The determinants and control measures of the expansion of aquatic macrophytes in wetlands

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Abstract

More attention was paid to the excessive expansion of macrophytes which would accelerate the bioaccumulation and the terrestrialization. Studies on the relationship between the occurrence of plant spread and environmental variables are important because they would provide understanding of the impacts of natural and human factors on terrestrialization in wetland ecosystem. The review summarized the determinants of the aquatic macrophytes expansion. The ecological characteristics of the plants, community features and environmental conditions were included. The reliability and validity of water quality regulations, hydrological regulation, biological control, and other common control measures were also discussed in the paper.

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1. Introduction.

Wetlands are increasingly valued for ecosystem services, such as improving water quality through nutrient removal and filtration of sediments and chemicals, controlling and storing surface water, recharging ground water, and proving wildlife habitat [1]. Wetlands also provide recreational, educational, research, economic and aesthetic functions for individuals [2, 3]. Different types of wetlands around the world were often severely altered or have completely disappeared due to the natural and anthropogenic factors [4, 5], and the growing pressure due to
intensification of human activities is a common reason for wetlands degradation worldwide [6]. Nowadays, wetlands exhibit successional processes that lead to eutrophication and then to terrestrialization. Numerous works have been carried out on the mechanism, the prevention and counter measures of eutrophication [7, 8, 9, 10]. However, the researches on the factors and control strategies for terrestrialization are still limited. There are relatively small amount of management of the crazy plant growth and decomposition of these large quantities of plant biomass, which accumulate on the lake bottom, causes accelerated ageing and succession to more terrestrial habitats of the wetland.

Obviously, the disappearance of wetlands due to terrestrialization has become one of the major problems that the wetland managers are facing and great attention have been paid to wetland restoration in environmental science and policies in recent years [11]. Terrestrialization starts from the formative stage of a lake and takes thousands of years to complete in natural successions, however, with areas of vegetations rising rapidly and the limited-speed decomposition of plant materials, multitudinous wetlands were threatened by the expansion of aquatic macrophytes which accelerate the rate of terrestrialization by bioaccumulation. Macrophyte tissue is more resistant to decomposition than phytoplankton and animal matter for their biomass is characterized by the species-specific content of structural materials, such as cellulose and lignin [12, 13]. Plant growth and structure is one of the key determinants in the evolution of wetlands. Plant residues sink to the bottom of the lake after the plant’s death, and the parts which being decomposed slowly would gradually accumulate on the lake bed [14]. The fast deposition speed makes the depth of the lake less and less, resulting in plants growing from the shore to the center of the lake. Which means the filling of lakeshore with plant remains and the slow changes of the shore, eventually will lead to the reduction of the water surface area and terrestrialization.

The rapid increase of aquatic macrophytes vegetation has been reported in several regions [15, 16]. Detailed field studies, topographic map and aerial photograph examinations in several projects recently have indicated clear changes in a number of wetland ecosystem [17]. From the spatio-temporal analysis of the stored data about Lake Stymphalia in Greece, the reed beds expanded dramatically, increasing by 89.3%, and open water areas and wet meadows decreased by 53.7 and 96.5% respectively between the year 1945 and 1996 [6]. Phragmites australis (common reed) in the Liaohe Delta, in north-east China, has expanded from 78 078 ha in 1984 to 91 262 ha in 2006, averaging over 600 ha year⁻¹ based on satellite images and historical vegetation maps [18]. North America has experienced large scale and aggressive invasion of Phragmites australis [19, 20]. The deposition depth has reached 360mm at the speed of 7-13mm/a and the area of the reed zone has grown approximately by seven times in Lake Wuliangsuhai of Inner Mongolia which will turn into a swamp in the 30 years according to the present degradation rates [21]. The study on Lake East Taihu has shown that there was remarkable accelerating effect of aquatic plants on silting-up, mean depth of sludge (hardness <5kg/cm²) was 0.96m, and the total amount (dry weight) 149 370 000t, and the organic matter made the sludge very loose (loosening-effect) which added 0.20m sludge depth [22].

