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Spatial patterns of Organic Matter content in the surface soil of the salt marshes of the Venice Lagoon (Italy)

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Abstract

Salt marshes are crucial eco-geomorphic features of tidal environments as they provide numerous important ecological functions and deliver a wide range of ecosystem services that contribute to human well-being. Being controlled by the interplay between hydrodynamics, geomorphology and vegetation, the deposition of both organic matter (OM) and inorganic sediments drives salt-marsh vertical accretion. This allows marshes to keep pace with relative sea-level rise, and likewise capture and store carbon, making them valuable allies in climate mitigation strategies. Thus, Soil Organic Matter (SOM), i.e. the organic component of the soil, plays a key role within salt-marsh environments, directly contributing to soil formation and supporting carbon storage. This study aims at inspecting spatial patterns of OM in surface salt-marsh soils, providing further insights into the physical and biological factors driving OM dynamics, affecting salt-marsh survival and carbon sink potential. Our results reveal two scales of variations in sedimentary OM content in salt-marsh soils. At the marsh scale OM variability is influenced by the interplay between surface elevation and changes in sediment supply linked with the distance from tidal channels. At the system scale, OM content distribution is dominated by the gradient generated by marine and fluvial influence. Variations in inorganic and organic inputs, both autochthonous and allochthonous, sediment grain size, and preservation conditions may explain the observed variations in SOM. Our results highlight marsh importance as carbon sink environments, furthermore emphasizing that environmental conditions within a tidal system may generate strongly variable and site-specific carbon accumulation patterns, enhancing blue carbon assessment complexity.

1. Introduction

Salt marshes may be defined as halophytic grasslands or dwarf brushwoods encroaching sediment platforms bordering saline tidal water bodies (Beeftink, 1977; Silvestri and Marani, 2004). Salt marshes lie at the upper margin of the intertidal environment and they are regularly flooded by the tides and occasionally by storm surges (Allen, 2000; Friedrichs and Perry, 2001; D’Alpaos and D’Alpaos, 2021; D’Alpaos et al., 2007; D’Alpaos, 2011). They occur worldwide, particularly in middle and high latitudes on low-energy coasts, both in microtidal and macrotidal regimes (Allen and Pye, 1992). Coastal wetlands, situated at the interface between terrestrial and marine ecosystems, often lie in some of the World’s most densely populated areas and deliver a wide range of ecosystem services that contribute to human well-being, being simultaneously some of the most economically relevant and vulnerable ecosystems on Earth (D’Alpaos and D’Alpaos, 2021; Costanza et al., 1997; de Groot et al., 2012). Salt marshes provide critical habitat for numerous species, protect coastal areas by buffering floods and wave action, improve water quality, support commercial fisheries, provide recreational opportunities and contribute to climate regulation by acting as carbon (C) sinks (e.g. Barbier et al., 2011; Boesch and Turner, 1984; Costanza et al., 1997; Lefeuvre et al., 2003; Temmerman et al., 2013; Fairchild et al., 2021; Möller et al., 2014).

However, salt-marsh ecosystems are exceptionally vulnerable to the effects of climate changes and increasing human pressure such as accelerating relative sea-level rise, declining sediment supply, and coastal land reclamation (D'Alpaos et al., 2011; Gedan et al., 2009; Kirwan et al., 2010; Marani et al., 2007; Morris et al., 2002; Mudd et al., 2004; Mudd, 2011; Temmerman et al., 2005; Silvestri et al., 2018; Breda et al., 2022) having lost between 25% and 50% of their global historical coverage (Mcowen et al., 2017).

Salt marshes are intrinsically dynamic environments and their evolution importantly depends on complex feedbacks between physical and biological components. The interplay between hydrodynamics, geomorphology and vegetation controls marsh vertical accretion, which has allowed marshes to keep pace with relative sea-level rise over thousands of years (D'Alpaos et al., 2007; Marani et al., 2007; Fagherazzi et al., 2012; Mudd et al., 2009; Allen, 2000; Mudd et al., 2004; Brückner et al., 2019). Vertical accretion in tidal marshes is driven by the deposition of both Organic Matter (OM) and inorganic sediments (Mudd et al., 2009; Fagherazzi et al., 2012; Nyman et al., 2006; Neubauer, 2008). Tides, wind waves, and storms are the main mechanisms for sediment transport, deposition or mobilisation on the marsh platform, shaping marsh morphology, which in turn influences water depth and flow velocity. Halophytic plants, spatially organized in characteristic patches related to soil elevation and hydroperiod (Bertness and Ellison, 1987; Pennings and Callaway, 1992; Silvestri et al., 2005; Silvestri and Marani, 2004), contribute considerably to marsh accretion, influencing the water flow, enhancing sediment settling, damping sediment resuspension and producing biomass, which results in OM accumulation (D'Alpaos et al., 2007; Marani et al., 2006; Mudd et al., 2009). In some cases, OM contribution to tidal marsh volume and surface accretion can be much greater than that of mineral material (Ewers Lewis et al., 2020; Morris et al., 2016; Allen et al., 2021). The organic material that helps to build marsh elevation is likely a combination of in situ production of belowground root tissue inserted into the sediments (Craft et al., 1993; Day et al., 1999) and autochthonous or allochthonous organic materials that are deposited over the surface in association with mineral sediment particles (Nyman et al., 2006; Mudd et al., 2009; Ewers Lewis et al., 2019; Mueller et al., 2019). Furthermore, tidal flooding inhibits microbial aerobic activity and slows down decomposition, fostering C accumulation in marsh soils (Keuskamp et al., 2013; Mueller et al., 2018; Kirwan et al., 2014; Morris et al., 2016). Thanks to these dynamics, the C captured through plant photosynthesis is buried and preserved as soil organic carbon (SOC) and may be locked away from the atmosphere over centennial to millennial time scales (Perillo et al., 2009; Duarte et al., 2005). The C sink function of vegetated coastal ecosystems, including salt marshes, mangrove forests and seagrass meadows, has been increasingly recognised in recent years and the term "blue carbon" was coined to indicate the C sequestered in these ecosystems, with a potential role in climate change mitigation (Chmura et al., 2003; Duarte et al., 2005; McLeod et al., 2011; Macreadie et al., 2019; Nellemann et al., 2009).

Recent models of intertidal system dynamics predict marsh evolution incorporating both physical and ecological processes (e.g. D'Alpaos et al., 2007; Kirwan & Murray, 2007; Marani et al., 2007, 2013; Morris et al., 2002; Mudd et al., 2004, 2009). However, to refine current representations of OM accumulation, a deeper understanding is needed of crucial biogeomorphological factors driving OM dynamics in tidal environments.

Drivers of Soil Organic Matter (SOM) variability in salt marshes are innately difficult to identify as SOM content is the result of many complex processes acting simultaneously. The study of the interplay between these processes is complicated by the fact that they occur over a wide range of spatial scales (Marani et al., 2006; Ewers Lewis et al., 2020).

