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Depth-Distribution Patterns of Soil Organic Matter in the Tidal Marshes of the Venice Lagoon (Italy): Signatures of Depositional and Environmental Conditions

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Key Points:

- Changes in the depositional environment crucially impact organic matter depth distribution, and need consideration in blue carbon assessment
- Marshes exhibit double the organic matter density of transition zones and tidal flats, with brackish marshes exceeding salt marshes
- High organic content was observed in fine sediments, which are associated with a strong potential for protecting organic matter from decay

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Salt marshes are depositional landforms lying at the upper margin of intertidal environments. They provide a diverse range of valuable ecosystem services and yet are exceptionally vulnerable to climate change and human pressure. Salt marshes are intrinsically dynamic environments, shaped by complex feedback between hydrodynamic, morphological, and biological processes. Soil Organic Matter (SOM) has a crucial role within salt marsh environments, as on the one hand, its accumulation contributes to the build-up of marsh elevation which is necessary for marshes to keep pace with sea-level rise, and on the other it supports the high carbon sink potential of wetlands. To better understand variations in SOM depth distribution and further comprehend SOM drivers, we analyzed soil organic content in 10 salt marshes of the microtidal Venice Lagoon from 60 sediment cores to the depth of 1 m, relating SOM spatial and vertical patterns to the temporal and spatial variability of depositional sub-environments recorded in the study deposits. Our results suggest that changes in the depositional environment are of primary importance in determining organic matter depth distribution and caution is needed in SOM prediction at unsampled soil depths. We observed relationships between SOM vertical patterns and factors such as autochthonous and allochthonous organic inputs, sediment properties, relative sea level rise, fluvial inputs and wave action. Our findings emphasize the considerable carbon storage potential of marshes in intertidal environments and provide a conceptual framework for understanding the dynamics of SOM and their drivers, which can inform and enhance coastal management strategies.

Plain Language Summary

Salt marshes are crucial coastal ecosystems periodically inundated by tides, supporting salt-tolerant plants and offering vital services like carbon storage, coastal protection, and biodiversity. Despite their significance, salt marshes face threats from climate change and human activities. Organic matter in marsh soil plays a pivotal role, contributing to marsh elevation for resilience against sea-level rise and fostering a high carbon sink potential. Salt marshes as "blue carbon" sinks are key in climate strategies, yet uncertainties persist in estimating salt marsh carbon stock and sequestration. To address this, we analyzed soil organic content in 10 salt marshes of the Venice Lagoon, examining variability in depositional and environmental conditions through sedimentological analysis. Our findings underscore the paramount influence of changes in the depositional environment on the depth distribution of organic matter. The evolution from tidal flats to marshes affects hydrodynamic, morphological, and biological conditions, leaving distinctive imprints on sediment deposits. Furthermore, current or past freshwater inputs, vegetation type and sediment supply and characteristics were identified as significant contributors to variations in soil organic matter. This study underscores marshes' role as carbon sinks and the complex, site-specific carbon patterns, informing coastal management strategies.

1. Introduction

Salt marshes are depositional landforms lying at the upper margin of the intertidal environment (Beeftink, 1977; FitzGerald & Hughes, 2021). They are characterized by the presence of vegetation mostly dominated by herbaceous halophytes adapted to regular inundation by saltwater (Perillo et al., 2009; Silvestri & Marani, 2004) and occur on low-energy coasts worldwide, particularly in middle and high latitudes, from micro- to macrotidal regimes (Adam, 1990; J. R. L. Allen & Pye, 1992; Mcowen et al., 2017). Salt marshes deliver a wide range of ecosystem services that contribute to human well-being, including carbon (C) storage, coastal protection and increase in biodiversity (e.g., Barbier et al., 2011; Boesch & Turner, 1984; Costanza et al., 1997; Lefeuvre et al., 2003; Temmerman et al., 2013). However, salt marsh ecosystems are exceptionally vulnerable to the effects of climate change and increasing human pressure, such as accelerating relative sea-level rise, declining sediment supply and coastal land reclamation (D'Alpaos et al., 2011; Fagherazzi et al., 2020; Gedan et al., 2009; Kirwan et al., 2010; Marani et al., 2007; Morris et al., 2002; Mudd, 2011; Silvestri et al., 2018; Temmerman et al., 2004), having lost between 25% and 50% of their global historical coverage (Crooks et al., 2011; Duarte et al., 2008).

Salt marshes are dynamic components of the intertidal system, shaped by intricate feedbacks between hydrodynamic, morphological, and biological processes (e.g., D'Alpaos et al., 2007; Marani et al., 2006, 2013; Mudd et al., 2009). Key factors such as tidal range, sea level fluctuations, sediment supply and vegetation drive the formation and evolution of these environments. Salt marsh landforms typically arise through the vertical accretion of a muddy to sandy sedimentary platform above some critical elevations, at which conditions become suitable for the settlement of pioneer vegetation (Balke et al., 2014; Hu et al., 2015; Perillo et al., 2009; Silvestri & Marani, 2004; Silvestri et al., 2005). The growth of salt marsh vegetation influences the water flow, favors sediment trapping and deposition, and stabilizes the marsh platform, favoring its vertical accretion and enabling it to keep pace with relative sea level rise (e.g., D'Alpaos et al., 2007; Kirwan and Murray, 2007; Leonardi et al., 2018; Marani et al., 2007, 2013; Mudd et al., 2009). Furthermore, in situ production of belowground biomass, composed by, for example, roots, rhizomes and tuber tissues (Craft et al., 1993; Rybczyk & Cahoon, 2002) and autochthonous or allochthonous organic debris that are deposited over the salt marsh surface (Ewers Lewis et al., 2019; Mudd et al., 2009; Mueller et al., 2019; Nyman et al., 2006), directly contribute to soil formation. Although the organic matter (OM) content varies markedly between systems driven primarily by the accumulation of internally produced organic material and those characterized by the deposition of inorganic sediments (Perillo et al., 2009), soil organic matter (SOM), owing to its high porosity and low density, may contribute 1.5–3 times more toward vertical accretion than inorganic matter, having a key role in the persistence of coastal wetlands with low mineral sediment supply (J. R. Allen et al., 2021).

