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Effectiveness of microtopographic structure in species recovery in degraded salt marshes

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ABSTRACT

Topographic heterogeneity is an important determinant of the distribution of resources and species and of species assembly. For example, the lack of microtopography in degraded salt marshes might restrict processes involved in the recovery of such ecosystems, such as seed retention. Therefore, we conducted a restoration study in degraded middle to high salt marshes, where self-recovery might be restricted by poor seed retention. We investigated the impact of microtopographic structures on seed retention and the re-establishment of pioneer vegetation patches. Our results showed that hollowed microtopographic structures are effective tools for allowing the re-establishment of pioneer vegetation patches by acting as seed traps and sustaining the recovery process that follows. Larger, deeper microtopographic structures entrapped more seeds and formed larger patches over the long term compared with smaller structures, highlighting the value of such structures to the successful recovery of degraded salt marshes.

1. Introduction

Salt marshes occupy a critical interface between the land and sea, and provide important ecological and economic services, such as nutrient removal, storm protection for coastal cities, carbon sequestration, and habitats for numerous species of fish, birds, and invertebrates (Deegan et al., 2012). However, despite various protective measures, losses of these ecosystems have accelerated worldwide in recent decades (Beck et al., 2011; Friess et al., 2012; Millennium Ecosystem Assessment, 2005; Waycott et al., 2009; Wilkinson, 2008). Conservation efforts over the past decade have shifted from a focus on the preservation and protection of intact systems to the restoration of degraded systems (Dobson et al., 1997; Young, 2000; Silliman et al., 2015).

For degraded salt marshes, key species recruitment is vital for the recovery and restoration processes. A variety of biotic and abiotic factors and their interactions can restrict plant recruitment (Friess et al., 2012) and, therefore, delay or accelerate the covering of bare areas (Connell and Slatyer, 1977; Farrell, 1991). Only once bottlenecks (i.e., diaspore availability) are overcome can recruitment succeed in bare area (Friess et al., 2012). Generally, factors affecting successful plant recruitment include: (1) dispersal and supply of seeds or propagules (Levine and Murrell, 2003); (2) germination of seeds or propagules (Rand, 2000; Xie et al., 2017); and (3) survival of seedlings (Ellison, 2000; Friess et al., 2012). In a tidal system, tidal waters are important in dispersing seeds (Chang et al., 2007) and determine whether a seed arrives at the target site. In the subsequent stages of plant establishment, physical stresses (i.e., tidal inundation, soil salinity, and moisture stresses) (Friess et al., 2012; Xie et al., 2017) and interactions between species (i.e., herbivory and competition) (Connell and Slatyer, 1977; Bertness and Shumway, 1993; He, 2012) can limit successful restoration.

Seed dispersal, as the initial constraining factor affecting species richness, can influence the structure of plant populations (Kudoh et al., 2006) and communities in systems dominated by water dispersal (Honnay et al., 2001; Nilsson et al., 2002; Jansson et al., 2005). Except for enclosed ecosystems (without tidal events), seed dispersal might not be affected as long as the tidal waters arrive, and this is aided by plant species in salt marshes having a relatively long dispersal stage. However, a recent review suggested that spatial variation in seed deposition in most empirical studies is more easily related to landscape elements that trap seeds than to the theoretical probability of dispersal distance travelled from the seed source (i.e., dispersal kernel) (Levine and Murrell, 2003). Physical structures encountered by dispersing stages of plants (e.g., seeds and propagules) can significantly influence plant recruitment (Schneider and Sharitz, 1988; Sousa et al., 2007). This is especially true of aquatic plants that require stranding; in fact, the recruitment success of these plants can be limited by the availability of structures that entrap seeds or propagules (Nilsson et al., 2010). The final distribution of a seed is influenced by interactions between waves, tidal flows, and trapping agents (i.e., vegetative or microtopographic

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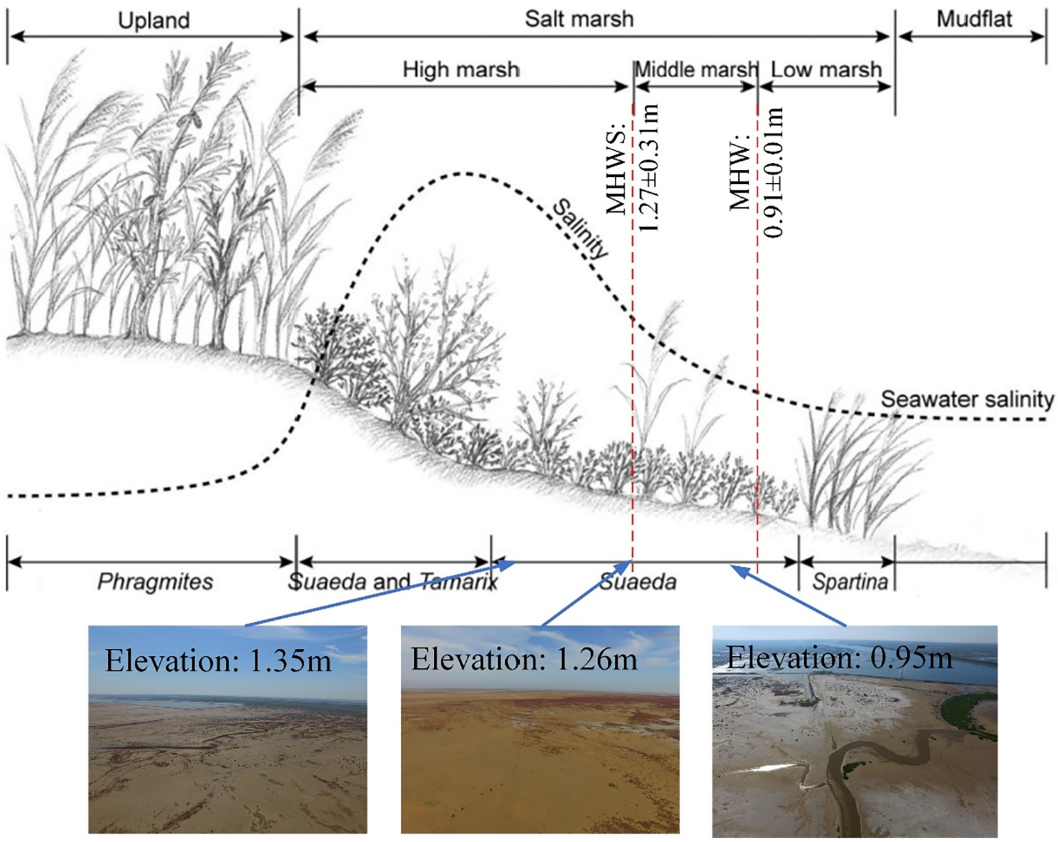