While at the global scale, climatic parameters appear to be important drivers for C sequestration and storage (Chmura et al., 2003), at the system scale, the position within the gradient generated by marine and fluvial influence was observed to be a key predictor of organic content, with the environmental conditions resulting from the interplay between physical and biological factors (Kelleway et al., 2016; Van De Broek et al., 2016). Geomorphological factors and vegetation characteristics appear to be important drivers of organic content variability when considering fine spatial scales (e.g. Chen et al., 2016; Leonard et al., 2002; Roner et al., 2016). For instance, elevation, hydroperiod and sediment supply affect sediment deposition and organic-matter trapping capacity (Chmura et al., 2003) other than microbial community and organic-matter preservation conditions (Kirwan et al., 2013; Marani et al., 2006; Mudd et al., 2009; Yousefi Lalimi et al., 2018). The latter are influenced also by sediment type and grain size, which are additionally associated with different concentration of suspended particulate organic matter (Kelleway et al., 2016; Van De Broek et al., 2016; Saintilan et al., 2013). Therefore, sediment grain size was pointed as a key predictor of organic content by Ford et al. (2019) and Kelleway et al. (2016), whereas Van De Broek et al. (2016) reported variations in suspended sediment concentration and stable particulate OC as the main drivers of observed differences in organic storage. Considerable variability in sediment organic content has also been observed at different scales across vegetation types (Ewers Lewis et al., 2020; Saintilan et al., 2013), which determine above and belowground biomass production both quantitatively and qualitatively, in terms of decay resistance (Scarton et al., 2002; Stagg et al., 2018).

Here we aim at inspecting spatial patterns of OM in salt-marsh soils, providing further insights into the physical and biological factors driving OM dynamics, affecting salt-marsh survival and C sink potential. Toward these goals, we analysed soil organic content for the surface soil layer (0–20 cm) in 10 salt marshes of the Venice Lagoon from 60 sediment cores, together with different variables including soil, morphological and vegetation characteristics.

By contributing to a better understanding of OM distribution and its controls in tidal marshes, our study has the potential to improve spatially explicit biomorphological models of salt-marsh evolution, allowing the evaluation of marsh resilience and associated C storage as an ecosystem service. Improved representation of SOM dynamics in biomorphodynamic models will provide critical information for management and conservation strategies, favouring the identification of optimal locations and actions where to direct protection and restoration efforts.

2. Material and methods

2.1. Study site

The Venice Lagoon, situated in the northwestern Adriatic Sea (Italy), is the largest brackish tidal waterbody within the Mediterranean Sea. It is a shallow, microtidal, back-barrier system, characterized by a semidiurnal tidal regime with an average range of 1.0 m and a mean water depth over tidal flats of about 1.5 m, and is connected to the Adriatic through three inlets known as Lido, Malamocco, and Chioggia (Figure 1).

The Venice Lagoon is also highly influenced by meteorological forcings, with the south-easterly Sirocco wind responsible for severe storm surges flooding the city of Venice, north-easterly Bora wind responsible for large wind waves (Tommasini et al., 2019). The present-day morphology of the Venice Lagoon is strongly affected by the intense human pressure occurred over the last centuries, going from the diversion of the main rivers, which are now debouching out of the Lagoon, to the more recent construction of jetties at the inlets and the excavation of large navigable channels, to the rash groundwater exploitation in the 20th century. The above interventions have seriously modified sediment supply and dynamics, local hydrodynamics and morphology, together with rates of relative sea level rise, favouring sediment starvation and the deepening of the lagoon (Zecchin 2009, Brambati 2003). The recent activation of storm-surge barriers, designed to prevent flooding of the city of Venice, was proved to further alter the lagoon hydrodynamics (Mel et al., 2021) contributing to the deepening of the tidal flats and reducing salt-marsh sedimentation (Tognin et al., 2021, 2022). Salt-marsh areas of the Venice Lagoon have dramatically shrunk in the last centuries, with a decrease in extension from about 180 km^2 in 1811 to about 43 km^2 in 2002 (Carniello et al., 2009; D'Alpaos, 2010; Tommasini et al., 2019).

The study sites are located in 10 salt marshes of the Venice Lagoon, at variable distances from the inlets (Figure 1). In the northern lagoon, the Sant'Erasmo (SE), San Felice (SF) and Saline (SA) salt marshes border large tidal channels departing from the Lido inlet. These marshes host exclusively halophytic vegetation, mainly constituted by *Salicornia veneta, Limonium narbonense,* and *Sarcocornia fruticosa,* associated with *Spartina maritima, Juncus maritimus, Puccinellia palustris, Inula crithmoides, Suaeda maritima* and *Arthrocnemum macrostachyum* (Silvestri, 2000; Silvestri et al., 2005; Yang et al., 2020). In contrast, Pagliaga (PA) and Campalto (CA) sites are located at the lagoon-mainland boundary in the northern lagoon, with PA being close to the estuary of the springwater Dese River which debouches into the lagoon carrying an average 65 m^3 s^{-1} freshwater discharge and negligible sediment supply. Freshwater inputs at PA site maintain a near-freshwater plant community dominated by *Phragmithes australis*, together with the halophytic species *Juncus maritimum, Salicornia veneta* and *Halimione portulacoides* (Silvestri, 2000). The CA marsh, whose main edge faces a shallow tidal flat exposed to Scirocco wind, hosts halophytic species dominated by *Limonium narbonense,* associated with *Sarcocornia fruticosa, Spartina maritima, Salicornia veneta,* and scarce *Suaeda maritima, Triglochin maritima* and *Juncus gerardii.* In the southern part of the Venice Lagoon, the Mira (MI) marsh is close to the landward boundary and it is characterized by the presence of *Phragmithes australis* on the marsh edge, together with the halophytic species *Juncus maritimum, Puccinellia palustris, Limonium narbonense,* and *Sarcocornia fruticosa.* Canale Virgilio (CV) and Fossei (FO) are located within the marsh belt in front of Malamocco and Chioggia inlets and host halophytic vegetation consisting mainly of *Limonium narbonense, Sarcocornia fruticosa, Puccinellia palustris,* together with *Juncus maritimum, Spartina maritima, Salicornia veneta* and *Suaeda maritima.* The Conche (CO) salt-marsh fringes the mainland and faces the wide subtidal flat that occupies the central-southern Venice Lagoon, being exposed to Bora wind. CO hosts halophytic species dominated by *Sarcocornia fruticosa*, *Suaeda maritima, Inula crithmoides,* and *Halimione portulacoides.* Finally, the Valle di Brenta (VB) salt marsh, at the southern end of the lagoon, is separated from the mainland by a channel and is characterized by the dominance of *Juncus maritimum, Sarcocornia fruticosa, Limonium narbonense* and *Puccinellia palustris*, with the presence of *Triglochin maritima*. 140

Figure 1. Location of the study areas within the Venice Lagoon (Italy). Insets show the position of the 30-m-long transects (orange lines) within each study area located perpendicularly to the main marsh edge: MI, CA, PA, SA, SF, SE, VB, CO, FO, CV (Map data: ©2022 Google-Landsat/Copernicus, Maxar Technologies).

2.2. Experimental design and sample analysis

Sediment cores were collected along transects from the marsh edge to the inner part of the 10 salt marshes, for a total of 60 cores. In most cases, transects start on the marsh edge facing a channel, with the exception of CA and CO, that face tidal flats. At each site, 6 cores were collected (at a distance of 0, 2.5, 5, 10, 20 and 30 m from the edge) so as to represent morphological and vegetation zonation. At each site where a core was collected, elevation above Mean Sea Level (MSL) and geographic location were measured using a GPS in RTK mode (Leica GS16) and vegetation characteristics were surveyed within a 1 x 1 m quadrat by the Braun-Blanquet method (Braun-Blanquet, 1964) and registering species cover percentages (Table A1 in Appendix A). For each quadrat, we estimated the aboveground biomass on the basis of species cover and live plant biomass as ash-free dry weight (AFDW) for each species from literature (Table A2 in Appendix A). Shannon diversity index was used to measure the diversity of species in each sample community.

