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Development of an integrated stress index to determine multiple anthropogenic stresses on macrophyte biomass and richness in ponds

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ABSTRACT

Ponds significantly contribute to local and regional biodiversity by supporting wide-ranging communities of aquatic organisms. However, ponds are often disturbed by intensive anthropogenic activities because of their accessibility. Hence, methods to assess the effects of anthropogenic activities on ponds are of great importance. In this study, we developed an integrated stress index (ISI) to characterize the integrated stress from different types of anthropogenic activities on ponds and then tested the robustness of this index through sensitivity analysis. We also examined the relationships between ISI and the species richness and biomass of different macrophytes through regression analyses. Results showed that ISI significantly negatively correlates with total species richness but significantly positively correlates with total biomass. Emergent, floating-leaved, and submerged species exhibited different responses to ISI. Moreover, ISI produced more significant effects on species richness and biomass of different macrophytes than eutrophication. Therefore, eutrophication is not the only stress to be treated in the area of study. These findings provide pond restoration-useful insights into the relationships among inhibiting anthropogenic activities, water level management, harvesting, and species composition.

1. Introduction

Ponds significantly contribute to local and regional biodiversity by supporting wide-ranging communities of aquatic organisms (Gioria et al., 2010). Ponds also largely benefit human society because of their use in irrigation, drinking for cattle, water transportation, and tourist or recreational use (Søndergaard et al., 2005; Declerck et al., 2006; del Pozo et al., 2010). Therefore, ponds are intensively disturbed by different types of anthropogenic activities and face many ecological and environmental problems, such as nutrient enrichment (De Backer et al., 2012), water level drawdown (Usio et al., 2013), physical destruction (Biggs et al., 2005), and area losses (Curado et al., 2011). In particular, decreased diversity of aquatic macrophytes has been observed in ponds over the past few decades (Williams et al., 2004; Akasaka et al., 2010).

Anthropogenic activities around ponds are often represented as the proportions of different land-use types around ponds (Rolon et al., 2012; Raebel et al., 2012), as well as the properties of anthropogenic activities, such as population density, number of villages and docks, and grazing intensity (De Meester et al., 2005; del Pozo et al., 2010, 2011). These activities can greatly influence the growth, distribution, and community composition of aquatic macrophytes by altering many environmental factors (e.g., light availability, pH, and nutrient level) (Radomski and Perleberg, 2012; Karus and Feldmann, 2013). Specifically, agricultural production and residential development can cause water eutrophication, which eventually results in the loss of aquatic macrophyte species, especially submerged ones (Barker et al., 2008; Kolada, 2010; Sass et al., 2010). Excessive water extraction and desiccation related to agricultural practices also have been proved closely related to species loss (Chappuis et al., 2011). The construction of docks around ponds changes sediment quality and slope in littoral zones, ultimately inhibiting the distribution of aquatic macrophytes (Radomski and Goeman, 2001). These docks can also increase boating activity, which directly destroys macrophytes through wave erosion (Alexander et al., 2008). Forests surrounding ponds may suppress the growth of aquatic macrophytes by litter accumulation and shading effects (Declerck et al., 2006). Residential development surrounding ponds also reduce macrophyte coverage because shoreline land owners often directly remove macrophytes to create beach conditions (Jennings et al., 2003; Hicks and Frost, 2011).

Aquatic macrophytes are key components in freshwater ecosystems (Søndergaard et al., 2010). They can stabilize sediments (Madsen et al., 2001), absorb and store nutrients (Dai et al., 2012), enhance water clarity (Søndergaard et al., 2010), and support other aquatic organisms (e.g., zooplankton, fish, and invertebrates) in

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freshwater ecosystems (Jeppesen et al., 2000). Thus, declines in the species composition and abundance of aquatic macrophytes because of intensive anthropogenic activities could exert lasting, substantial, negative effects on the biodiversity, structure, and function of pond ecosystems (Heino, 2002; Ribeiro et al., 2011). Accordingly, some ecological engineering approaches aiming to restore aquatic macrophytes need to be implemented in ponds.

Ecological engineering is defined as the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both, and the most fundamental concept of ecological engineering is self-design (Mitsch, 1996a,b; Mitsch and Jørgensen, 2003; Odum and Odum, 2003). Ecological engineering is being practiced over a wide spectrum of approaches to restore wetlands with different ecological problems (Mitsch, 2012). For instance, a modest intervention (e.g., continual inflow of river water) has been proven for facilitating the introduction and optimization of species composition without planting by self-design in a created wetland ecosystem (Mitsch et al., 1998). Some ecological approaches including modified agricultural practices (e.g., reduced chemical fertilizer use) and landscape restoration (e.g., creation and restoration of riparian buffers and wetlands) were proposed to restore wetlands in river basins affected by excessive nitrate–nitrogen inputs from increased fertilizer use (Mitsch and Day, 2006; Mitsch, 2014). The restoration of approximate original hydrological conditions by breaking dikes or removing impediments to flooding have been proven successful for the restoration of a marshland dramatically disturbed by upstream dams and water control structures (Mitsch and Gosselink, 2007; Mitsch, 2014).