Vertical accretion and SOM accumulation dynamics give salt marsh environments a great potential for C storage and accumulation, as the C captured through plant photosynthesis is buried and preserved in SOM over centennial to millennial time scales (Duarte et al., 2005; Perillo et al., 2009), also thanks to anaerobic tidal conditions slowing down OM decomposition (Keuskamp et al., 2013; Kirwan et al., 2014; Morris et al., 2016; Mueller et al., 2018; Puppin et al., 2023). This provides the opportunity to include salt marsh conservation and restoration among greenhouse-gas-offset activities in climate mitigation strategies, increasing the scientific and policy interest toward SOM dynamics in salt marsh environments (e.g., Macreadie et al., 2017; McLeod et al., 2011; Puppin, Tognin, Paccagnella, et al., 2024; Saintilan et al., 2013). Thus, organic matter plays a key role in salt marsh dynamics as it strongly contributes to marsh surface accretion, furthermore feeding the high C sink potential of these environments.

Distribution patterns of SOM in salt marshes may vary in space and time across the range of tidal wetland types and within individual wetlands depending on different conditions such as sediment supply and primary production (Kolker et al., 2009; Morris et al., 2016; Nyman et al., 2006; Turner et al., 2002). Numerous authors suggest geomorphic setting as the most important predictor of SOM content, with fluvially-influenced sites having twice the stocking capability in comparison with seaward-placed sites (e.g., Kelleway et al., 2016; Macreadie et al., 2017). SOM variations may be due to differences in vegetation types (Ewers Lewis et al., 2020; Saintilan et al., 2013), both in terms of in situ biomass production and recalcitrant tissue variations (Scarton et al., 2002; Stagg et al., 2018), sediment and stable allochthonous OM supply (Van de Broek et al., 2016), and sediment grain size (Ford et al., 2019; Kelleway et al., 2016; Mariottiet al., 2020).

In response to the increasing demand for estimation and mapping of soil organic carbon (SOC) storage at large spatial scales, in order to reduce sampling efforts, numerous studies have proposed predictive models for SOM in salt marshes (e.g., Bai et al., 2016; Ford et al., 2019; Wiese et al., 2016). The exponential depth model is the most widely accepted in SOM vertical distribution modeling (Bai et al., 2016; Wiese et al., 2016). The strong decline of SOM content with soil depth is attributed to the contribution of roots and the effect of decomposition (Balesdent & Balabane, 1996; Mueller et al., 2019; Sokol et al., 2019; X. Yang et al., 2023). However, besides the effect of root distribution and OC decay down-core, spatial and temporal variations in organic and inorganic sediment accumulation, related to the ontogeny of salt marsh environments, should be reflected in SOM distribution (Miller et al., 2022). Variations in organic content were reported for deposits accumulated in different intertidal depositional environments (Brevik & Homburg, 2004), thus the investigation of stratigraphic patterns and interpretation of related paleo-environments may be crucial for the representation of SOM depth-distribution.

Although our understanding of the factors influencing SOM in coastal wetlands has advanced, there remains a significant gap in comprehending how the interaction among various drivers (e.g., vegetation type, surface accretion rate, sediment supply) is reflected in the stratigraphic record. Current models rely on strong simplifications of ecomorphodynamic processes, limiting their accuracy. Therefore, further investigation is required to improve model representation of SOM distribution in these heterogeneous and dynamic intertidal landscapes. Enhancing SOM and SOC distribution representation is crucial for accurate C assessments and effective planning of greenhouse-gas-offset activities.

The aim of our study is to better understand SOM depth distribution variations across different depositional sub-environments on a system-wide scale, while also identifying the key drivers influencing salt marsh resilience and C sink potential. Toward these goals, we analyzed soil organic content in 10 salt marshes of the microtidal, sediment-starved Venice Lagoon using 60 sediment cores to the depth of 1 m. We examined SOM spatial and vertical patterns in relation to temporal and spatial variability of depositional sub-environments recorded in the study deposits. Furthermore, we applied the widely accepted exponential SOM vertical distribution model to test its applicability and develop a framework that could lead to a more accurate model, capable of capturing the observed complexities. The Venice Lagoon offers a nearly unique case study shaped by the interplay of natural forces and human interventions over the past centuries. This context allows us to analyze the impacts of various drivers, which are also significant on a broader scale, supported by a wealth of historical data that enriches our understanding of these dynamics.

2. Materials and Methods

2.1. Study Site

The Venice Lagoon is a back-barrier system located in the north-western Adriatic Sea, Italy, and connected to it by three inlets, namely Lido, Malamocco, and Chioggia (Figure 1). It is a shallow lagoon (average depth of tidal flats and subtidal platforms of about 1.5 m), with a total extent of about 550 km^2, and a semi-diurnal micro-tidal regime with an average tidal range of 1.0 m. The present-day morphology of the Venice Lagoon is the result of the joint effect of natural forcings and human interventions that occurred over the last centuries. To preserve channel and port functions, several hydraulic works have been carried out, which modified sediment supply, local hydrodynamics and the morphological setting, favoring sediment starvation and the deepening of the lagoon (Brambati et al., 2003; L. D'Alpaos, 2010; Zecchin et al., 2009). Between 1400 AD and 1600 AD the diversion of the major tributaries dramatically decreased the fluvial sediment input in the lagoon (Figure 1) and since 1800 the excavation of new deep canals together with inlet modifications exacerbated sediment export toward the sea (Brambati et al., 2003; L. D'Alpaos, 2010; Finotello et al., 2023). Furthermore, intertidal areas were reclaimed to provide industrial and urban space, and between 1930 and 1970 intense groundwater exploitation for industrial purposes enhanced local subsidence (Brambati et al., 2003). As a consequence, salt marsh areas of the Venice lagoon have dramatically shrunk in the last centuries, with a decrease from about 180 km^2 in 1811 to about 43 km^2 in 2002 (Carniello et al., 2009; L. D'Alpaos, 2010; Tommasini et al., 2019). In addition, 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., 2022). As external fluvial and marine sources of sediment are negligible, nowadays, sediments available for deposition mainly derive from resuspension, rework and redistribution of intra-lagoonal sediments by the hydrodynamic processes, such as tidal currents, wind waves and storm surges (Tognin et al., 2021, 2025).