Soil samples were taken every 5 cm up to the depth of 20 cm (0, 5, 10, 15, 20 cm) from each core, collected through a Eijkelkamp auger, 3 cm diameter corer) (Howard et al., 2014) and subsamples were oven dried at 60 °C for 48 h or to constant weight and prepared for different analyses, including OM and C content, soil density, and grain size distribution. Percent OM of each sample was determined through a loss-on-ignition (LOI) procedure by combusting ~2 g of ground sediment in a muffle furnace at 375 °C for 16 h of ground samples (Ball, 1964; Frangipane et al., 2009; Roner et al., 2016). The difference in weight between pre- and post-treatment provided the OM content as a weight percentage. Percent organic C was calculated from LOI using a local conversion equation built on a subsample analysed with an Elemental Analyser (Puppin, 2023; Puppin et al., 2023b). Sediment Dry Bulk Density (DBD) was calculated from the water content, as the difference in weight between wet and dry samples, and organic and inorganic fractions, according to Kolker et al., (2009), by assuming water density = 1.02 g m^{-3}, and mineral and organic sediment density of $\rho_i = 2.6$ g m^{-3} and $\rho_o = 1.2$ g m^{-3}, respectively, knowing the inorganic sediment and OM percentage from LOI analysis (Kolker et al., 2009). The product of percent OC and DBD determined soil carbon density (SCD). Soil carbon stocks in the top 20 cm soil were calculated based on Howard et al. (2014) summing the C content in each soil interval along the core in order to better represent OM content variability within the depth interval. Inorganic particle size distribution analyses were performed, after the removal of the OM through a treatment with 35% hydrogen peroxide (H_2O_2) for 36 h, using laser granulometry (Mastersizer 2000 - Version 5.40, MALVERN INSTRUMENTS).

As to the analysis of OM content, we considered sediments up to the depth of 20 cm because we wanted to investigate the soil layer directly impacted by current vegetation. Indeed, according to Trumbore (2009), in most vegetated ecosystems the majority of underground plant biomass and microbial activity exists within the top 20 cm of soils. Conversely, in order to analyse sediment characteristics with reference to current hydrodynamics and morphological dynamics, we limited the reference depth for grain size analysis to 5 cm, considering the accreting behaviour of salt marshes.

Values of water salinity for each study area were calculated as the last-5-years mean of the quarterly measurements from the CTD multiparameter probes of the Veneto Region Environmental Protection Agency (ARPAV) (Table A3 in Appendix A).

2.3. Statistical analysis

Statistical analyses were performed using MATLAB R2021a. Analyses included the use of the Kendall test, Kruskal-Wallis H test and post hoc median comparisons. The Kendall test is a non-parametric, rank-based method, aimed to determine whether there exists a monotonic relationship between two variables of interest. The value of the τ coefficient ranges from 1 to -1, indicating a positive or a negative association, respectively. The Kruskal-Wallis test is a nonparametric version of classical one-way ANOVA using ranks of the data to compute the chi-square statistic and compare the medians of the groups of data to determine if the samples come from the same population. When Kruskal-Wallis test showed a significant difference between groups, a multiple comparison test was used to determine which pairs of means were significantly different.

3. Results

3.1. Distribution of surface sediment variables along the transects

Figure 2 and Figure 3 show the distribution of the surface sediment variables analysed, namely OM content, DBD, grain size distribution, and the vegetation cover along the surface elevation profile of study transects, in the northern and southern lagoon, respectively.

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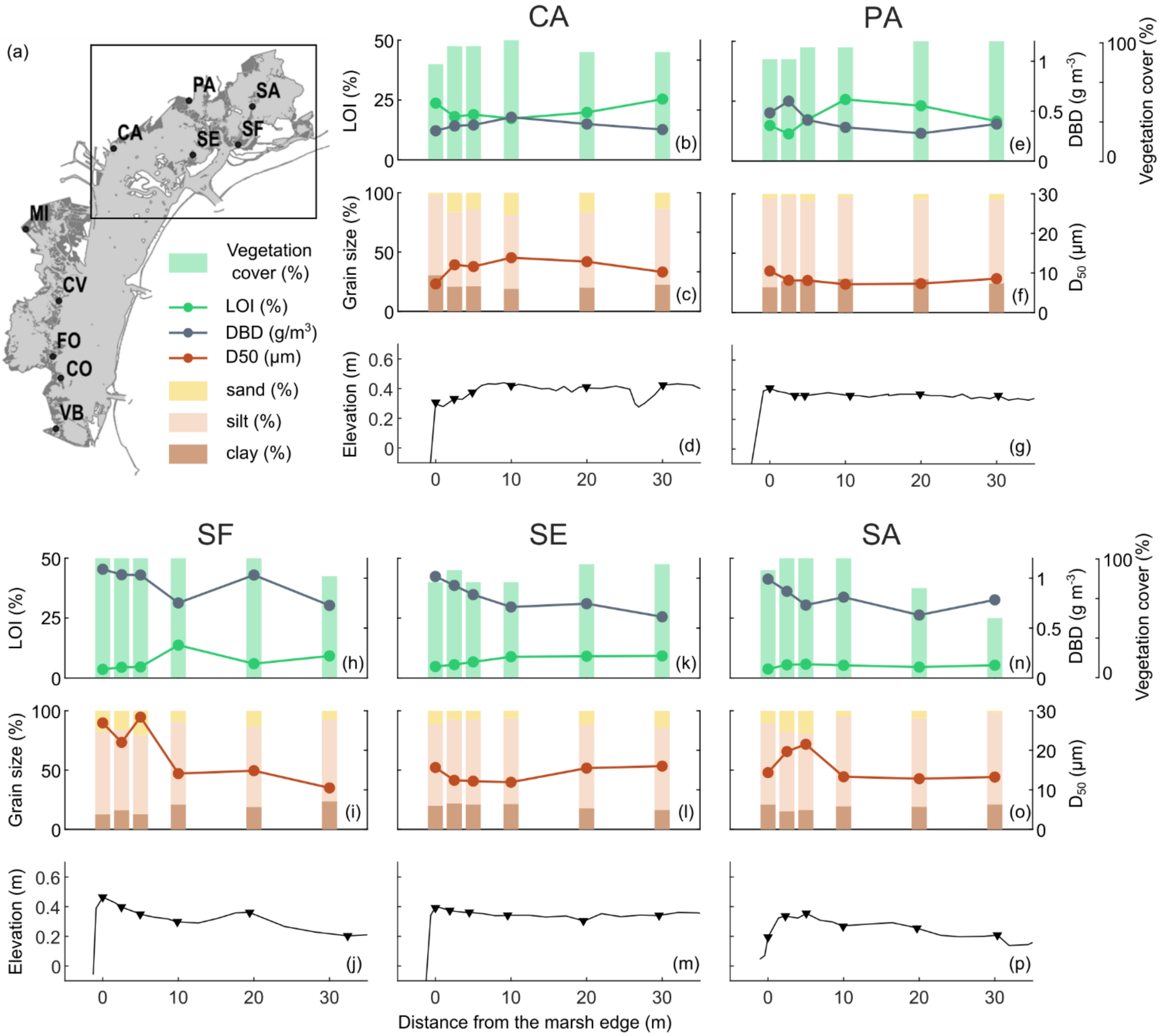


Figure 2. Distribution of surface sediment variables analysed and surface elevation profile along the transects in northern lagoon: organic matter content (LOI % - mean value in top 20 cm), Dry Bulk Density (g cm-3 - mean value in top 20 cm), vegetation cover (%), grain size distribution (D50 µm and sand-silt-clay percentage - mean value in top 5 cm) and surface elevation (m a.MSL).

