Ecological Engineering 123 (2018) 212–225

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Designing topographic heterogeneity for tidal wetland restoration

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ARTICLE INFO

Keywords:
Constructed mound
Engineering design
Hummock
Levee
Marsh
Microtopography
Mound
Restoration
Ridge
Soil moisture
Tidal freshwater
Tidal marsh
Tidal wetland
Topographic heterogeneity
Terrace
Wetland

ABSTRACT

Topographic heterogeneity affects abiotic and biotic components of vegetated ecosystems and has the potential to provide functions and services such as promoting floral and faunal biodiversity. Yet, few studies have documented the design, implementation, and outcomes of mound-type features in estuarine and tidal freshwater wetland restoration projects. Here we report data from a synoptic survey of soil temperature and moisture on mounds at tidal wetland restoration sites in the Pacific Northwest, together with the results of a literature review, and the insights of regional restoration practitioners regarding ecological and practical considerations for mound construction. Few papers reviewed addressed conditions for plant establishment on mounds, such as soil moisture, which is important in climates with annual dry seasons, like the Pacific Northwest. We report 2015 data on soil moisture and temperature for the tops, sides, and toes of 15 mounds constructed between 2001 and 2013 of fill dirt, or dirt and logs, at 5 tidal wetland restoration sites. Two of the restoration projects studied are located in the lower Columbia River and estuary, one is in the Puget Sound, and two are in outer Pacific coastal estuaries in Oregon. The heights of mounds ranged from 0.5 m to 1.5 m above the marsh plain, and the area of individual mounds ranged from 21 m^2 to 5185 m^2, while most published information treated somewhat smaller topographic features (termed mounds, hummocks, tussocks, ridges, levees, fans, or terraces). Differences in the minimum and maximum values of moisture between the toe and the top of mound in summer ranged from 2.9% to 40%. Statistical analysis strongly suggested stratification of soil moisture by elevation. Analysis of soil temperature was less conclusive, but temperature appeared to be positively correlated with elevation. Soil moisture relative to mound aspect (cardinal direction) was significant in some cases, but inconsistent between mounds. We also report our observations from a third recent restoration project on the tidal Columbia River, and observations made by other practitioners who have designed and installed mounds from San Francisco Bay to northern Puget Sound. Our findings will support design of wetland restoration sites where topographic heterogeneity is an objective.

1. Introduction

1.1. Background

Different groups of plant species have long been observed to occur along gradients in land elevation. Ecologists and agricultural scientists have elucidated how elevation gradients are related to the tolerance of plants for variation in fundamental environmental conditions such as temperature, moisture, light, soil nutrients, and the disturbance regime. Even topographic differences on the order of a few centimeters have been linked to micro-environments that affect seed germination and establishment (Harper et al., 1965). The term microtopography has been defined as variability on the scale of individual plants, or ~1 cm to 1 m, and has components of both relief (vertical extent) and roughness (topographic variability) (Moser et al., 2007). Microtopography is particularly important to plant distribution in floodplain wetlands because of its direct association with surface and groundwater dynamics and edaphic gradients (Huenneke and Sharitz, 1986; Titus, 1990). Topographic heterogeneity has been shown to affect numerous aspects of ecosystems in addition to the distribution of organisms and patterns of abiotic factors. It affects ecosystem processes, animal behavior and habitat use, herbivory and other trophic interactions, competitive exclusion, development, and genetic and reproductive attributes (Larkin et al., 2006).

In intertidal areas, it is clear that elevation strongly controls wetland plant distribution, but the proximity to tidal creeks is also a controlling factor (Zedler et al., 1999), as are soil permeability and surface and groundwater dynamics. Microtopography and flood disturbance

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https://doi.org/10.1016/j.ecoleng.2018.07.027
Received 25 May 2018; Accepted 24 July 2018

interact on marsh plant species survival and distribution (Pollock et al., 1998; Tessier et al., 2002). In swale and dune habitats, plants with better drainage respired aerobically in contrast to those in lower, poorly drained marsh areas (Burdick and Mendelssohn, 1987). Bubier et al. (1993) showed that seasonal mean water table position can explain the variability in methane emissions at the hummock and hollow scale. Plant species richness on hillocks in salt marshes of southeastern Denmark is higher (Vestergaard, 1998) and the surface area of tussocks is positively correlated with species richness (Werner and Zedler, 2002). Seed banks in sheltered micro-habitats in salt marshes are larger than areas that have greater sediment mobility (Inglis, 2000).

Through these types of mechanisms, topographic heterogeneity can increase plant biodiversity in marshes. Microtopography (e.g., mounds, hummocks) has been used as a wetland restoration and management technique for this purpose, for example, increasing roughness with tilling at non-tidal wetland creation sites (Moser et al., 2007), or retaining and protecting mounds with shrubby vegetation at a coastal wetland restoration site (Gallego Fernández and García Novo, 2007). For coastal restoration, the germination and establishment of plants is one of the most important criteria for any technique under consideration, and it is generally understood that the design specifications of mounds, hummocks, ridges, peninsulas, and berms have the potential to affect environmental conditions and therefore the success or failure of plantings and the degree of natural colonization. For instance, smoothly mounded higher-elevation islands made from dredged material at a San Diego Bay salt-marsh restoration site caused salts to be wicked to the surface preventing plant establishment because of soil salinity (Larkin et al., 2006).