The study sites are located in 10 salt marshes of the lagoon, at variable distances from the inlets (Figure 1). These sites are representative of different combinations of the key geomorphic factors that define the lagoon's landscape. In the northern lagoon, Sant'Erasmo (SE), San Felice (SF), and Saline (SA) salt marshes are located at the edges of large tidal channels departing from the Lido inlet (channel width is of the order of 50 and 200 m for the Sant'Erasmo channel and San Felice channel, respectively). In contrast, Pagliaga (PA) is located at the border of one of the few rivers still entering the lagoon, the springwater Dese River. The northern part of the lagoon is a sheltered environment, where the mainland reduces the fetch of the northeasterly Bora wind, the most intense and geomorphologically significant in the Venice Lagoon, while extensive salt marshes and islands further disrupt

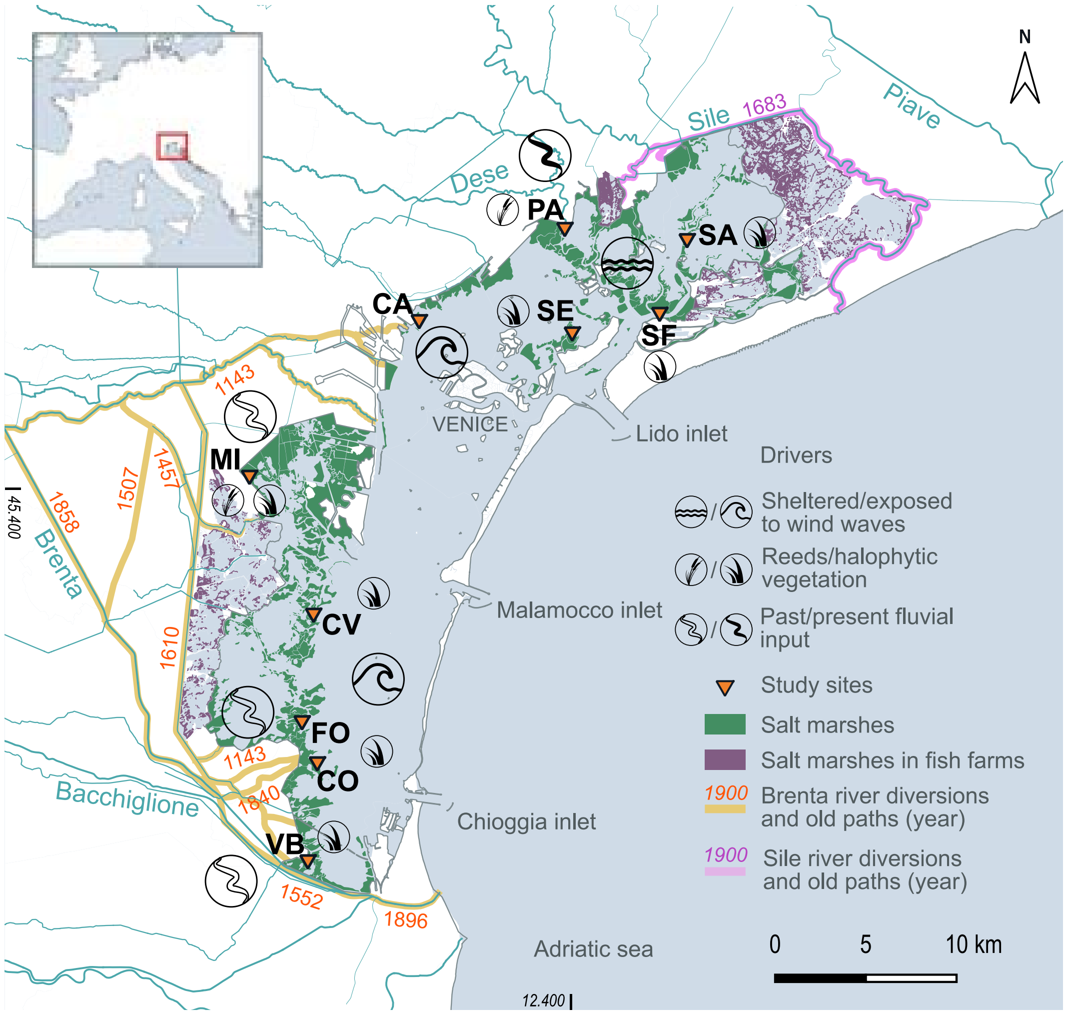


Figure 1. Location of the study areas within the Venice Lagoon (orange inverted triangles). Salt marsh areas are in green. Yellow and purple signs represent Brenta and Sile river diversions and old paths, respectively.

wind waves. The Campalto (CA) site, in the central part of the lagoon, is found at the lagoon-mainland boundary and originated on continental ground (Bonometto, 2005). In the southern lagoon, Mira (MI) and Valle di Brenta (VB) sites are located close to the landward boundary, whereas Canale Virgilio (CV) and Fossei (FO) are located within the marsh belt in front of Malamocco and Chioggia inlets. The Conche (CO) salt marsh edges the mainland and faces toward the wide subtidal flats (see Figure 1) that occupy the central-southern Venice Lagoon. Salt marshes of the southern part of the Venice lagoon are known to originate from pre-existing brackish environments or salinized freshwaters arising from river diversions (Bonometto, 2005). This area was strongly influenced by fluvial inputs from the Brenta River, which was repeatedly diverted away from and re-introduced into the lagoon until its final diversion at the end of the 19th century, as shown in Figure 1 (e.g., Bondesan & Furlanetto, 2012; D'Alpaos, 2010; Roner et al., 2017). Additionally, salt marshes bordering the extensive subtidal flats in the central-southern Venice Lagoon are exposed to strong wind waves generated by the Bora wind.

Marsh surface average accretion rates over the past 100 years, calculated by Bellucci et al. (2007) based on sediment core sampling and ^{210}Pb and ^{137}Cs profiles, are 0.2 and 0.5 cm yr^{-1} for the northern and the southern parts of the Venice Lagoon, respectively.

Salt marsh vegetation in the Venice Lagoon is characterized by numerous halophytic species forming distinct associations, organized into characteristic patches that mostly depend on topographic elevation, which can vary over very small scales (Silvestri et al., 2005; Z. Yang et al., 2023). The most common associations are *Limonio narbonensis-Puccinellietum festuciformis*, *Puccinellio festuciformis-Sarcocornietum fruticosae*, and, to a lesser extent, *Salicornietum venetae* and *Limonio narbonensis-Spartinetum maritimae*. *Limonio narbonensis-Puccinellietum festuciformis* and *Puccinellio festuciformis-Sarcocornietum fruticosae* are more widespread in the southern basin. *Puccinellio festuciformis-Phragmitetum australis* mainly develops along the lagoon margins, where freshwater input lowers salinity levels (Cazzin et al., 2009). Thanks to its proximity to the freshwater input of the Dese River, vegetation at the PA site is dominated by *Phragmitetum australis*. In contrast, other study sites are characterized by halophytic associations, with the most abundant species being *Sarcocornia fruticosa*, *Juncus maritimus*, *Puccinellia palustris*, and *Limonium narbonense*. Further details on the vegetation characteristics at each study site can be found in Puppin, Tognin, Ghinassi, et al. (2024).