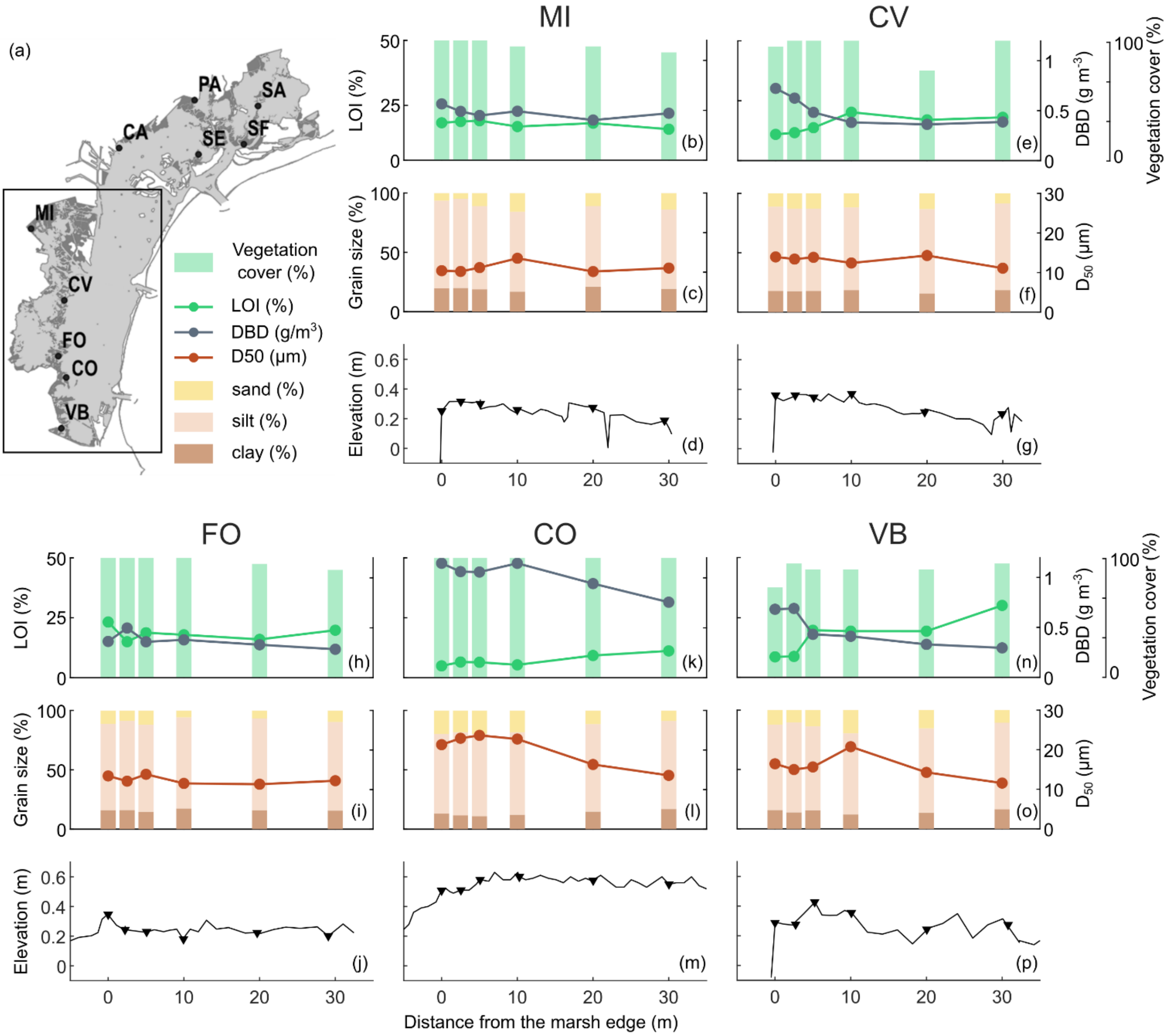


Figure 3. Distribution of surface sediment variables analysed and surface elevation profile along the transects in southern lagoon: organic matter content (LOI % - mean value in top 20 cm), Dry Bulk Density (g cm-3 - mean value in top 20 cm), vegetation cover (%), grain size distribution (D50 µm and sand-silt-clay percentage - mean value in top 5 cm) and surface elevation (m a.MSL).

The topographic GPS field surveys (Figure 2 and Figure 3, d, g, j, m, p) show that marsh surface elevations along the transects range between about 0.20 and 0.60 m above MSL. CO is the highest site, with an average elevation along the transect of 0.55 m above MSL, while FO is the lowest site, with an average elevation of 0.24 m above MSL. Surface elevations are generally higher near the marsh edge, adjacent to the channel levees, and they decrease toward the inner marsh. Some sites show a pronounced levee morphology (i.e. SF, SA and FO), while in other sites the latter is less distinct due to irregular profiles (i.e. MI, CV, VB) or flattened profiles (i.e. PA, SE). CA and CO transects, which face a tidal flat and are exposed to wave energy, are characterized by higher surface elevations toward the inner marsh, with a convex shape profile (Tognin, 2022).

The vegetation cover is generally high (never below 50%), with no detectable trends along the transects.

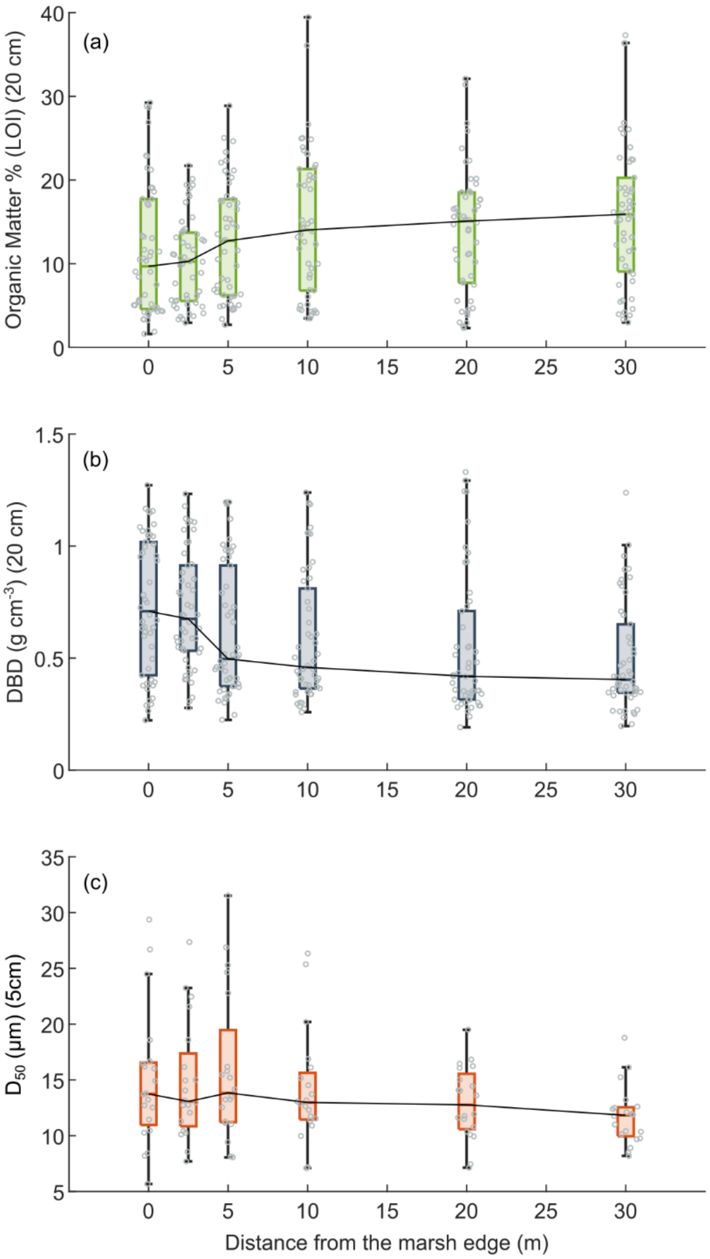
OM content in surface soils (mean value in top 20 cm) ranges between 4% and 30% (green lines in Figure 2 and Figure 3, b, e, h, k, n) and shows important differences both within and among study areas. CA, FO, PA, VB, CV and MI show generally higher organic content, with average OM content values along the transects ranging between 15 and 21%, than CO, SF, SE and SA, with average OM content values along the transects ranging between 5 and 7%. OM content trend along the transects follows a more or less marked increase toward the inner marsh in most of the study sites (e.g. CA, PA, SF, SA, CV, CO, VB).