Similarly, different ecological engineering approaches are also required for pond restoration because they are widely distributed over a long anthropogenic stress gradient and often show diverse problems owing to anthropogenic stress (Gioria et al., 2010). Thus, an urgent demand to quantify anthropogenic stress for pond categorization and to explore changes in species composition along the stress gradient exists. However, a holistic perspective on the integrated stress of different anthropogenic activities remains lacking, and less is known about the effects of integrated anthropogenic stress on aquatic macrophytes in ponds.

Lake Baiyangdian was made up of 140 ponds before 1990s. However, the continuously decreasing water input, increased population, and rapid economic development have severely impacted this region (Zhong et al., 2005; Zhuang et al., 2011); the number of ponds is only less than 30 nowadays, accompanied by substantial species losses (Han and Cui, 2015). With the increase in awareness on ecological conservation and restoration, the local wetland management office has formulated several plans to regulate anthropogenic activities within this region, and eutrophication control is viewed as the main strategy for pond restoration. However, the integrated anthropogenic stress suffered by each pond has not yet been quantified in these plans, and effects of integrated anthropogenic stress on aquatic macrophytes in ponds have not yet been analyzed. To develop effective restoration strategies for different ponds, the integrated stress of different types of anthropogenic activities and the changes in aquatic macrophytes along a stress gradient are important to quantitatively assess.

The present study aims to (1) develop an integrated stress index (ISI) and test its robustness, (2) analyze the relationship between aquatic macrophytes and ISI, and (3) summarize some implications for pond restoration.

2. Materials and methods

2.1. Study area

Lake Baiyangdian (38°38′N, 115°54′E) is the largest macrophyte-dominated shallow lake in Baoding City, North China. Before the 1990s, the lake had an average water level of >8.5 m and comprised 140 ponds that were interconnected through water channels. Nowadays, the number of ponds is only less than 30 because of to continuously decreasing water input, as well as expansions of residential areas, docks, and cropland within this region over the past few decades. Most of these ponds are also isolated. Meanwhile, substantial species loss and large spatial variability of community structure among different ponds were also observed. In this study, we presented the results of a field survey on aquatic macrophytes in 20 ponds that were selected based on a gradient of surrounding anthropogenic stress (Fig. 1).

2.2. Data collection

2.2.1. Integrated stress

We developed an ISI to characterize the integrated stress of the following four types of anthropogenic activity around each pond: (1) residential development, (2) dock construction, (3) cropland reclamation, and (4) raised field construction. A raised field (1.0 m to 1.5 m higher than the water surface) was constructed by local farmers with pond sediment and planted with *Phragmites australis* for economic value. The ISI, which contains data on the area and property of the four types of anthropogenic activity, was calculated as follows:

$$\mathrm{ISI} = \sqrt{P_{\mathrm{rd}} + A_{\mathrm{rd}}} + \sqrt{P_{\mathrm{dc}} + A_{\mathrm{dc}}} + \sqrt{P_{\mathrm{rc}} + A_{\mathrm{rc}}} + \sqrt{P_{\mathrm{cr}} + A_{\mathrm{cr}}} \qquad (1)$$

where, A is the area of an anthropogenic activity, P is the property of an anthropogenic activity, rd means residential development, dc

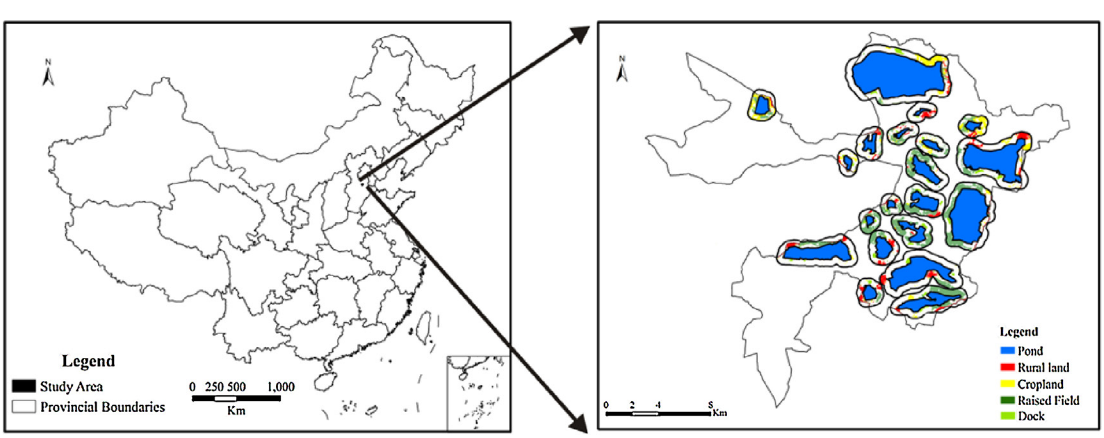

Fig. 1. Study area within Anxin County, Baoding City, China (a), and location of the sampled ponds (b).