2.2. Sediment Sampling and Sedimentological Analyses

Sediment cores were collected in the 10 considered marshes along transects from the marsh edge to the inner marsh, for a total of 60 cores to the depth of 1 m. The analyzed 1-m layer represents deposits that have accumulated over approximately the last 200–500 years, based on the marsh accretion rates of different areas (Bellucci et al., 2007). Transects start on an edge facing a channel, with the exception of CA and CO, as these marshes face a tidal flat. In each transect, six cores were collected (0, 2.5, 5, 10, 20, and 30 m from the edge, respectively) so as to represent morphological and vegetation zonation. Core collection points were surveyed using a GPS in RTK mode (Leica GS16) and vegetation characteristics were recorded within a 1 × 1 m quadrant by the Braun-Blanquet method and registering species cover percentages.

Soil samples were taken at 12 depths (0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 75 cm) from each core (Howard et al., 2014). Each sample was divided into subsamples which were prepared for different analyses, including OM and C content, soil density and grain size distribution. Subsamples were oven dried at 60°C for 48 hr or to constant weight. 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 hr (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. Two methodologies were used to determine the sediment Dry Bulk Density (DBD) (g m^{-3}). First, DBD was determined as the ratio between sample dry weight and estimated wet volume using the depth interval of the section and the diameter of the core barrel. In addition, DBD was calculated from the water content as the difference in weight between wet and dry samples and between organic and inorganic fractions, according to Kolker et al. (2009), by assuming a water density of 1.02 and a 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 OM content (LOI) and DBD determined organic matter density (OMD). Inorganic particle size distribution analyses were performed using laser granulometry (Mastersizer 2000–Version 5.40, MALVERN INSTRUMENTS), after the removal of the OM through a treatment with 35% hydrogen peroxide (H_2O_2) for 36 hr.

Sedimentological analyses were carried out on the study cores through the principles of facies analysis in order to link them with the corresponding sedimentary processes and depositional sub-environments (Roner et al., 2017). Different types of deposits were differentiated on the basis of their distinctive features through the observation of their color, grain size, texture, sedimentary structures and macroscopical biogenic content (e.g., shells, plant debris and vegetal remains). The different depositional environments identified include salt marsh, brackish marsh, tidal flat, and transition zones, as further detailed in the Results section (3.1: Depositional Environment Interpretation). Differentiation of depositional environments within core stratigraphy allowed us to analyze the variability of soil characteristics in different types of deposits.

2.3. Statistical Analysis

Statistical analyses were performed using MATLAB R2021a. The non-parametric rank-based Kendall test was used to determine whether there exists a monotonic relationship between 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, a non-parametric version of classical one-way ANOVA using ranks of the data to compute the chi-square statistic, was used to compare the medians of the groups of data to determine if the samples come from the same population. When the Kruskal-Wallis test showed a significant difference between groups, a multiple comparison test was used to determine which pairs of means were significantly different.

2.4. Depth Model

As the exponential depth model is the most widely accepted in SOM vertical distribution modeling (Bai et al., 2016; Wiese et al., 2016), in order to test its viability for SOM prediction at different depths in our study case, we fitted our SOM data using an exponential function:

$$\mathrm{SOM} = a \cdot e^{-bD} \tag{1}$$

where SOM is the percentage by weight of organic matter, D is the depth below the marsh surface (cm), and *a* and *b* are the parameters of the exponential function. We included only data from the current marsh deposits (i.e., salt marsh or brackish marsh, and transition zone) for the model calculations, given our aim to model SOM distribution within the current environment. This approach excludes any data from underlying soil layers that accumulated prior to the development of the current marsh environment (e.g., pre-existing tidal flat). We adopted this strategy to ensure the model is tested on relatively homogeneous deposits, thereby minimizing major sources of variability identified through sedimentological analyses.

3. Results

3.1. Depositional Environment Interpretation

Sedimentological analyses allowed us to distinguish four depositional sub-environments: tidal flat deposits, salt marsh deposits, brackish marsh deposits, and transition deposits. Both salt marsh and brackish marsh deposits formed in the upper intertidal zone and are rich in live roots and plant debris. Brackish marsh deposits develop in areas with localized freshwater inputs, supporting vegetation dominated by *Phragmites australis*. Given the gradual nature of changes between depositional types, transition zones were also identified. A detailed description and interpretation of the results from the sedimentological analyses are provided in the Supporting Information.

3.2. The Study Transects: Sedimentological and OM Variability

The sedimentological interpretation and the OM content based on the analysis of the cores at sites SE, SF and SA are shown in Figure 2. Sites SE, SF, and SA show a similar stratigraphy consisting of salt marsh deposits grading downward into transitional and tidal flat deposits (Figure 2). Oxidized salt marsh deposits are 20–30, 25–50, and 10–20 cm thick at sites SE, SF, and SA, respectively, and in all the sites show a progressive downward decrease in plant debris content. Underlying transitional deposits range from 15 (site SA) to 30 (site SE) cm in thickness, and show a clear decrease in root density in comparison to overlying marsh deposits. The basal tidal flat deposits are up to 80 cm thick (site SA). OM concentration at SA, SE, and SF sites rapidly decreases with depth, moving from marsh deposits to tidal flat deposits, and becomes stabilized roughly under 30 cm depth (Figure 2). OMD depth-distribution follows OM patterns. Mean OM content in 1 m top soil is between 3% and 7%, reaching about 10% at SF when considering the surface soil layer.

At the PA site (Figure 3a), core deposits entirely consist of brackish marsh deposits, which are at least 1 m thick. These deposits are deeply permeated by the dense stem and root networks of the current vegetation community dominated by *Phragmites australis* at least down to 50 cm depth along the entire transects (Figure 3 insert d). Below live plant tissues, the deposits are still rich in plant debris and clear rests of reeds (Figure 3 insert e). Mean organic matter in the 1 m top soil ranges between 14% and 26% (Figure 3a).

