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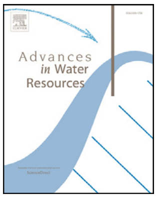

Spatial variation of salt-marsh organic and inorganic deposition and organic carbon accumulation: Inferences from the Venice lagoon, Italy

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ABSTRACT

Salt marshes are ubiquitous features of the tidal landscape governed by mutual feedbacks among processes of physical and biological nature. Improving our understanding of these feedbacks and of their effects on tidal geomorphological and ecological dynamics is a critical step to address issues related to salt-marsh conservation and response to changes in the environmental forcing. In particular, the spatial variation of organic and inorganic soil production processes at the marsh scale, a key piece of information to understand marsh responses to a changing climate, remains virtually unexplored. In order to characterize the relative importance of organic vs. inorganic deposition as a function of space, we collected 33 shallow soil sediment samples along three transects in the San Felice and Rigà salt marshes located in the Venice lagoon, Italy. The amount of organic matter in each sample was evaluated using Loss On Ignition (LOI), a hydrogen peroxide (H_2O_2) treatment, and a sodium hypochlorite (NaClO) treatment following the H_2O_2 treatment. The grain size distribution of the inorganic fraction was determined using laser diffraction techniques. Our study marshes exhibit a weakly concave-up profile, with maximum elevations and coarser inorganic grains along their edges. The amount of organic and inorganic matter content in the samples varies with the distance from the marsh edge and is very sensitive to the specific analysis method adopted. The use of a H_2O_2+NaClO treatment yields an organic matter density value which is more than double the value obtained from LOI. Overall, inorganic contributions to soil formation are greatest near the marsh edges, whereas organic soil production is the main contributor to soil accretion in the inner marsh. We interpret this pattern by considering that while plant biomass productivity is generally lower in the inner part of the marsh, organic soil decomposition rates are highest in the better aerated edge soils. Hence the higher inorganic soil content near the edge is due to the preferential deposition of inorganic sediment from the adjacent creek, and to the rapid decomposition of the relatively large biomass production. The higher organic matter content in the inner part of the marsh results from the small amounts of suspended sediment that makes it to the inner marsh, and to the low decomposition rate which more than compensates for the lower biomass productivity in the low-lying inner zones. Finally, the average soil organic carbon density from the LOI measurements is estimated to be $0.044\ \mathrm{g\ C\ cm^{-3}}$. The corresponding average carbon accumulation rate for the San Felice and Rigà salt marshes, $132\ \mathrm{g\ C\ m^{-2}\ yr^{-1}}$, highlights the considerable carbon stock and sequestration rate associated with coastal salt marshes.

1. Introduction

Coastal salt marshes represent a transition zone between submerged and emerged environments, occupying the upper margins of the intertidal landscape. Because of their unique position in the tidal frame, salt marshes represent a crucially important ecosystem. They offer valuable services, by providing a buffer against wave and storm surges [e.g., 1–4], nursery areas for coastal biota [e.g., 5,6] and filtering of nutrients and pollutants [e.g., 7,8]. In the last few decades a number of authors also highlighted the importance of salt marshes serving as an organic carbon sink due to their great ability to sequester atmospheric carbon [e.g., 9–13]. The future of these valuable

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coastal landforms and ecosystems is today at risk, exposed as they are to possibly irreversible transformations due to the effects of climate changes and human interferences [e.g., 11,14–19]. The extent of these coastal features, in fact, has dramatically decreased worldwide in the last century [10,15,20–23]. For example, salt-marsh areas in the Venice lagoon decreased from about 180 km^2 in 1811 to about 50 km^2 in 2002, a reduction of more than 70% [15,22,24]. Losses of vast amounts of marsh areas have also been documented for San Francisco Bay (about 200 km^2, [23]) over the last century, while vast amounts of wetlands disappeared in the Mississippi Delta plain (about 4800 km^2 [16,20]).

The rising sea level and the lack of available sediments are key factors in determining the drowning and disappearance of salt marshes worldwide [15,17,20,23,25–29]. In the horizontal plane the prevalence of wind-wave induced lateral erosion over marsh progradation is responsible for the retreat of salt marsh edges [22,30–32]. Once the marsh drowns or is laterally eroded and converted to tidal flat or to a subtidal platform, unless the environmental conditions change (i.e. the sediment concentration increases) the re-growth of the marsh platforms is unlikely because the system is characterized by a hysteretic behavior [e.g., 33,34].