In this paper we summarize literature focusing on the determinants and control measures of the aquatic macrophytes expansion which would accelerate the terrestrialization process of wetlands in the world. Though efforts to restore wetlands with anthropogenic interference are complicated, numerous control measures are available and necessary for the ecological protection to researchers. Our aim is to discuss the role of macrophytes in the accumulation of sediments and the infilling of lakes and to analysis the different methods such as water quality regulation, hydrological regulation, and biological control to suppress the rapid expansion of aquatic macrophytes.

2. Determinants

Aquatic macrophytes have significant effect on purifying water and maintaining the ecological balance of wetland ecosystem and are the key link of material cycle in wetland ecosystem. It was regarded that macrophytes are one of the most important components of lakes in wetlands [14]. Optimum growth improves the biodiversity of wetlands which would further improve the ecosystem stability [23]. Vegetations regulate the nutrients balance of water bodies by the absorption, assimilation and harvesting of nutrient elements such as Carbon, Nitrogen, Phosphorus. It is proved that macrophyte possesses the important function of environmental ecology and the elementary function of production in wetland ecosystem.

Human cultivation, random discharge of pollutants, and tremendous change of water level are all able to induce the great changes of the orientation and the rate of aquatic vegetations community succession. Serious human activities will affect macrophytes indirectly as with altered hydrological regime, changed physicochemical
characteristics of the water. The alteration of water level and nutrient concentration has been shown to have impacts on macrophytes communities, quantitatively and qualitatively. Both the fadeaway and excessive growth of Macrophyte cause the biological diversity to descend and become fragile and unstable [24]. The disappearance of aquatic plants provides favourable conditions for the growth of phytoplankton. Phytoplankton becomes the dominant specie to induce the alienation of the function and structure of the aquatic ecosystem and eventually lead to the decline of dissolved oxygen in the water, transparency of the water and the death of a large number of fish and other creatures. The expansion of macrophytes lays an important material basis to accelerate the terrestrialization process [25]. The deposition of plant residues which is called biodeposition accumulate at the bottom of lake. At the same time, the organic matter makes the sludge looser and increases the thickness of silt layer. The high silt bed creates comfortable conditions for the expansion of macrophytes and speeds up the process of terrestrialization. These changes of macrophytes lead to serious decline in species diversity and affect the animals in the wetlands. The expansion of reeds has significantly changed the habitat for fauna communities in the littoral zone of the Lake Stymfalia [6]. The loss of specie diversity results in loss of habitats for fauna species and changes in food-webs, carbon and nutrient cycles [26].

Extensive researches have carried out on the cause and characteristic of plant spread worldwide [27, 28]. The plant species that consistently showing a capacity for spread have a high reproductive capacity and a tolerance to a wide range of environmental conditions, which is the result of ecological characteristics of plants, community features and environmental conditions of aquatic habitat [29, 30].

The genotype, mechanism of seed dispersal, germination requirements, reproductive capability, competitive ability all may influence the expansion of macrophytes [31, 32]. The clonal species generally have a greater power of vitality than non-clonal species in plant communities for clonal integration allows organisms to invade physically harsh habitat and spread into conditions that are more stressful in which they are unable to establish from seed [33, 34]. Clonal integration contributed greatly to growth, photosynthetic efficiency and biomass allocation of the clonal species [35]. Another major factor is known to influence the structure of natural plant communities is inter-specific competition, and the environmental-stress model shows that the importance of negative competitive effects is higher under benign environmental conditions [36]. With the environmental conditions dramatically varying, both spatially and temporally, the characteristics in morphology and growth changed response to the availability of limiting resources such as nutrients or light [37]. In the United States, researchers use plants selected from wild populations to block Phragmites Australis' reinvansion of restored marshes [38].