At the CA site (Figure 3b), salt marsh deposits dominate the study stratigraphy, with an average thickness of 90 cm. They are characterized by a dense network of mainly fine roots, with discontinuous plant-debris-rich laminations (Figure 3 insert f). Below 30–40 cm from the modern surface, scattered, large-sized, roots in life position are visible within a mud matrix. At the bottom of the cores, a peaty brackish marsh deposit with abundant reed fragments occurs (Figure 3 insert h). This site shows quite irregular depth profiles of OM concentration, with mean values in 1 m top soil ranging between 15% and 22% (Figure 3b). A generally decreasing trend with depth can be observed, with some peaks (up to 40%) around 20–40 cm depth. OMD, instead, displays a much more constant trend without the presence of peaks, as OM increase is caused by OM rich layers with a low density.

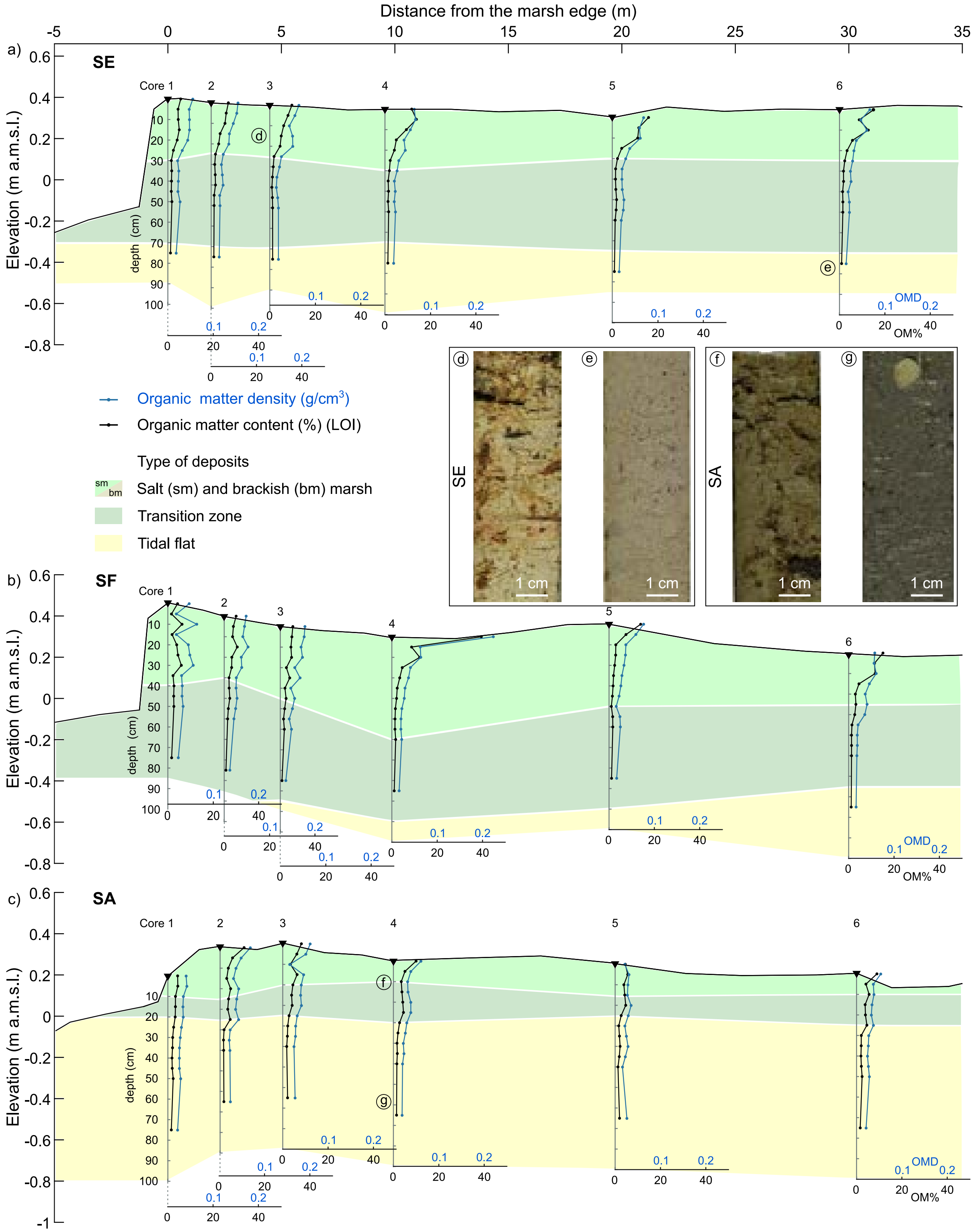
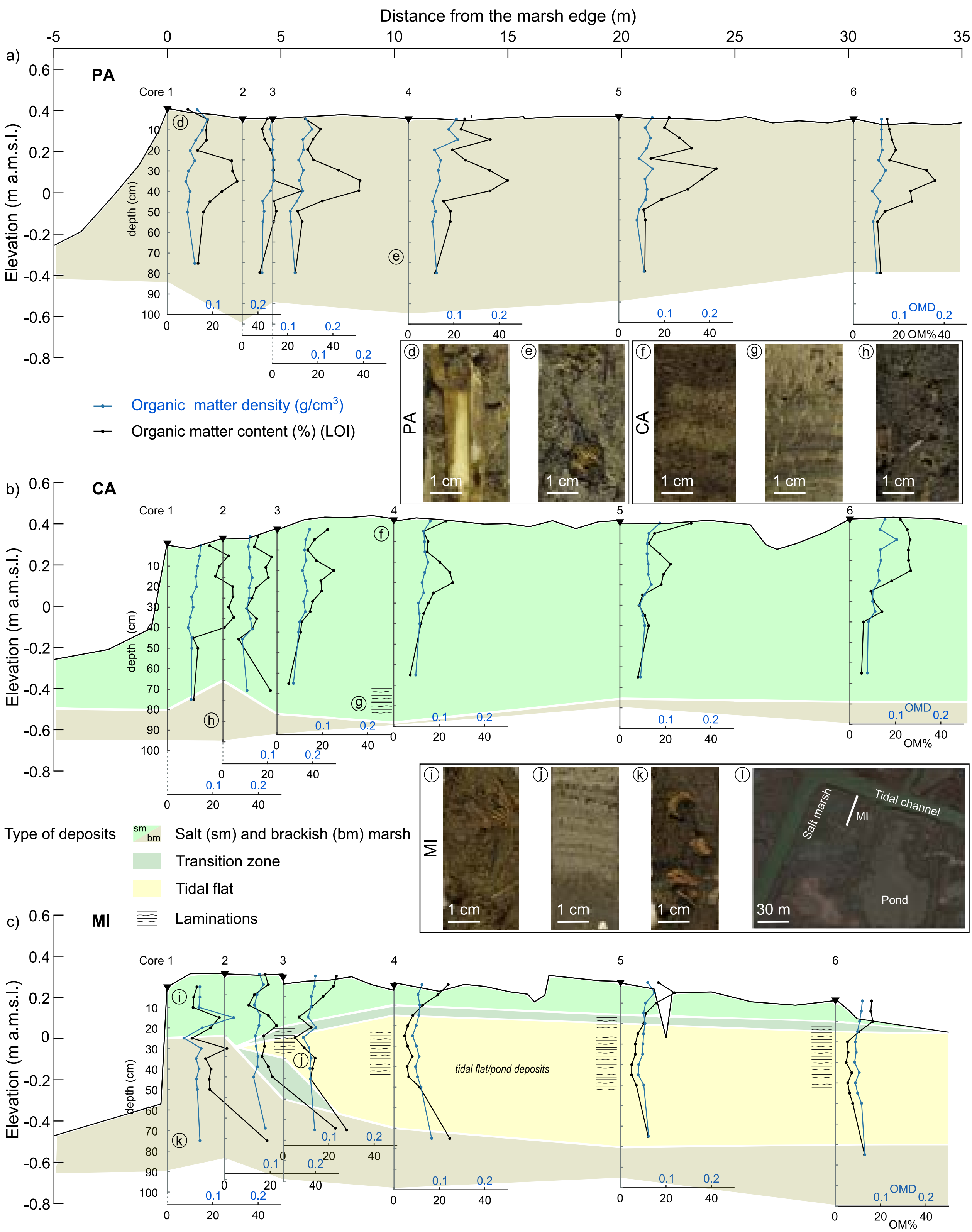