In addition to plant community effects, other potential benefits of using mounds in tidal wetland restoration include diverse edaphic conditions (Cantelmo and Ehrenfeld, 1999; Bruland and Richardson, 2005; Courtwright and Findlay, 2011), and edge effects on aquatic species productivity (Rozas et al., 2005). They may also provide ecosystem services, such as resilience to variable environmental conditions (Doherty and Zedler, 2015), and slowing the rate of wetland loss (Zedler and Kercher, 2005). Elevation is a central element of coastal wetland restoration designs because it affects the inundation regime, which together with sediment supply and wetland plant productivity control the rate at which coastal marshes sequester sediments, a fundamental process in these depositional ecosystems (Allen, 2000). The rate of sediment accretion is often very important in regions with subsidence behind dikes, which may take decades for elevation to equilibrate with surrounding areas once they are reconnected with adjacent waterways, and thus retard the ability of desired plant species to establish (Diefenderfer et al., 2008). The timing of excavation and grading that expose soil, and of plantings to enhance retention, thus are important in coastal wetland restoration planning because of the positive feedback on increased elevation. With inundation, the soil environment can rapidly change from oxidized to reduced, and previously thriving plants such as pasture grasses are likely to die back and be replaced by more hydrophytic species (Frenkel and Morlan, 1991; Blackwell et al., 2004). However, oftentimes there is excess mineral sediment available in coastal wetland projects in comparison with more nitrogen-rich organic soils, and depositing it on sites can adversely affect ecosystem development, retarding root development and reducing above ground biomass (French, 2006). The construction of mounds has been proposed to coastal restoration program reviewers on the basis of providing topographic diversity with the potential to reduce the impacts of subsidence behind dikes, accelerate the development of woody plant communities, control an invasive non-native plant (reed canary grass (*Phalaris arundinacea*)), produce a plant-community mosaic, and generally increase habitat complexity at the restoration site (Krueger et al., 2017).

1.2. Study purpose

Both restoration practitioners and reviewers of the Columbia Estuary Ecosystem Restoration Program (CEERP) on the West Coast of the continental United States (Diefenderfer et al., 2012, 2016), have requested guidance regarding the right balance between practical concerns and ecological function. Specifically, science-based construction specifications for mounds (e.g., height, width, aspect [cardinal direction], and slope) used to increase topographic heterogeneity had not been established for the program. On some projects, grading is required to produce a land-surface elevation suitable for wetland restoration given the prevailing hydrologic regime, and the formation of mounds may help defray the costs of moving excavated material offsite. However, data on the effectiveness of mounds for tidal wetland restoration in the Pacific Northwest were not available in the peer-reviewed literature. In fact, information about the ecological and practical considerations for designing mounds for tidal wetland restoration was needed to reduce uncertainties in program planning.

The purpose of this study was to provide the missing science-based information to practitioners and managers of restoration projects in the CEERP. It was specifically intended to improve the effectiveness of restoration actions, through the CEERP's adaptive management program (Ebberts et al., 2017). The objectives of this research were to compile published literature that is highly relevant to mound design for tidal wetland restoration, obtain insights from regional restoration practitioners regarding ecological and practical considerations for mound construction, and generate new data on environmental conditions and plant establishment from mounds previously constructed at tidal wetland restoration projects in the Pacific Northwest.

2. Methodology

2.1. Study area

The climate of the coastal Pacific Northwest (PNW) is characterized by high annual rainfall but summer drought. Due to the proximity of coastal mountain ranges to the Pacific coast and ubiquitous rocky headlands, tidal wetlands are generally smaller and more isolated than those on the Gulf and Atlantic coasts. Two of the largest complexes of wetlands on the Pacific coast are the lower Columbia River and estuary (LCRE) and Puget Sound (Callaway et al., 2012). Field data were collected from six tidal wetland restoration sites in these two areas and the outer Pacific coast in the U.S. states of Washington and Oregon (Fig. 1). The wetlands are subject to a mixed, semi-diurnal mesotidal regime. In the 234 km tidal portion of the Columbia River, floodplain wetlands are also strongly affected by river flows from the 668,000 km^2 basin, and during low to moderate flows salinity extends only 20–40 km inland from the river mouth, so there is a large expanse of tidal freshwater area (Jay et al., 2016).

The six tidal wetland restoration sites were identified through outreach to practitioners involved with current and past restoration projects in the PNW to learn where mounds had been incorporated in project designs (Appendix A, Table A.1). The criteria for selecting study sites were that the object of ecological restoration was a wetland with a tidally influenced hydrologic regime, that one or more mounds had been constructed for the purpose of restoration, and that access to the site was feasible and permissions to conduct research could be obtained through land owners. On this basis, three sites were selected on the LCRE (Colewort Creek, Ruby Lake, and Seal Slough), one on the Puget Sound (Marietta Slough), and two on the outer PNW coast (Anderson Creek and Drift Creek) (Fig. 2).

The six sites are all located on the tidally influenced sections of river floodplains. All sites, with the exception of Marietta Slough and