DBD in surface soil (grey lines in Figure 2 and Figure 3, b, e, h, k, n) shows a distribution mirrored to that of OM content, with values ranging between 0.28 and 1.15 g cm^{-3}, displaying a more or less marked decrease toward the inner marsh in most of the study sites. The highest values of DBD are found at CO, SE, SF and SA sites, with average values of 1.02, 0.81, 0.94 and 0.80 g cm^{-3}, respectively.

Grain size of the surface inorganic sediment fraction (Figure 2 and Figure 3, c, f, i, l, o) ranges from clay to very fine sand, with a D_{50} (mean value in top 5 cm) ranging between 7 µm and 28 µm, with a mean value of 14 µm. Finer median grain size values are found at the PA site (average D_{50} value of 5 µm), which is characterized by higher percentages of clay. Whereas, coarser median grain size values are found in SF and CO sites (average D_{50} value of 19 and 20 µm, respectively), with the latter being characterized by some shell layers on the marsh surface. As to the distribution of the median grain size, D_{50}, along the transects, we observe coarser grains along the marsh edges (i.e. along the tidal channel levees) at SF, SA and VB. CA and CO median grain sizes show a smooth trend with coarser particles in the central part of the transects. The SE transect shows slightly coarsening sediments toward the inner marsh, bordered by a tidal flat.

3.2. Dependence of sediment variables on the distance from the marsh edge

Considering the data from all our study areas, OM content in surface soils was significantly positively correlated with the distance from the marsh edge (Kendall's tau test, $\tau = 0.1532$ p-value = 0.0002) (Figure 4 a), whereas DBD was significantly negatively correlated with the distance from the marsh edge (Kendall's tau test, $\tau = -0.2243$ p-value = 6.3002e-08) (Figure 4 b). A significant negative correlation was found also between the median sediment grain size (D_{50}) on the marsh surface and the distance from the marsh edge (Kendall's tau test, $\tau = -0.1509$ p-value = 0.0222) (Figure 4 c). Distance from the marsh edge resulted to be negatively correlated to surface elevation in our study case (Kendall's tau test, $\tau = -0.1199$ p-value = 0.0041), thus, as expected, DBD and D_{50} were positively correlated to marsh surface elevations ($\tau = 0.1387$ and 0.1966 p-value = 0.0003 and 0.0015, respectively). Nevertheless, no significant relationship was found between the OM content and surface elevation.



235 **Figure 4. Effects of the distance from the marsh edge on OM, DBD and grain size: organic matter content (LOI % - mean value in top 20 cm) (a), Dry Bulk Density (g cm^{-3} - mean value in the top 20 cm) (b), sediment median grain size distribution (D50 µm - mean value in the top 5 cm) (c). In the box plots the central mark indicates the median, the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively, the whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using a thick circle. Swarm plots show single values (circles).**

3.3. Vegetation influence on SOM

Estimated aboveground biomass was highly variable in the analysed plots, ranging between about 200 and 1500 g cm^{-2} (AFDW) and showed no significant relationship with OM content in surface soils (Figure 5 a). When considering the dominant species, OM content of marsh surface soil displayed a wide variability (Figure 5 c). Higher mean organic content was observed in the presence of *Limonium narbonense* (Figure 5 e), *Phragmites australis* (Figure 5 d) and *Puccinellia palustris* as dominant species. Although highly variable, organic content showed a significant positive correlation with vegetation species diversity (Kendall's tau test for Shannon Diversity Index H and OC stock in top 20 cm: τ = 0.2011 p-value = 0.0239; with mean SCD in top 20 cm τ = 0.1818 p-value = 0.0412) (Figure 5 b).

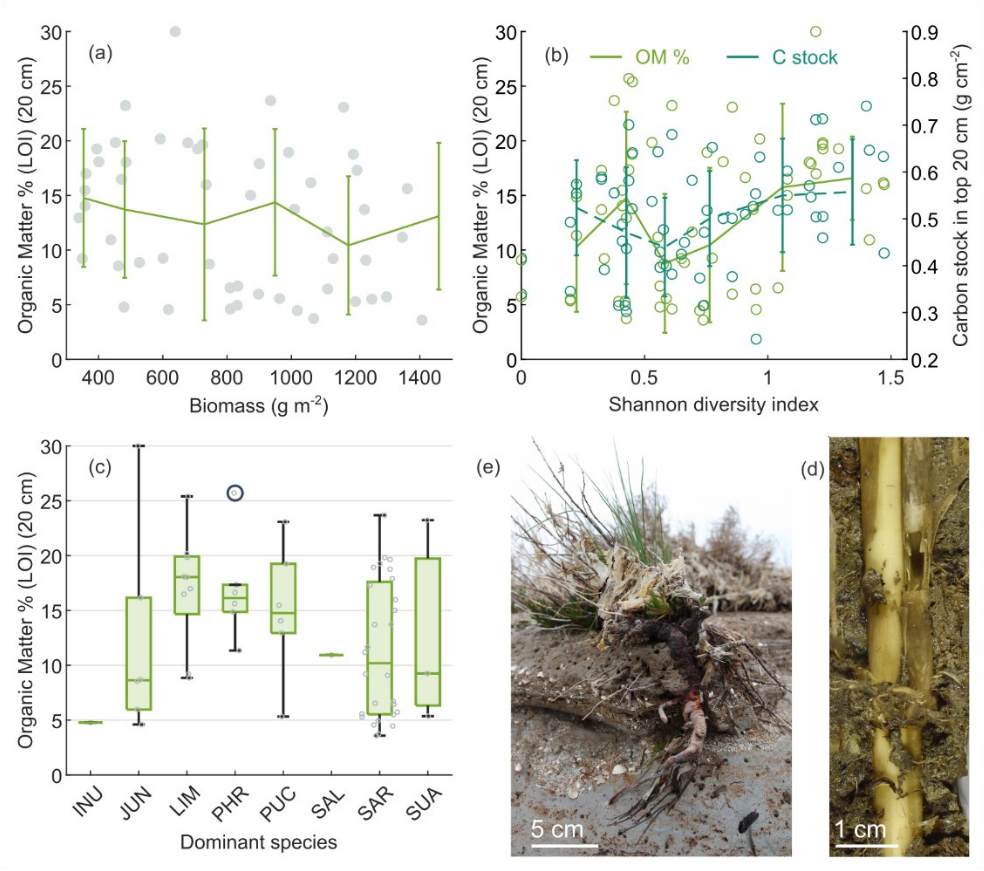


Figure 5. Vegetation influence on SOM. Organic matter content in marsh surface soils (LOI % - mean value in top 20 cm) as a function of biomass estimates (a) and dominant species (c) (INU = Inula crithmoides, JUN = Juncus maritimus, LIM = Limonium narbonense, PHR = Phragmites australis, PUC = Puccinellia palustris, SAL = Salicornia veneta, SAR = Sarcocornia fruticosa, SUA = Suaeda maritima). Organic matter content in marsh surface soils (LOI % - mean value in top 20 cm) and OC stock in top 20 cm as a function of Shannon Diversity Index H (b) in 1x1 m plot around core sites. *Limonium narbonense* roots exposed by marsh edge erosion at SE site (e) and *Phragmites australis* roots and stems within PA site soil (d). Panels (a) and (b) show median and standard deviation of binned values. In the box plots the central mark indicates the median, the bottom and top edges of the box indicate the

25th and 75th percentiles, respectively, the whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using a thick circle. Swarm plots show single values (circles).