Aquatic macrophytes depend on the water environment to live on and have limitations to adapt to it by studying [39]. The main distinct environmental impact factors on growth of aquatic macrophytes include water depth and waves, light intensity, sediment characteristics, morphology and distribution of nutrients, grazing ability of fish, salinity, oxygen, temperature, and so on [40], and a optimal value range of each factor existed to meet the best growing state of macrophytes which changed with the types and growth periods of the macrophytes. For example, macrophyte communities’ composition can shift from a dominance of submerged to floating leaves and to emergent vegetation as water transparency decreases. Elevated levels of nutrients could enhance the spread of some clonal species obviously [41]. The impacts of inserted algae, heavy metals and pH on the growth were less than that of the above mentioned factors [42]. Macrophyte species richness has been observed to decrease as lakes eutrophy due to light limitation to submerged vegetation [26]. Morphological plasticity in growth, such as the total biomass, root, shoot allocation, photosynthetic efficiency and coverage, responses to environmental variability. By harmonising these environmental factors, optimal or adverse conditions were created for the natural expansion of aquatic macrophytes [18].

3. Control measures

In order to reach the prevention purpose, the governance of the expansion of macrophytes should achieve the following goals according to comprehensive features of different wetlands: We should establish and reconstruct a healthy ecosystem which is conducive to sustainable development, build a reasonable food chain and maximize the rational utilization of the productivity of wetlands. A wide variety of control measures are used to slow the rapid expansion of macrophytes in wetlands and produce various degrees of effects.
3.1 Water quality regulation

Water quality is the most important control factor of the wetland [43, 44]. The deterioration of water quality has potential impacts on the stability of wetland ecosystem, especially on the dynamics of wetland communities [45]. The growth of plants, and the dominant species of plant communities and their richness are decided by the status of water resources and supplies in wetland. Water changes have significant effects on the primary productivity, biomass and its allocation, and on the species diversity of wetland plants.

The accumulation of nutrient is the main issue on the water conditions which lead to the eutrophication of lakes that has become a global environmental problem. We take into account that the exogenous and endogenous nutrients equally when seeking control of nutrient accumulation. The exogenous nutrients coming from water that affected by human activities caused eutrophication in most wetlands. In order to combat the nutrient accumulation and accelerate wetland recovery, some requests have been made. Firstly, it is important to enact the emission standards, water quality standard, and exert control over total amount of pollutions. Secondly, point and non-point pollution control can be applied to reduce the nutrients loaded to the lakes by developing the ecological agriculture, Basin-wide soil and water conservation, and making reuse of waste water. It should be noted that the exogenous nutrient is very difficult to control presently. The comprehensive and effective measures to purify the municipal and rural sewage are inadequate. Internal nutrient loading originates from a pool accumulated in the sediment at high external loading and may eventually be released to the lake water, which promote the formation of endogenous [46]. The nutrient concentration was raised by the release of ammonium and phosphorous in the overlying water [13, 47], and the reduction of oxygen consumption dissolved oxygen level in the overlying water and sediments in the biological process that occurs after death [48]. There are a wide variety of techniques have been developed and tested [49, 50]. The physical measures, such as sediment dredging by which nutrient rich sediment is removed is most adopted, diluting by adding a lot of water from the reservoirs or rivers. The chemical methods aim to influence the nutrients by either improving the sorption of the elements already present in the sediment or by adding new sorption capacity, but it can often lead to secondary pollution. Because sediment bacteria play a significant role in the uptake, storage and release of nutrient, the biological measures are used to control the excessive nutrients [51]. The cultured bacteria and virus control method is not widely used due to unsolved problems with its safety and handling. The study shows that the biomass of Carex stricta and Typha latifolia decreased obviously with the lowering of nutrient concentrations. The accumulation of nitrate nitrogen is conducive to the growth of Phalaris arundinacea, but reduces the community diversity and evenness of sedge meadow [52].

There existed other desirable measures to improve water quality and enhance the ecological restoration except nutrient control. A very promising and environmentally friendly way to do this is to use natural, nontoxic and inexpensive clays to flocculate and remove algal cells [53, 54]. Pan developed a technique using modified clays which can combine phosphorus fixation, algae flocculation and reversing of anaerobic environment in the sediment (CN200310113305.5). An invention is related to a composite material which can removal harmful algal blooms and turn them into submerged macrophytes (US 2009/0107912 A1). A deep water aeration plant was installed and a technical iron-phosphate was carried out to control algal bloom [55]. By manipulating the fish populations, the zooplankton, phytoplankton, and benthic plant communities were changed in nutrient-rich ponds [56]. These methods to improve water quality need a long period usually several years to work effectively, the manipulation is time consuming and arduous, and the cost is very high. Moreover, these techniques can’t be used in super-eutrophication water.

