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Interactive effects of vegetation and sediment properties on erosion of salt marshes in the Northern Adriatic Sea

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A B S T R A C T

We investigated how lateral erosion control, measured by novel photogrammetry techniques, is modified by the presence of *Spartina* spp. vegetation, sediment grain size, and the nutrient status of salt marshes across 230 km of the Italian Northern Adriatic coastline. *Spartina* spp. vegetation reduced erosion across our study sites. The effect was more pronounced in sandy soils, where erosion was reduced by 80% compared to 17% in silty soils. Erosion resistance was also enhanced by *Spartina* spp. root biomass. In the absence of vegetation, erosion resistance was enhanced by silt content, with mean erosion 72% lower in silty *vs.* sandy soils. We found no relevant relationships with nutrient status, likely due to overall high nutrient concentrations and low C:N ratios across all sites. Our results contribute to quantifying coastal protection ecosystem services provided by salt marshes in both sandy and silty sediments.

1. Introduction

Vegetated coastal habitats such as salt marshes provide multiple ecosystem services, including habitat provisioning, nutrient cycling, climate regulation, and cultural services (Duarte et al., 2013; Gedan et al., 2009). The use of salt marshes in ecosystem-based approaches to flood defence is highly promising (Bouma et al., 2014; Narayan et al., 2016), as they have been demonstrated to attenuate waves even under storm-surge conditions (Möller et al., 2014). There has thus been a focus in recent decades on the conservation and restoration of salt marshes to protect coasts from erosion, storm surges and sea level rise (Curado et al., 2013), and to prolong the life of traditional engineered structures such as sea walls and embankments (Spalding et al., 2014; Temmerman et al., 2013). The perennial saltmarsh grasses of the *Spartina* genus are of particular interest in coastal protection as they are pioneer species (Bouma et al., 2016) with a global distribution (Duarte et al., 2013; Silliman, 2014). Their ecosystem engineering properties include trapping sediments from the water column, which enables accretion and establishment at the low marsh (Bouma et al., 2005).

Salt marshes are highly dynamic ecosystems with cyclic behavior, and the stability and size of salt marshes are governed by horizontal and vertical processes (Kirwan and Megonigal, 2013). Horizontally, periods of seaward expansion alternate with periods of shoreward (lateral) erosion due to tidal or wave-induced currents (Bouma et al., 2016; van de Koppel et al., 2005; Yapp et al., 1916). Sediment supply, depth and width of adjacent tidal flats, and wave action affect the balance between erosion and progradation (Mariotti and Fagherazzi, 2013). Density and flexibility of the salt marsh vegetation canopy also play a role in decreasing flow velocity and enabling sediment-trapping, while attenuating waves and slowing erosion (Bouma et al., 2005; Heuner et al., 2015; Möller

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et al., 2014). Vertically, the ability of salt marshes to keep pace with sea level rise by accretion is also dependent on sufficient sediment supply and the rate of landward expansion (Kirwan and Megonigal, 2013). While research has mainly focused on vertical dynamics of salt marshes, especially in the context of sea level rise, there has been comparatively less research on the factors affecting the horizontal dynamics of salt marshes (Kirwan et al., 2016), which may be more important to marsh stability as marshes are more resistant to vertical change but less resistant in the lateral dimension (Fagherazzi et al., 2013). In order to use salt marshes for coastal defence, we need a greater understanding of these horizontal factors, including those controlling resistance to lateral erosion.

Previous studies have shown that below-ground vegetation can aid in inhibiting erosion by stabilizing soils via roots and rhizomes which enhances cohesion and tensile strength, resulting in higher soil shear strength (Micheli and Kirchner, 2002; Turner, 2011). Moreover, roots and rhizomes can provide a physical barrier between water and soil (Wolanski, 2007). It has been demonstrated that the loss of below-ground biomass can result in reduced soil strength or marsh erosion (Sheehan and Ellison, 2015; Silliman et al., 2016). Feagin et al. (2009) suggested that sediment properties can influence lateral erosion rates more than vegetation, with vegetation indirectly contributing to erosion resistance by incorporating detritus and fine-grained sediments into the soil matrix, rendering the soil less dense, less coarse and more cohesive. Deegan et al. (2012) suggested that long-term nutrient addition to salt marshes could cause eventual collapse of the system, as increased availability of nutrients reduces relative investment in below-ground biomass and enhances microbial decomposition, thereby destabilizing soils. Wong et al. (2015) further demonstrated that saltmarsh vegetation can be more vulnerable to increased inundation in medium organic matter soils, particularly under high nutrient availability. Combining these findings suggests that a complex interplay between vegetation, sediment properties and anthropogenic-influenced nutrient levels can influence erosion resistance of salt marshes.