3.4. Variability of sediment characteristics among study sites

As to the variability of marsh soil characteristics in different areas, the Kruskal-Wallis analysis indicated that there was a significant difference between OM content in the 10 sites (p-value = 4.49285e-34), and the post hoc test confirmed that CO, SA, SE and SF have significantly lower mean OM content in surface soil (Figure 6 a). Study sites were characterized by different mean water salinity ranging between 24.3 and 32.4 ‰, which revealed a significant negative relationship with OM content (Kendall's tau test, $\tau = -0.2574$ p-value = 0.0061). CO, SA, SE and SF also show significantly higher values of DBD (Kruskal-Wallis, p-value = 2.31627e-36) (Figure 6 b).

Mean SOC density in the top 20 cm (product of percent OC, which is function of OM, and DBD determined) ranged between 0.014 and 0.026 g cm^{-3} with lower values at SA, SF and SE (Figure 6 b). Carbon stock in top 20 cm ranged between 0.31 and 0.58 g cm^{-2} with lower values at SA, SF and SE (Figure 6 c). CO, which showed mean organic matter percentage similar to SA, SF and SE, displays, in contrast, higher values of SCD and C stock compared to SA, SF and SE, due to particularly high DBD values at this site.

Median sediment grain size (D50) on marsh surface was not equal in different study sites (Kruskal-Wallis, p-value = 9.96865e-11), although not showing clear distribution patterns (Figure 6 d).

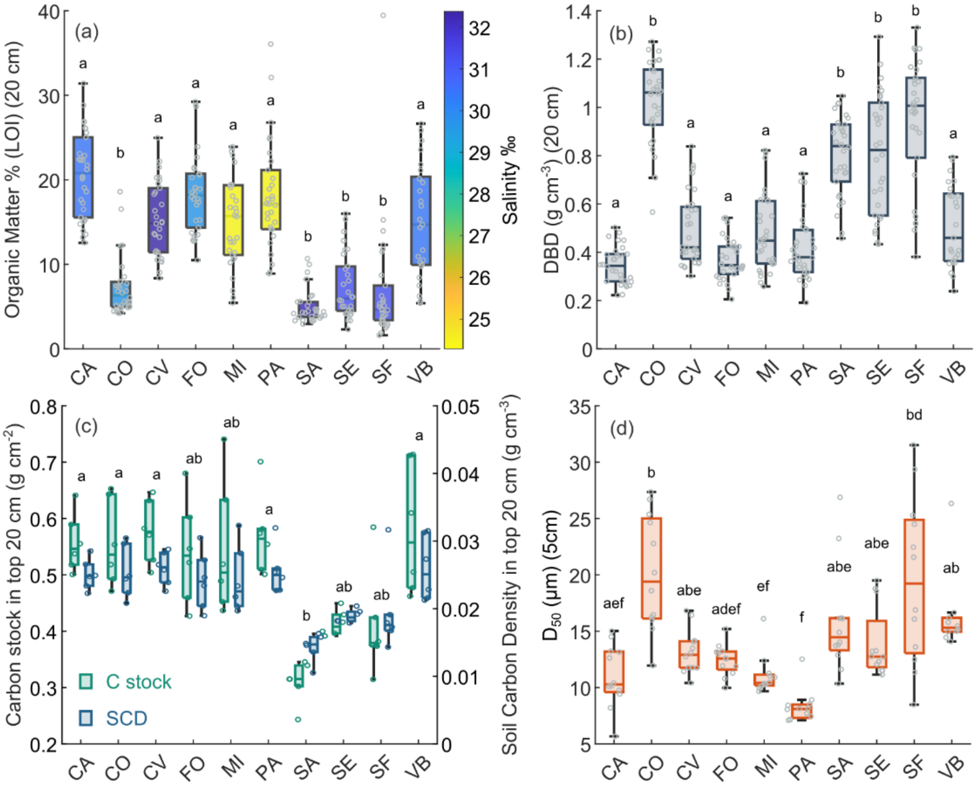


Figure 6. Surface sediment variables at different study sites: organic content (LOI % - mean value in top 20 cm) and water salinity at each study area (a), grain size distribution (D50 µm and sand-silt-clay percentage - mean value in top 5 cm) (b), Dry Bulk Density (g cm^{-3} - mean value in top 20 cm) (c), OC stock in top 20 cm (g cm^{-2}) and SOC Density (g cm^{-3} - mean value in top 20 cm) (d). In the box plots the central mark indicates the median, the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively, the whiskers extend to the most extreme data points not considered outliers. Swarm plots show single values (circles). Different letters above the box plots indicate significant difference on the basis of Kruskal-Wallis test and post hoc multiple comparison test (when two groups do not show a significant difference, then they have at least one letter in common).

4. Discussion

4.1. Elevation profiles and grain size characteristics

Tidal currents deliver suspended sediments onto the marsh platform through inundation by apical flow at creek heads and by overbank flow along tidal channels (Torres and Styles, 2007). As soon as the flow reaches the vegetated marsh platform, current velocities and turbulent energy rapidly decrease (D'Alpaos et al., 2007; Mudd et al., 2010), thus promoting the deposition of coarser and more abundant sediments in proximity of the channel edges (Christiansen et al., 2000; Roner et al., 2016). Indeed, elevation profiles and grain size characteristics observed along the transects reflect sediment supply dynamics, with the formation of levees along the tidal channels and the presence of coarser sediments on their top (Figure 2 and Figure 3), where tidal current flow is firstly slowed down favouring coarser particle settling. The increasing elevations and the grain size coarsening observed at the inner end of SE transect are likely due to the presence of a tidal flat at the inner border of the salt marsh, representing another source of sediment supply.

The general pattern of sediment grain size is confirmed when considering all data together (Figure 4 b), as median sediment grain size (D50) on the marsh surface was found to be significantly correlated to the distance from the marsh edge and to surface elevations.

Interestingly, CA and CO transect, which are located on marsh edges adjacent to tidal flats and exposed to energetic wind-waves, displayed different surface morphology, characterized by higher surface elevations toward the inner marsh, and sediment grain size patterns (Figure 2 and Figure 3) likely due to wave action pushing sediments and coarser particles further toward the inner marsh, as observed by (Duvall et al., 2019).

At the lagoon scale, higher values of median grain size were observed at sites closer to the inlet (i.e., SF, SE) or adjacent to first order channel connected to them (SA) (Figure 6 d), whereas higher fractions of fine sediments were observed at the lagoon-mainland boundary, near to the Dese River mouth (PA) (Figure 2). This pattern is consistent with the general grain-size gradient observed in the Venice Lagoon, reflecting the typical pattern of decreasing hydrodynamic energy conditions from the inlets to the landward shore (Zonta et al., 2018). Accordingly, marsh edge levees seem to be more pronounced along the main channels departing from the inlets and influenced by hydrodynamic conditions along those channels.