Salt marshes are populated by halophytic vegetation species, adapted to saline environments. The spatial distribution of halophytes over salt marshes is organized in characteristic patches, a phenomenon known as *zonation* [35–40]. It has been recently shown that zonation patterns are not just the result of ecological and physiological processes and that their emergence is the consequence of the feedback on soil accretion of organic soil production by plants, which act as a landscape engineer [41,42]. The development of vegetation over salt marshes is mainly determined by the frequency and duration of marsh flooding [e.g., 25,37,43], which, in turn, depend on elevation, position and local topography of the marshes. Halophytic vegetation species which populate marsh platforms control sediment trapping efficiency, by enhancing particle settling via reduction of turbulence kinetic energy [e.g., 44,45], by directly capturing sediment particles [e.g., 46,47], and determine vertical organic accretion, by directly depositing organic matter due to root growth and litter deposition [48–50]. Halophytes interact with inorganic sedimentation and the rate of Relative Sea Level Rise (RSLR, sea level variations plus local subsidence), their combined effects controlling marsh surface elevation. Surface elevation, in turn, affects the vegetation productivity [25] which influences inorganic sediment deposition and control organic accretion, thus closing the bio-geomorphic feedback. In this framework it is clear that the interaction between physical and biological processes acting within salt marsh systems plays a fundamental role in salt-marsh survival or disappearance. Although in the last few decades a number of studies have analysed salt-marsh biomorphological evolution [e.g., 15,18,25,33,41,50–55], a predictive understanding of the two-way feedbacks between physical and biological processes still appears to be elusive. Moreover, analyses of bio-geomorphic feedbacks based on data collected in the field at the marsh scale are rare [14,25,48,49,56–59]. The evolution in time of marsh elevation z ($\boldsymbol{x}$, t) (referenced to Mean Sea Level – hereinafter MSL) at a given site $\boldsymbol{x}$ and at time t, is governed by the sediment continuity equation (where erosion is neglected because of the stabilizing presence of vegetation, see [34,41]):

$$\frac{\partial z(\boldsymbol{x},t)}{\partial t} = Q_i\,(\boldsymbol{x},t) + Q_o(\boldsymbol{x},t) - R \tag{1}$$

where $Q_i(\boldsymbol{x}, t)$ and $Q_o(\boldsymbol{x}, t)$ are the local rates of inorganic and organic deposition, respectively, and R is the rate of RSLR. In equilibrium conditions, the marsh elevation referenced to MSL is constant over time and therefore the left-hand side term in the above equation vanishes. The sediment balance equation then reads:

$$Q_i\,(\boldsymbol{x},t) + Q_o(\boldsymbol{x},t) = R \tag{2}$$

Hence, in a stable marsh, if Q_i increases, Q_o needs to decrease by the same magnitude, and vice versa, such that the forcing rate of RSLR is matched everywhere in the marsh. Field observations and numerical models [e.g., 52,60–62] suggest that marsh inorganic accretion rates, and the related platform elevations, decrease with distance from the main channels. Therefore, the organic accretion should be expected to gradually increase as the distance from the main channel increases for the equilibrium assumption to hold. However, a direct and detailed characterization of spatial variations in the accretion rates, and, in particular, in the organic soil production, is still lacking, and is the focus of the present work.

The paper is organized as follows. In the next section we provide a brief description of our study sites within the Venice lagoon. We then fully describe the methods used to determine the organic and inorganic sediment content, grain size distribution, above-ground biomass. The subsequent Results and Discussion sections analyze the role of physical and biological factors shaping the tidal landscape, and how these factors influence salt-marsh biogeomorphic patterns.

2. Study area

The Venice lagoon (Fig. 1a) is part of a foreland basin located between the NE-verging northern Appenninic chain and the SSE-verging eastern South-Alpine chain (Italy). Located in the north-western Adriatic Sea, the Venice lagoon is the largest lagoon in the Mediterranean, with an area of about 550 km^2, a mean water depth of 1.5 m, and a semi-diurnal micro-tidal regime (maximum water excursion at the inlets of ± 70 cm around MSL). The Lagoon is connected with the Adriatic Sea via three inlets: Lido, Malamocco and Chioggia (Fig. 1a).

The two study areas (Fig 1a, b, c) are the San Felice and the Rigà salt marshes, located in the northern Venice lagoon, close to the Lido inlet and adjacent to the San Felice Channel (see [21,37,63], for a detailed description of the study sites from a geomorphological and ecological perspective). These marshes, about 2 km apart, have been studied for more than 10 years and a large amount of data is available. In addition, it is worth noting that these marshes maintained their main characteristics because of their location in the most naturally preserved portion of the lagoon. The San Felice and the Rigà salt marshes are incised by meandering tidal networks and are colonized by a wide range of halophytic vegetation species: *Salicornia veneta, Spartina maritima, Limonium narbonense, Sarcocornia fruticosa, Juncus maritimus, Inula crithmoides, Puccinellia palustris, Halimione portulacoides, Suaeda maritima, Arthrocnemum macrostachyum, Aster tripolium* [63]. The marsh soil is composed of clayey sandy silt and of a large organic fraction. Accretion rates in the San Felice area were estimated in 3.0 mm yr^{-1} by Day et al. [57], whereas the rate of sea-level rise is of about 2.0 mm yr^{-1} [64], and the local subsidence is about 1.0 mm yr^{-1} [64,65], for a total rate of relative sea level rise of about 3.0 mm yr^{-1}.

3. Materials and methods

We collected 33 undisturbed cubic sediment samples with side of 5 cm, delimited at the top by the present-day depositional interface, to study the spatial variations of the soil inorganic and organic matter content, for the determination of the inorganic (Q_i) and the organic (Q_o) accretion rates, respectively. Each sample consists of massive brownish to blackish silt and contains abundant stems and roots. Some of the samples also contained scattered mm-size bivalve and gastropod shells and/or shell fragments. The samples were collected along three 40 m long transects in two salt marshes in the Northern Venice lagoon (Fig. 1a). Transect 1 and 2 were located in the San Felice salt marsh, whereas Transect 3 was located in the Rigà salt marsh (Fig. 1b, c). At both sites the transects started on the marsh edge close