Fig. 1. Study sites in the Yellow River Delta (YRD). The pattern of plant zonation in the YRD is taken from He (2012). Mean high water spring (MHWS) and mean high water (MWH) were measured by Odyssey Water Level Loggers. 2-column fitting image**.**
Cui (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

structures). In addition, seed traits also have a role in the dispersal and retention processes (Chambers, 2000; Chang et al., 2008).

Retention of seeds or propagules by vegetative structure exemplifies one mechanism by which the recruitment process can be facilitated by established plants with appropriate architecture (i.e., salt marsh plants with different growth forms, Peterson and Bell, 2012). This facilitation mechanism has been widely studied in tidal systems, such as propagule entrapment by salt marsh plants to facilitate recruitment in mangrove ecosystems (Huxham et al., 2010; McKee et al., 2007; Peterson and Bell, 2012; Stevens et al., 2006) and sea grass fruit entrapment by algae to facilitate recruitment in sea grass ecosystems (Turner, 1983). Restoring diverse native ecosystems requires the creation of soil surface features that can trap and retain seeds (Chambers, 2000). Microtopographic structures can entrap seeds carried by the tide or in sediment (Moser et al., 2007; Chang et al., 2008; Courtwright and Findlay, 2011) during the dispersal stage. On bare, flat, topographic heterogeneity-lacking surfaces, seeds or propagules are not easily retained (Johnson and Fryer, 1992; Huxham et al., 2010). Thus, this could explain the slow or stagnant natural recovery of flat, bare patches in salt marsh ecosystems.

Given that positive interactions among plants via seed or propagule entrapment might not occur on bare patches, microtopographic structures could be used to entrap seeds or propagules to facilitate plant recruitment. Microtopography is defined as topographic variability on the scale of individual plants (Huenneke and Sharitz, 1986; Titus, 1990; Bledsoe and Shear, 2000), and describes soil surface variation within an elevation range from approximately 1 cm to 1 m, encompassing both vertical relief and surface roughness (Moser et al., 2007). Microtopography significantly influences the hydrology and physicochemistry of the salt marsh environment, including soil nutrient availability, habitat variability (including vegetation patterns), and thus, ecosystem functioning (e.g., Pollock et al., 1998; Moser et al., 2007). Small-scale variations in surface elevation are important for the temporal and spatial variability in flooding, water flow, and seed retention. Microtopographic heterogeneity can be caused by sedimentation, erosion, root growth, litter accumulation, animal activity, peat compaction, or shrink/swell processes (Vivian-Smith, 1997; Rogers et al., 2006; Moser et al., 2007; Cahoon et al., 2011). To ameliorate the site conditions and reduce seedling mortality, the creation of microtopography has been used extensively in many ecosystems during the initial stages of seedling plantation and vegetation establishment (Wei et al., 2012). However, the usefulness of microtopographic structures in facilitating plant recruitment by seed retention is unclear in terms of the most appropriate size and relative surface elevation to use, leaving their potential use in achieving successful restoration unclear.

The current study focuses on plant recruitment in bare salt marsh areas in the Yellow River Delta (YRD), via the facilitation of microtopographic structures during the dispersal stage to entrap seeds. To quantitatively evaluate the effectiveness of microtopographic structures in salt marsh species recovery on bare patches, we established hollowed microtopographic structures of specific sizes and depths in degraded areas across middle/high salt marshes. The re-established patches were monitored over three years to determine the sustainability and stability of recovery processes over a longer timescale. We hypothesized that seed retention is a limitation of plant recruitment in bare salt marsh areas because of the lack of trap agents and, thus, that microtopographic structures can facilitate plant recruitment by trapping seeds, but that their effectiveness is affected by the relative size and depth of the structures. We concluded that the creation of appropriate artificial microtopographic structures can be used during the dispersal stage to speed up the recovery process of plants on bare patches in degraded and created coastal wetlands and other ecosystems (such as forests, bogs, freshwater wetland, and grassland).