4.2. Organic content variability

The OM content in salt-marsh soils is likely a combination of in situ production of belowground biomass (root, rhizome and tuber tissue) inserted into the sediments (Craft et al., 1993; Rybczyk et al., 2002) and autochthonous or allochthonous organic materials that are deposited on the salt marsh (Nyman et al., 2006, Mudd et al., 2009, Ewer Lewis 2019, Mueller 2019). Spatial patterns in OM content are influenced by different conditions such as sediment supply, primary production and decomposition rates (Nyman et al., 2006; Morris et al., 2016; Kolker et al., 2009; Turner et al., 2002; Kirwan et al., 2013; Mudd et al., 2009). Overall, our data reveal two scales of variations in sedimentary OM content: one occurs on the order of meters to tens of meters along the transect, and another one is associated with the lagoon scale. The topographic and textural sedimentological features of the salt marsh can influence a range of biological and physical processes and consequently affect the distribution of OM content (Chen et al., 2016). These features reflect sediment supply dynamics from the marsh edge (i.e. sediment source) to the inner marsh, together with the dynamic feedbacks between surface elevation and primary productivity and vegetation characteristics (Perillo et al., 2009). Consistently with previous findings (e.g. Chen et al., 2016; Leonard et al., 2002; Roner et al., 2016) and despite a considerable variability, we found a significant correlation between OM content in surface soils and the distance from the marsh edge, with organic content generally increasing toward the inner marsh. The inner marsh areas, often displaying lower elevations, are suggested to be characterized by better preservation conditions, as anaerobic environments in frequently flooded sites reduce microbial respiration, slowing down organic matter decomposition (Halupa and Howes, 1995; Kirwan et al., 2013; Puppin et al., 2023a; Roner et al., 2016). In addition, finer sediment grain size in inner marsh areas may affect OM preservation conditions, through a reduced oxygen exchange due to lower porosity and drainage capacity and through their greater potential for protection of C by means of organic-mineral interaction and micro- or macro-aggregates (Kelleway et al., 2016). Furthermore, the enriched OM content of inner marsh may also be explained by the different sources of material available for salt marsh accretion across the platform (Miller et al., 2022). Due to the preferential deposition of the denser inorganic fraction of suspended sediments within tidal flow during the initial phase of inundation, inorganic sediment is mainly deposited near the marsh edge, whereas the inner marsh is supplied with more organic material due to, the transport and deposition of less dense organic particles, in addition to in situ decaying vegetation (Leonard et al., 2002; Miller et al., 2022). Organic supply includes allochthonous particulate OM and organic debris and wrack deposited during storms (Miller et al., 2022), and autochthonous plant litter collected and moved above the marsh platform (Leonard et al., 2002).

As different species have different biomass productions and different resistance against decomposition, the type of vegetation populating the different marsh areas is another possible controlling factor for SOM content (e.g. Van De Broek et al., 2016; Ewers Lewis et al., 2020; H Ford et al., 2019; Saintilan et al., 2013; Yuan et al., 2020). However, we observed no detectable trend of vegetation cover or plant biomass along the transect, nor a significant relationship between OM content and aboveground biomass estimates (Figure 5 a and c). In fact, a major influence was expected by belowground biomass, which inserting into the sediments directly contributes to SOM content (Craft et al., 1993; Rybczyk et al., 2002), and, unfortunately, lacks sufficient available estimates. Thus, our results suggest that aboveground species productivity is not a determinant in SOM at our study area. Furthermore, our aboveground biomass estimates neglect intraspecific biomass variability at the catchment scale, which could be represented only through direct measurements.

While our data do not allow for a full statistical analysis of the relationship between OM content and vegetation type, we observed higher mean OM content in presence of *Limonium narbonense*, *Phragmites australis* and *Puccinellia palustris*. We also observed that *Phragmites australis* is characterized by a high belowground biomass, forming a dense and deep network of leathery stems, roots and rhizomes (Moore et al., 2012; Scarton et al., 2002) (Figure 5 e), *Limonium narbonense* produces massive woody roots (Figure 5 d) and *Puccinellia maritima* creates a dense root mat (Brooks et al., 2021), which can importantly contribute to SOM content quantitatively and qualitatively, as belowground litter decomposition was observed to decline with increasing lignin content (Stagg et al., 2018). In addition, OM content showed a significant positive correlation with vegetation species diversity (Figure 5 b), in agreement with Ford et al., 2019. Ford et al. (2016) found that plant species richness was one of the most important explanatory variables of root biomass and Xu et al. (2020) suggested that species richness may increase biomass productivity due to multiple mechanisms including competition reduction, niche complementarity, selection effects, and biotic and abiotic facilitation.

At the catchment scale, the position within the gradient generated by marine and fluvial influence was previously observed to be a key predictor of organic content (e.g. Van De Broek et al., 2016; Ewers Lewis et al., 2020; Kelleway et al., 2016; Macreadie et al., 2017). Our results show lower mean OM content in surface soil in areas which are directly affected by marine influence, being closer to the inlets or along the main channels leading away from them (CO, SE, SF, SA) (Figure 6 a). Conversely, higher OM contents were observed at sites closer to the mainland. In agreement with this result, a significant negative relationship was observed between OM content and water salinity. This tendency meets observations from other studies (e.g. Van De Broek et al., 2016; Gorham et al., 2021; Hansen et al., 2017; Omengo et al., 2016) which attribute OM content increase toward the mainland to an increasing supply of already stabilized organic suspended particles from terrestrial sources and increasing macrophyte biomass. However, in the Venice Lagoon, after historical river diversions, fluvial supply of organic and inorganic material dramatically decreased. Freshwater inputs currently flow in the lagoon through twelve main tributaries distributed along the landward boundary of the lagoon, with a mean annual contribution of about 35 m^3 s^{-1} and a peak discharge of 344 m^3 s^{-1} (Zuliani et al., 2005). In addition, spatial and temporal variability of salinity in the Venice Lagoon is influenced by groundwater inputs (Gieskes et al., 2013). Estimates of the volume of underground freshwaters entering the lagoon floor vary widely, from 15% of total freshwater flow to more than 100% (Zirino et al., 2014). Another hypothesis is that at sites where inorganic sediment inputs are greater, soil organic fraction is lower due to a dilution effect, reproduction of organogenic and minerogenic behaviour of salt marshes at different scales (Allen, 2000). Furthermore, considering the landward decreasing grain-size gradient observed within the lagoon, enhanced C preservation capacity of fine sediments (Kelleway et al., 2016) may have a role in the observed organic content pattern. However, as previous observations suggest an inverse relationship between soil salinity and decomposition (Hemminga et al., 1991; Wang et al., 2019), it is unlikely that salinity as such directly controls soil organic content, being this effect overcome by the co-occurring effect of freshwater inputs.

As a consequence of organic content variability, C stock and SOC density show irregular values in different salt marshes, enhancing the complexity of blue C assessment. Based on our estimates of mean SOC density in top 20 cm, and considering for salt marshes in equilibrium with RSLR an expected accretion rate of about 0.3 cm yr^{-1} (Day et al., 1998), the average C accumulation rate for the Venice Lagoon salt marshes is estimated to be approximately equal to 69 g C m^{-2} yr^{-1}. Our result is consistent with the mean C accumulation rate in the Australian tidal marshes of 54.52 m^{-2} yr^{-1} calculated by Macreadie et al. (2017) from 323 soil cores to the depth of 30 cm all around Australia and using a mean accretion rate of 0.21 cm yr^{-1}. However, we observed that, under the same accretion rate, estimated SOC from our study may result in C accumulation rates varying up to 50% from one place to another.