3.2 Hydrological regulation

Water is the key factor for the sustainability of wetlands. The changes of hydrological condition straightly influence the plant biomass, the species composition and diversity, and plant community succession. Several studies have a clear relationship between hydrological conditions and overgrowth. The wetland structure and characteristics show significant responses to these changes [57]. Water level which changes the slope of the water body is one of the most important environment gradient in wetland system, and water level fluctuation create a crucial impression on the characteristics of wetland [58, 59]. Aerial photographs for the period 1993–2005 show a transition from the floating leaf Nuplumbo lute to a mixed-emergent community, to increasing large monotypic beds of Phragmites
The anthropogenic modulation of hydrology can mediate the dominance and structure of macrophyte communities [6]. Prolonged high water kills emergent and woody vegetation and promotes plant communities dominated by floating or submerged species. Low water exposes sediment, allows recruitment from the buried seed bank, and allows plants less tolerant of standing water to become established [61]. The exposure of the shore has been regarded as one of the most important factors determining aquatic macrophyte growth [60]. A study on common reed in eutrophic wetland in western China have show that aboveground and belowwater biomass increased and the ratio of belowground to aboveground biomass decreased with water depth, water depth affected reed biomass by changing the morphology and structure of the reed community [62]. Spring wells brought large quantities of water to the Lake Stymfalia, causing an increase in local water volume and in the lake’s depth, and at the same time preventing the spread of reeds of reeds on lakeshores [6]. It was suggested that water depths can be a controlling factor on the growth and spread of *Phragmites australis*. Deep freshwater irrigation and seawater irrigation eliminated some weeds in the Liaohe Delta [18].

3.3 Biological Control

The biological control is a rapid developing measure in the range expansion and population explosion of aquatic macrophytes which is regarded as a potential promising alternative to the currently implemented conventional physical and chemical managements [63]. The goal of biological control is to reduce populations of a plant to an acceptable level but not eradicate some aquatic species in general [64].

Natural enemies which are reported in the literature to feed on several species play a significant role on biological control. Several invertebrate herbivores to its host plant may reach outbreak levels with considerable negative impacts on the performance and biomass production of this plant [65]. Various types of organisms and a large number of species are found to attack a plant species and researchers select the optimal species according to their impact on plant performance, feeding niche and distribution [66]. The lepidopterans *Rhizedra lutosa*, *Phragmataecia castaneae*, *Chilo phragmitella*, and *Schoenobius gigantella* sever and disconnect the below ground rhizomes, reduce storage reserves and recovery potential, further reduce the competitive superiority of *Phragmites australis* [64]. *Eucryptorrhynchus brandti* and *E. chinensis* are reportedly restricted to tree-of-heaven, showing promise as potential biological control agents [67]. A root-boring weevil *Hylobius transversovittatus* was favored to achieve good control of *Lythrum salicaria* [66]. A European stem-mining weevil *Mecinus janthinus* has been established in North America as a biological control agent against the invasive European weeds *Linaria vulgaris* P. Mill. and *Linaria dalmatica* (L.) P. Mill [68].

In literature, many pathogens were used as practical, safe and environmentally beneficial biological control agents for many serious weeds and invasions [69]. The use of pathogens as a bioherbicide or classical strategy has increased steadily for its significant effect on reducing density of the target species to an acceptable level and producing the long-term beneficial changes in vegetation, and the foliar pathogens are preferentially selected which obtain nutrients directly from living host tissue [70].

The complex of insects and pathogens needed to be identified thoroughly through extensive field surveys. Study of the plant’s ecological characteristics and community features will be undertaken in order to effectively manage and predict its spread. Risk assessment and long-term monitoring is necessary to evaluate the influences of biological control on the target plant and its associated plant and communities.