Figure 2. Representation of transect vertical sections, OM content and sedimentological interpretation for the SE, SF and SA marshes (a–c). Along the surface elevation profile, at each core site (from 1 to 6 respectively at 0, 2.5, 5, 10, 20, and 30 m from the marsh edge) depth-distribution of organic matter content (LOI—% weight—black scale from 0 to 50) and organic matter density (g cm^{-3}—blue scale from 0 to 0.25) are depicted. An interpretation of the study transect depositional environments is schematically illustrated by polygons of different colors on the basis of the sedimentological features and the spatial distribution of the different sedimentary deposits that we have differentiated. Inserts (d–g) are pictures of core details and their position is indicated on transect section representations: d and f—roots and plant debris in salt marsh deposits, e—massive tidal flat deposits with plant fragments, g—shell fragments in sandy tidal flat deposits.



Distance from the marsh edge (m)
a)
PA
b)
CA
c)
MI
Elevation (m a.m.s.l.)
depth (cm)
Core 1
Organic matter density (g/cm3)
Organic matter content (%) (LOI)
OMD
OM%
Type of deposits
Salt (sm) and brackish (bm) marsh
Transition zone
Tidal flat
Laminations
tidal flat/pond deposits
1 cm
30 m
Salt marsh
Tidal channel
Pond

Figure 3.

At the MI site (Figure 3c), stratigraphy shows a clear variability from the edge to the inner marsh. Core 1 and 2, near the marsh edge, consist of 30–40 cm of deeply rooted salt marsh deposits covering brackish marsh sediments. Moving toward the inner marsh, salt marsh and brackish marsh deposits are separated by transitional and tidal flat deposits, which increase in thickness inland. Mean organic matter in 1 m top soil ranges between 10% and 20% (Figure 3c). The depth profiles of OM concentration generally show a decrease in the upper layer (30–40 cm) and then again, an increase in the deeper layer, reaching the highest values at 75 cm depth in the edge core, with 40% of organic matter, where brackish marsh peats are observed. OM depth profiles are highly variable near the margin and more regular toward the inner marsh. OMD depth-distribution generally follows OM patterns. However, although OM shows very high value at 75 cm deep, the increase in OMD is much more reduced because of the lower DBD of the peaty deposit.

At the CV site, abundant roots and plant debris are visible along the entire profile in all the cores. Salt marsh deposits, covering brackish marsh sediments, form a wedge that increases in thickness from 15 to 100 cm moving from core 6 to 1. The profiles of OM concentration with depth show no clear trend, with mean OM contents in 1 m top soil ranging between 10% and 17% (Figure 4a). They are approximately linear at the marsh edge, slightly decreasing in surface layer toward the inner marsh but with an increase at the core bottom. OMD distribution generally follows OM patterns. However, OMD is reduced when low-density peaty deposits are encountered toward the inner marsh.

At the FO site, roots and plant debris are generally abundant all along the profiles (Figure 4 insert f), being the site characterized by dominance of salt marsh deposits in the study stratigraphic interval. Tidal flat and overlying transitional deposits form a 25 cm thick interval at base of core 6. Two distinct layers of tidal flat facies (10–15 cm thick) occur also in core 4 and 5 at 90 and 70 cm from the surface, respectively. The depth profiles of OM concentration show no clear trend, with mean OM contents in 1 m top soil ranging between 14% and 24%, and some peaks at different depths with values higher than 40% (Figure 4b). In contrast, OMD displays a much more constant trend without the presence of peaks, as OM increase is caused by low density layers.

The CO site shows a vertical stacking of tidal flat, transitional and salt marsh deposits. Salt marsh deposits are deeply rooted and up to 20 cm thick, and contain localized shell-layers up to 2–3 cm thick (Figure 5 insert c). Underlying transitional deposits are characterized by a pervasive horizontal lamination that locally hosts 1–20 mm thick layers entirely consisting of plant debris, probably derived from seagrass (Figure 5 insert d and e). Mean organic matter in the 1 m top soil ranges between 6% and 7% (Figure 5a). OM concentration generally shows a decrease with depth. The decrease is more pronounced toward the inner marsh, whereas the marsh edge displays quite irregular depth profiles. Some peaks in organic matter concentration, reaching up to 25% at a depth of 30 cm, are observed, which occasionally coincide with buried seagrass layers. OMD distribution generally follows OM patterns.

