop theory that could guide fish manipulation for lake ecological remediation. In addition, fish manipulation should consider the protection of fish biodiversity to avoid the adverse impact on rare fish. Finally, the fish manipulation measure should also be coupled with ecological aquaculture in lakes, which promotes lake ecological restoration while make use of lake ecological service at the same time.

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