In addition to the strategies mentioned above, controlling and harvesting the growth of macrophytes directly are widely utilized to reduce the accumulation of organic matters especially in the wide range of lakes which are difficult to regulate water quality and hydrological conditions. Spraying the herbicides and operating the aquatic growth harvester have achieves differing levels of success in the rapid growing season. Chemicals are successfully employed in many effective maintenance management and restoration projects, sometimes with physical methods [71]. Herbicides is effective and currently available to stop the expansion of macrophytes which are more effective if applied early in the growing season, but managers note that chemicals also generate opposition that this may negatively affect adjacent non-target plant species [72]. Though it is widely accepted that herbicides have generally been most effective, large-scale and long-term herbicide application may be infeasible due to policy, political, or ecological concerns [67]. Harvesting which has been carrying out on a large-scale is the main conventional
approaches of ecological restoration project especially in the typical macrophyte-dominated lake. The planned and reasonable harvesting can effectively cut back the accumulation and release of inner nutrients loading, and it can’t affect the reproduce of macrophytes and result in the blooming of algae [21]. Hawk, U.S. Pat. No. 4696149 discloses a method for removal of aquatic weeds by first dragging the bottom of a lake with a horizontal bar to loosen the weeds from the bottom. Vaughan, U.S. Pat. No.7036295 describes an aquatic growth harvester that pulls Watermilfoil from a relatively shallow water bed and removes debris created during this process which helps to prevent regeneration. However, manual cutting is labor-intensive for resprouting and prohibitive when the plant grows on steep slopesv [73].

4. Discussion

In terms of the studies reviewed above, it is obvious that the internal determinancy and external constraints decide the growth trend of aquatic macrophytes. The prevention of the vegetation overgrowth and the eventual recovery of the wetland ecosystems are complicated and long-term, so comprehensive understanding of impact factors facilitates the choice of combating strategies. Identifying the main factors of the particular case is the key of the solution. We have to consider the ecological security, time and costs required in the practical applications. The physical methods such as sediment dredging are difficult to achieve ecological balance and temporarily ease the burden of bioaccumulation [74], water replenishment is an effective way to mediate the growth trends but consume more money especially in large waters, aeration which improves water quality of self-purification is also only suitable for small lakes for its high running cost [60]. Chemical measures, including oxidants and herbicides, can often lead secondary pollutions and do long-term harm to the ecosystem [74]. Biomanipulation are regarded as a promising, cost-effective remediation technology, but how to design a biocontrol program with minimal non-target risks and calculate the potential health risks is still challenging. It seems to be clearly, the methods have their own advantages and disadvantages as mentioned above. Meanwhile, a successful method applied in an area does not suit the whole cases for the impact of environmental variability. So combining prevention and control countermeasures are widely used and some high-tech methods employing sophisticated science are urgently needed [71]. The interdisciplinary cooperation needs to be strengthened to increase restoration legitimacy and validity.

Our aim to control the growth of aquatic macrophytes is reducing the population of a plant to an acceptable level. We should properly evaluate the expansion of macrophytes presently and predict the future development before control measures were adopted. According to historical literature, it was observed that many water bodies experienced a rapid expansion of macrophytes in recent years. The environmental changes and response were depicted in these information and we also need additional information to assess the role of human-induced disturbance. The decrease area of the open water surface, the growth rate of macrophytes, and the biomass accumulated on the lake bottom is necessary to be understood elaborated, these data were proved usefully for characterizing and calculating the dynamic ecological processes of the wetland ecosystems. As the analysis of the spread has showed much faster, some tough measures need to be undertaken urgently and long term monitoring system must be established simultaneously. In the past two decades, researchers developed many detailed ecological models to facilitate our understanding of the plant growth [75, 76]. A dynamic modeling was presented about the growth of *Phragmites australis* in the water bodies where no nutrient limitations exist [77]. The model CLOMO combined a stochastic description of clonal expansion with a ramet-based calculation of primary production and respiration [78]. These ecological models provide a way to evaluate the effects and trends of the expansion of macrophytes in wetland ecosystems. A more proper control program can be established based on the comprehensive understanding of overgrowth in a specific area.

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