At the VB site the uppermost part of the stratigraphy consists of 30–50 cm thick salt marsh deposits (Figure 5b), which are underlain by a continuous layer of 15–30 cm thick transitional deposits. At cores 1 to 5, these transitional deposits cover a wedge-shaped unit consisting of tidal flat sediments. This unit, up to 40 cm thick, shows an irregular shape and pinches out between core 5 and 6. Transitional deposits (up to 30 cm thick) occurring below the tidal flat sedimentary wedges, and cover salt marsh sediments at coring site 5 and 6. Observed mean organic matter in 1 m top soil displayed some variability ranging between 4% at the marsh edge and 17% in the inner marsh (Figure 5b). OM concentration, as well as OMD, generally shows a decrease with depth, following quite irregular depth profiles, although in some cases the 75-cm-depth sample displayed an increasing value.

Figure 3. Representation of transect vertical sections, OM content and sedimentological interpretation for the PA, CA and MI marshes (a–c). Along the surface elevation profile, at each core site (from 1 to 6 respectively at 0, 2.5, 5, 10, 20, and 30 m from the marsh edge) depth-distribution of organic matter content (LOI—% weight—black scale from 0 to 50) and organic matter density (g cm^{-3}—blue scale from 0 to 0.25) are depicted. An interpretation of the study transect depositional environments is schematically illustrated by polygons of different colors on the basis of the sedimentological features and the spatial distribution of the different sedimentary deposits that we have differentiated. Inserts (d–k) are pictures of core details and their position is indicated on transect section representations: d—Phragmites australis aboveground tissues, e—reed fragments, f—plant-debris-rich laminations in salt marsh deposits, g - plant-debris-rich laminae in pond deposits, h—reed fragments in peaty deposits, i—roots and plant debris in salt marsh deposits, j—plant-debris-rich laminae in pond deposits, k—reed fragments. Insert (l) shows a wide pond or a tidal flat in the inner marsh at MI site (Map data: ©2022 Google-Landsat/Copernicus, Maxar Technologies).

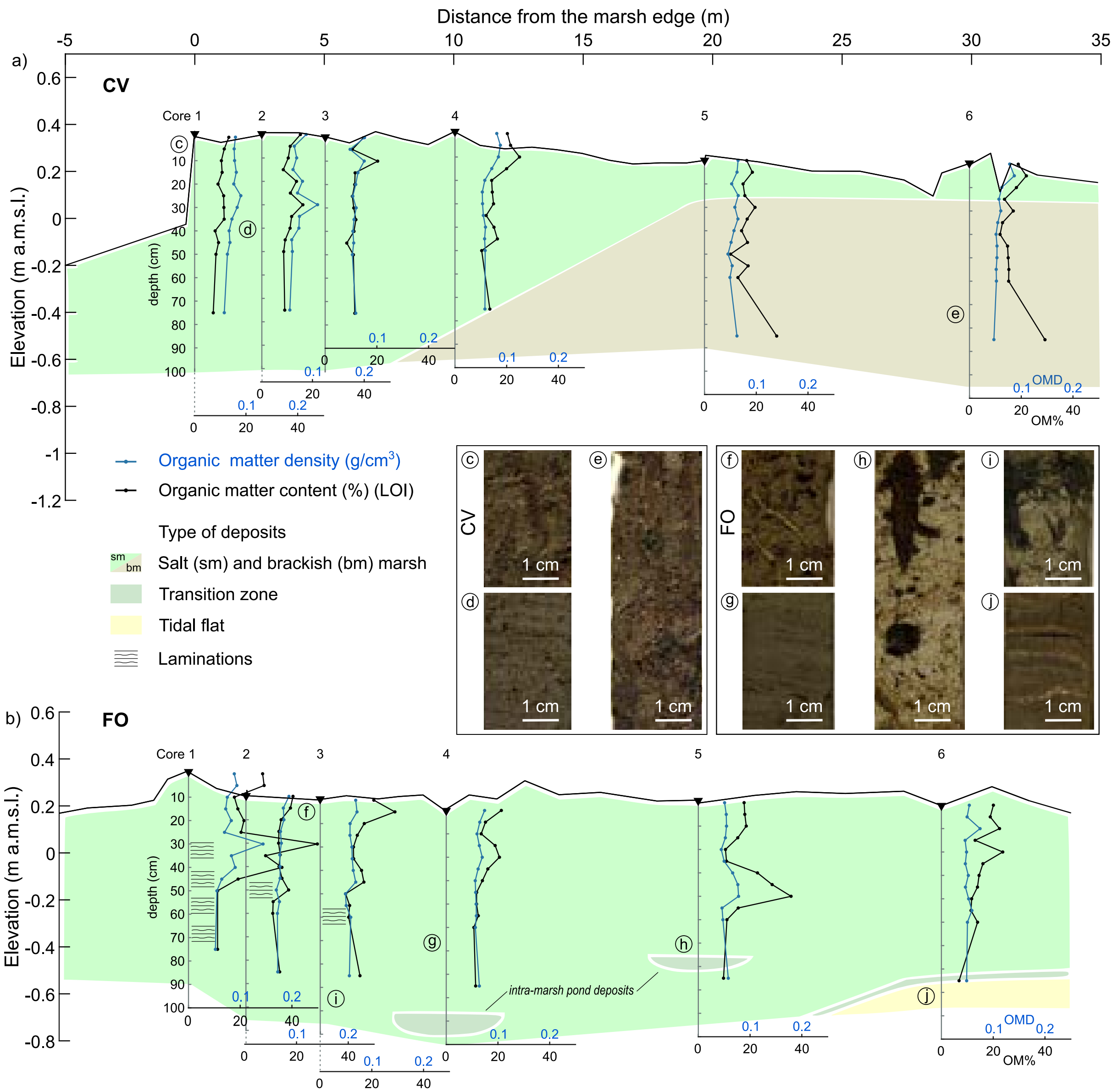


Figure 4. Representation of transect vertical sections, OM content and sedimentological interpretation for the CV and FO marshes (a, b). Along the surface elevation profile, at each core site (from 1 to 6 respectively at 0, 2.5, 5, 10, 20, and 30 m from the marsh edge) depth-distribution of organic matter content (LOI—% weight—black scale from 0 to 50) and organic matter density (g cm^{-3}—blue scale from 0 to 0.25) are depicted. An interpretation of the study transect depositional environments is schematically illustrated by polygons of different colors on the basis of the sedimentological features and the spatial distribution of the different sedimentary deposits that we have differentiated. Inserts (c–j) are pictures of core details and their position is indicated on transect section representations: c and d—plant debris and organic-rich laminae in salt marsh deposits, e—reed fragments, f—roots and plant debris in salt marsh deposits, g—plant-debris-rich laminae in pond deposits, h—*Limonium narbonense* root in life position, i—dark plant debris, j—millimetric, whitish, horizontal laminae.