The role of salt marshes in coastal defence is particularly important in the Mediterranean Sea, where humans have been inhabiting and shaping the coastlines for millennia (Airoldi and Beck, 2007). The coast has been dramatically transformed by altered sedimentation patterns, land reclamation, river diversions, embankments, and drainage, resulting in the loss of more than 70% of salt marshes in the region (Fontolan et al., 2012). Coastal defence with artificial structures such as groynes and breakwaters have been implemented on a large scale, leading to hardening of coastal areas and changes in sediment structure, and subsequent loss and alteration of native habitats and assemblages (Airoldi et al., 2005). The extensive construction of artificial infrastructures along these shorelines may limit land-ward rates of marsh expansion in response to sea-level rise, causing coastal squeeze (Doody, 2004). In addition to these development pressures, Mediterranean salt marshes are also impacted by climatic stressors including sea level rise, changed storminess, warm spells or heat waves (Airoldi and Beck, 2007; Christensen et al., 2013) resulting in their decline. Loss of salt marshes in the region has been caused by a reduction in sediment supply and land subsidence, exacerbated by sea level rise (Kirwan and Megonigal, 2013), increases in extreme water elevations (Masina and Lamberti, 2013), and wind-induced waves (Day et al., 1998; Fontolan et al., 2012). Climate extremes, such as heat waves, have accelerated some of these losses, modifying the composition of the dominant vegetation (Strain et al., 2017). Moreover, the dense populations and intensive agriculture and farming along the coast and the plain of the Po river have enhanced nutrient levels along the coastline, and eutrophic conditions are common (De Wit and Bendoricchio, 2001; Lotze et al., 2011), potentially increasing the sensitivity of salt marshes to erosion (Deegan et al., 2012). Given the growing evidence that salt marsh conservation/restoration can be effective as nature-based coastal protection schemes (Shepard et al., 2011), and their rapid rate of decline in the Mediterranean and globally, it is imperative to quantify their role in slowing of coastal erosion rates, and identify which factors or combinations of factors enhance or limit this valuable ecosystem service (Bouma et al., 2014).

Our main objective was to quantify the role of salt marshes in slowing lateral coastal erosion rates in the Northern Adriatic Sea along a broad gradient of physical and anthropogenic factors. We concentrate our investigation on the role of salt marshes in decreasing erosion at the cliff edge, focusing on below-ground factors affecting erosion. Specifically, we investigated how erosion resistance may be modified by the presence of *Spartina* spp., the local sediment grain size, and the local nutrient status of the marsh, using C:N-ratios of above-ground biomass as a proxy for nutrient levels. We hypothesized that *Spartina* spp. below-ground biomass would significantly reduce lateral erosion, and that this effect would increase with increased density of *Spartina* spp. and in cohesive silty soils, while it would decrease with increased nutrient levels.

2. Materials and methods

2.1. Study area

The Northern Adriatic Sea basin off the coast of Italy is the shallowest, northernmost region of the Mediterranean and among the most productive with high habitat diversity (Lotze et al., 2011). The area consists of lagoon-river delta systems which host numerous transitional water bodies and is characterized by moderate exposure to wave action and a semi-diurnal micro-tidal regime with average tidal amplitudes of approximately 65–80 cm (Fontolan et al., 2012; Silvestri et al., 2005). Average sea surface temperatures in the region vary between 7 °C in winter and 27 °C in summer, with highly variable average surface salinities between 30 and 38 psμ. Major activities in the region include the petrochemical industry, tourism, fishing, seaport/port activities and shipping (Torresan et al., 2012). Development pressures have resulted in overall reduced sediment supply in the region, and negative sediment budgets have been recorded in the lagoons of Venice and Grado-Marano due to subsidence, dredging and clam harvesting, such that the lagoons are experiencing accelerating erosion and unprecedented loss of salt marshes (Day et al., 1998; Fontolan et al., 2012; Sarretta et al., 2010; Torresan et al., 2012).

We sampled six sites in coastal lagoons along approximately 230 km of coastline along the regions of Emilia-Romagna, Veneto and Friuli Venezia Giulia (Fig. 1), aiming to include a wide range of environmental (i.e., nutrient status) and physical (i.e., sediment type) conditions. From south to north, sites were located: (1) in the natural reserve Sacca di Bellocchio (hereafter BEL), in the Valli di Comacchio lagoon ecosystem, Parco Delta del Po dell'Emilia-Romagna (44°37′47″N, 12°15′38″E) (further site description in Strain et al., 2017); (2) in the Vallona Lagoon (hereafter VAL), in an area that had previously been reclaimed for agriculture, and is currently being used for private aquaculture (45°1′42″N, 12°23′7″E) (further site description in Wong et al., 2015); (3) in the Coastal Botanic Garden of Veneto, municipality of Rosolina (hereafter ROS), in the southern portion of Caleri Lagoon, Parco Regionale Veneto del Delta del Po (45°5′42″N, 12°19′39″E); (4) in the Chioggia Inlet (hereafter CHI) in the southern part of Venice Lagoon (45°14′53″N, 12°13′34″E); (5) in Grado Lagoon (hereafter GRA), adjacent to an area privately used for aquaculture (45°42′13″N, 13°26′31″E), and (6) in another area in Grado Lagoon adjacent to a golf course