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Habitat heterogeneity affects the efficacy of ecological restoration by freshwater releases in a recovering freshwater coastal wetland in China's Yellow River Delta

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ABSTRACT

Releasing freshwater for wetland restoration is a globally recognized way to maintain wetland biodiversity while restoring or enhancing ecosystem services. However, habitat heterogeneity may influence the efficacy of such restoration activities. In this study, we collected macrobenthos and sediment samples to document the ecological responses of three areas in China's Yellow River Delta Wetlands with different landscape heterogeneity: planted *Phragmites australis* wetland (*vegetation*), a *Suaeda heteroptera* mudflat (*mudflat*), and bare ground. Freshwater was released annually from July to August. The sediment salinity decreased similarly in all three areas after freshwater releases, despite significant differences in salinity before the freshwater releases. The pre- and post-release composition of the macrobenthos community (based on number of individuals) showed little change in the *vegetation* habitat, but the dominant *mudflat* species changed from Crustacea to Insecta; in *bare ground*, where no species were found before the releases, Insecta, Crustacea, and Polychaetes appeared during and after the releases. The macrobenthos abundance and biomass generally increased after the freshwater releases, except in the *mudflat* habitat. The *H*', *D*, and *d* biodiversity indices increased significantly in the *vegetation* habitat, but no index changed significantly in the *mudflat* habitat. The post-release *H*', *J*, and *D* indices for *bare ground* were close to those for the *vegetation* habitat, and the *d* index was close to that for *mudflat* habitat. Our results showed a generally positive effect of freshwater releases, but suggest that adaptive freshwater releases (a long-term, habitat- and species-based freshwater release plan) will be necessary to achieve sustainable wetland biodiversity and improve the efficiency of freshwater utilization.

1. Introduction

Ecological restoration is a necessary component of biodiversity conservation and sustainable development, and is widely used to reverse the environmental degradation caused by human activities (Gann and Lamb, 2006). Past ecological restoration efforts have primarily focused on restoration regimes, and mainly examined the techniques, actions, and appropriate timing (Benayas et al., 2009). However, more and more studies have suggested that accounting for habitat heterogeneity greatly increases the efficiency of restoration activities, and should be considered when planning restoration activities (Miller et al., 2010; Shea et al., 2010; Tang et al., 2013; Collins and Baxter, 2014; Leung, 2015).

The habitat heterogeneity hypothesis (MacArthur and MacArthur, 1961) suggests that spatial variation in environmental conditions provides greater niche diversity and facilitates coexistence, thereby resulting in greater species richness (Simpson, 1964; Cramer and Willig, 2005). The term *habitat* is usually defined as a dominant vegetation formation (e.g., Ricklefs and Miller, 1999; Collins and Baxter, 2014). However, the definition and meaning of habitat *heterogeneity* varies considerably. Although some approaches have been developed to quantify heterogeneity in terms of environmental conditions, including levels of salinity and inundation in tidal marshes (Tang et al., 2013), regional variations in vegetation cover (Nieto et al., 2015), information entropy (Fukuda et al., 2015), and hydromorphological indices for streams and rivers (Hugue et al., 2016), the most common descriptions of habitat heterogeneity are still qualitative (McCoy and Bell, 1991; Cottet et al., 2007; Chaparro et al., 2015; Leung, 2015; Martínez et al., 2015; Li et al., 2016c).

Tews et al. (2004) found that 85% of the 85 studies they reviewed reported a positive correlation between habitat heterogeneity and species diversity. Miller et al. (2010) quantified macroinvertebrate responses to in-stream habitat restoration by applying a

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meta-analysis, and found that increasing habitat heterogeneity significantly increased macroinvertebrate species richness. Leung (2015) confirmed the importance of habitat heterogeneity in determining the macrobenthic infaunal community. Li et al. (2015, 2016c) found that wetland restoration was successful in a vegetated wetland in China's Yellow River Delta, but not in open-water wetland; the species richness, density, and Shannon diversity and Pielou evenness indices in the former habitat were comparable to those in an intertidal mudflat, whereas these indices in the open water wetland showed much lower diversity than a nearby *mudflat* habitat. They concluded that maintaining habitat heterogeneity was an effective way to achieve wetland restoration.

Because of the expense and important of wetland restoration, wetland managers have become increasingly concerned about the efficacy of ecological restoration projects, particularly since an increasing number of restoration projects are being implemented around the world (Clewel and Aronson, 2007; Benayas et al., 2009). Releases of environmental flows (generally, freshwater releases) into degraded wetlands is a popular direct restoration activity that is frequently implemented by allocating water from other systems (e.g., reservoirs) to maintain the minimum flows required by downstream ecosystems (Richter and Thomas, 2007; Cui et al., 2009) or to simulate the natural flow regime as closely as possible (Allison and Meselhe, 2010; Kemp et al., 2014). Yang et al. (2016) performed a meta-analysis of 102 published studies from a wide variety of wetland ecosystems around the world that considered the ecological outcomes of environmental flow releases, and concluded that a long-term implementation and a high-flow regime promoted biodiversity and improved provision of ecosystem services, particularly in river wetlands. However, the effects of freshwater releases on the macrobenthos community continue to raise concerns in terms of their effectiveness (Dukowska et al., 2007; Hose et al., 2007; Rolston and Dittmann, 2009). Hernández-Arana and Ameneyro-Angeles (2011) found a significant increase in species richness at locations adjacent to an artificial channel that carried freshwater and suspended sediments into the adjacent wetland. Li et al. (2016c) found that combining freshwater releases with replanting of vegetation could improve restoration performance.