4.3. Dry Bulk Density

Soil density is influenced both by OM content and grain size: various researchers found a strong and negative correlation between SOM and bulk density (e.g. Holmquist et al., 2018; Morris et al., 2016) and sand content showed a positive correlation with the soil bulk density (Tanveera et al., 2016). Our results further confirm this relationship showing higher soil densities along marsh edges and at CO, SE, SF and SA sites, where organic content is generally lower and coarser sediments are found.

Conclusions

Overall, our data reveal two scales of variations in sedimentary OM content in salt marsh soils. One occurs at the marsh scale and is influenced by the interplay between surface elevation and sediment supply dynamics along the distance from the marsh edge. The other occurs at the basin scale, dominated by the gradient generated by marine and fluvial influence.

Our results show that OM content generally follows an inverse relationship with the distance from the marsh edge and, broadly, is greatest in salt marshes subjected to freshwater inputs and characterized by the presence of fine-grained sediments. Although the interplay between physical and biological factors makes it difficult to unravel the direct cause-effect relationship, variations in allochthonous inputs, sediment grain size and/or preservation condition may explain the observed variation in SOM. Our data on local vegetation do not allow us to detect plant community characteristics controlling overall variations in SOM. Hence, we highlight the need for further analyses of quantitative and qualitative characteristics of different tidal marsh vegetation types. However, species diversity was observed to be an important factor influencing SOM content.

The observations on marsh morphology and grain size distribution further emphasize the interplay between hydrological, morphological and biological dynamics.

Our data on the spatial distribution of SOM provide additional insights on organic matter dynamics in salt marshes and constrain model representations of SOM accumulation, improving biogeomorphological model ability to describe marsh response to the effects of climate change and anthropogenic perturbation. Furthermore, our analyses further elucidate marsh importance within the global C cycle. Finally, our findings may inform conservation strategies and restoration interventions, giving directions on salt-marsh type prioritisation. They also provide valuable information on conditions promoting OM storage and preservation, such as the maintenance or recovery of freshwater inputs, the supply of finer sediments, and the enhancement of vegetation diversity.

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Appendix A

Site	*Inula crithmoides*	*Aster tripolium*	*Limonium narbonense*	*Salicornia veneta*	*Sarcocornia fruticosa*	*Spartina maritima*	*Halimione portulacoides*	*Suaeda maritima*	*Pucinellia palustris*	*Juncus maritimus*	*Phragmites australis*	*Triglochin maritima*	*Soil (%)*
SF1			+		3		3						0
SF2			+		4					3			0
SF3					2					4			0
SF4					1					1			0
SF5			1		3					3			0
SF6			3	2									15
CO1	3		+		3								0
CO2	3	+	+		3			1					0
CO3					4		2	2					0
CO4							1	1					0
CO5		+			3			4	+				0
CO6					1		2	+					0
SE1	4				2								20
SE2			2		4				+				10
SE3			2		4								20
SE4			3		2								20
SE5					1								5
SE6			1		1								5
PA1		1									1		15
PA2		1									1		15

Site	*Inula crithmoides*	*Aster tripolium*	*Limonium narbonense*	*Salicornia veneta*	*Sarcocornia fruticosa*	*Spartina maritima*	*Halimione portulacoides*	*Suaeda maritima*	*Pucinellia palustris*	*Juncus maritimus*	*Phragmites australis*	*Triglochin maritima*	*Soil (%)*
PA3		1									1		5
PA4		1									1		5
PA5		1								3	3		0
PA6		1					+			2	4		0
SA1			1		1	1							10
SA2					1				1				0
SA3					1								0
SA4			1		1				1				0
SA5			+	1	2				2				25
SA6			+	1					3				50
CV1	2		1	3				1	2				5
CV2			+		1	1			1				0
CV3			1		4	1			1				0
CV4			4		2	1			1				0
CV5			3	1		1		+		2			25
CV6			3		1				1	2			0
FO1					2			4					0
FO2				2	3			2	+				0
FO3					1	+		1	1				0
FO4			1		4	1		1	1				0
FO5			1	1	3	1			2	1			5
FO6			1	1	2				2				10

Site	*Inula crithmoides*	*Aster tripolium*	*Limonium narbonense*	*Salicornia veneta*	*Sarcocornia fruticosa*	*Spartina maritima*	*Halimione portulacoides*	*Suaeda maritima*	*Pucinellia palustris*	*Juncus maritimus*	*Phragmites australis*	*Triglochin maritima*	*Soil (%)*
MI1			1		2		1			1	2		0
MI2		1	1		2		1			2	1		0
MI3		1	4	1	1					1	1		0
MI4		1	1						1				5
MI5		1	1						1				5
MI6		1	1						1				10
CA1			1		4								20
CA2			4		1	1						1	5
CA3			1		4				1				5
CA4					1				1				0
CA5			4		2								10
CA6			4						1				10
VB1		1	2		1				1	2			25
VB2					2					4			5
VB3			1		2				1	2		1	10
VB4			2		2				1	2			10
VB5		2	1						3	1			10
VB6			1		2				1	3			5

Table A 1. Vegetation survey. Species composition at each studied site following Braun-Blanquet cover-abundance scale (5 = 75-100 %; 4 = 50-75 %; 3 = 25-50 %; 2 = 5-25 %; 1 < 5 % numerous individuals; + < 5 % few individuals). 410

Species	Live plant biomass (AFDW g m^2)	Source
Inula crithmoides	366	1
Aster tripolium	545	2
Limonium narbonense	276.3	3
Salicornia veneta	657.7	3
Sarcocornia fruticosa	1296.7	3
Spartina maritima	370.7	3
Halimione portulacoides	1540.7	3
Suaeda maritima	135.42	4
Pucinellia palustris	372.7	3
Juncus maritimus	601.3	3
Phragmites australis	1855	5
Triglochin maritima	500	6

Table A 2. Aboveground biomass. Live plant biomass as ash-free dry weight (AFDW) for the species found in our study area. 1 = Zurayk & Baalbaki (1996) ; 2 = Ingegnoli & Giglio (2004); 3 = Scarton (2006) ; 4 = Mitra et al. (2005); 5 = Windham (2001); 6 = Kibby et al. (1980). 415

Study site	ARPAV station	Mean salinity (ppt)	Standard deviation
CA	PNC1_7B	30.45	2.94
CV	ENC1_4	32.38	2.02
FO	ENC1_VS/PC2_16B	29.81	3.80
MI	PC4_10B	24.6	5.45
PA	PC1_1B/PNC2_2	24.29	1.03
SA SF	EC_Ve8	32.16	2.30
SE	PNC2_SG	31.21	2.40
VB	PC3_VDB	30.57	2.57

Table A 3. Water salinity. Values of water salinity for each study area as the last-6-years mean (2016-2022) of the quarterly measurements from the CTD multiparameter probes of the Veneto Region Environmental Protection Agency (ARPAV).

Data availability

The datasets needed to evaluate the conclusions in the paper are available at link https://researchdata.cab.unipd.it/id/eprint/709. Salinity data for the Venice Lagoon are also freely available at https://www.arpa.veneto.it/dati-ambientali/open-data/file-e-allegati/soaml/laguna-di-venezia/dati-sonda

Author contribution A.P., D.T., A.D. and M.M. designed the study. A.P., D.T., A.D. and M.M. developed the methodology. A.P. and D.T. collected the data and performed laboratory analyses. E.F. and N.R. provided the instrumentation and tools for grain-size analysis. A.P. and D.T. were responsible for data analysis and interpretation with the supervision of A.D., M.M. and M.G. All the authors discussed the data and agreed on their interpretation. A.P. wrote the original draft. D.T., A.D., M.G. and M.M. provided comments and suggestions to improve the original draft. All the co-authors contributed to the final polishing of the manuscript.

Competing interests The authors declare that they have no conflict of interest.

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