China's Yellow River Delta, which is listed in the Ramsar List (2017), is the youngest and most extensive wetland ecosystem in northern China. Since the early 21st century, the Yellow River Conservancy Commission has released freshwater from the Yellow River to help restore the degraded wetlands in the Yellow River Delta. Many researchers have surveyed the performance of these releases, and observed increases in the water-surface area (Zheng et al., 2012), increases in the number of bird species and individuals (Ge, 2012), improvements in the vegetation landscape (Shan, 2015), and decreases in the depth to the water table (Peng et al., 2015). In most cases, the freshwater is released as floodwater, and the total amount of flooding is managed with a coarse resolution. This is problematic because a high diversity of ecosystem types (e.g., vegetation-dominated, mudflat, bare ground) typically coexist in recovering wetlands, and differences in the environmental conditions (e.g., habitat heterogeneity) of the areas affected by the flooding could affect the efficacy of ecological restoration; this important topic has been rarely studied (Li et al., 2015).

In this paper, using the Yellow River Delta Wetlands as a case study, we assessed (1) the differences in the response of the macrobenthos community and related changes in the environmental characteristics of the sediments among three key habitats in the study area (vegetation-dominated, mudflat, and bare ground sites) and (2) whether differences in habitat heterogeneity affected the efficacy of ecological restoration by means of the freshwater releases. We hypothesized that the macrobenthos community and its responses to the freshwater releases would differ among the three habitat types and that differences in the habitat characteristics would be responsible for these changes. Our results will help wetland managers to assess the ecological effects of freshwater releases and improve their management of wetlands with heterogeneous habitats.

2. Methods and materials

2.1. Study area

The Yellow River Delta Wetland (37°40′N to 38°10′N, 118°41′E to 119°16′E), one of China's key national nature reserves, is located on the western coast of the Bohai Sea (Fig. 1). The Administration Bureau of the Yellow River Delta National Nature Reserve has promoted restoration of the wetlands by means of environmental flow releases combined with replanting of vegetation in a total area of 1.3×10^4 ha, with releases conducted in a series of phases. A primary goal of the restoration was to re-establish wetland habitat suitable for waterbirds. Establishment of 1.0×10^4 ha of restored wetlands, located where the river's modern channel reaches the sea, began in 2002, and the results have been previously described (Cui et al., 2009; Yang, 2011). In addition, freshwater releases to restore 0.3×10^4 ha, located in the Yiqianer Management District (where the old Yellow River channel reached the sea) started in 2010. There have been few studies of the effects of this restoration (e.g., Li et al., 2016b).

Because of a combination of excessive withdrawals of water in upstream regions and climate change, the average annual runoff at the Lijin Station (the hydrological station on the Yellow River closest to the delta) decreased from 10.01×10^{10} m^3 in the 1970s to 2.05×10^{10} m^3 at the end of the 1990s. As a result, the study region has no natural freshwater inflows and its original freshwater ecosystems have been adversely affected by seawater ingress and erosion of the coast, which were exacerbated by relocation of the Yellow River's mouth in 1976 (Li and Wang, 2003).

To prevent further wetland damage and restore the area's original freshwater wetlands, managers constructed a series of tidal barriers in 2010 that also provided more favorable conditions for the implementation of environmental flow releases. The tidal barriers are earth embankments, with timber pilings providing additional support. The barriers are 4–5 m tall, which is enough to prevent the entry of salt water by surface flows and to prevent flooding during storms. However, salt remains in the sediments at a relatively high concentration in the recovering wetlands because the average annual pan evaporation (1962 mm) is far greater than the average annual precipitation (552 mm), and this problem is exacerbated by inflows of salt in the groundwater.

The current freshwater releases are based on a single annual release, which coincides with the timing of water and sediment regulation activities in the upstream Xiaolangdi Reservoir that is the primary source of water for the wetlands. A total of six freshwater releases have been implemented since June 2010 (Table 1). The releases lasted from 10 to 45 days, and the duration did not vary among the habitats in a given year. The releases involved the transfer of 1.3×10^7–3.6×10^7 m^3 of water into the restoration areas. The leakage from the wetlands in these three years was estimated at about 1.4×10^4, 2.7×10^4, and 1.03×10^4 m^3/d, respectively (Peng et al., 2015), which is much greater than the leakage before the freshwater releases.

2.2. Habitat heterogeneities

In most habitats, plant communities determine the physical structure of the environment (Ricklefs and Miller, 1999; Tews et al., 2004). Thus, in our study, we defined the key habitat types based on the dominant vegetation and landscape characteristics.