3.3. Variations in Soil Characteristics in Different Depositional Environments

As to the variability of marsh soil characteristics in different depositional environments, a Kruskal-Wallis test indicates that there was a significant difference between OM content within the different types of deposits (p-value < 0.0001), with marsh deposits showing significantly higher OM content than tidal flat and transitional deposits (Figure 6a). Furthermore, brackish marsh deposits reveal a significantly higher OM content than salt marsh deposits. Dry Bulk Density is observed to be higher in tidal flat and transition zone deposits than in marsh deposits (p-value < 0.0001) (Figure 6b). OM density is significantly higher in marsh deposits than in tidal flat and transitional deposits (p-value < 0.0001) (Figure 6c). For median grain size, the same behavior of DBD is observed

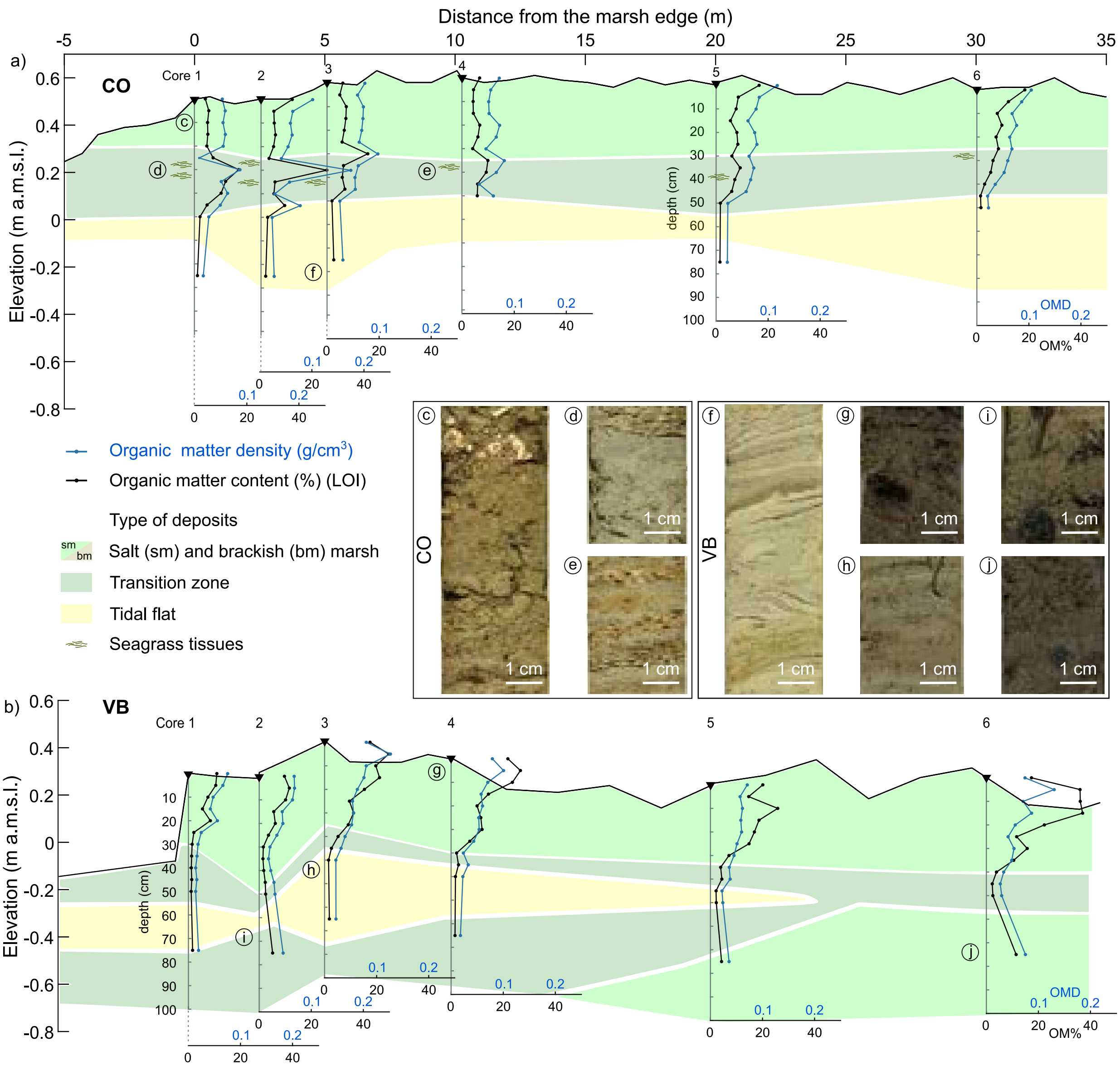


Figure 5. Representation of transect vertical sections, OM content and sedimentological interpretation for the CO and VB marshes (a, b). Along the surface elevation profile, at each core site (from 1 to 6 respectively at 0, 2.5, 5, 10, 20, and 30 m from the marsh edge) depth-distribution of organic matter content (LOI—% weight—black scale from 0 to 50) and organic matter density (g cm^{-3}—blue scale from 0 to 0.25) are depicted. An interpretation of the study transect depositional environments is schematically illustrated by polygons of different colors on the basis of the sedimentological features and the spatial distribution of the different sedimentary deposits that we have differentiated. Inserts (c–j) are pictures of core details and their position is indicated on transect section representations: c—shell fragments and plant debris in surface salt marsh deposits, d and e—seagrass leave layers, f—submillimetric to millimetric sandy laminations, g—plant debris in salt marsh deposits, h—sandy laminae in tidal flat deposits, i—dark plant debris, j—plant debris.

(p-value < 0.0001), with tidal flat and transition zone deposits showing coarser sediments than marsh deposits and brackish marsh deposits being characterized by finer sediments with respect to salt marsh deposits (Figure 6d).

3.4. Sediment Grain Size and Its Relationship With OM

Inorganic sediment fraction in 1 m marsh soils shows a median grain size (D_{50}) ranging between 5 and 54 μm, with a mean value of 15 μm (Figure 7). Finer median grain size values are found at sites located on the landward side of the lagoon (i.e., PA, CA, and MI), which are characterized by higher percentages of clay (20%–30%). In

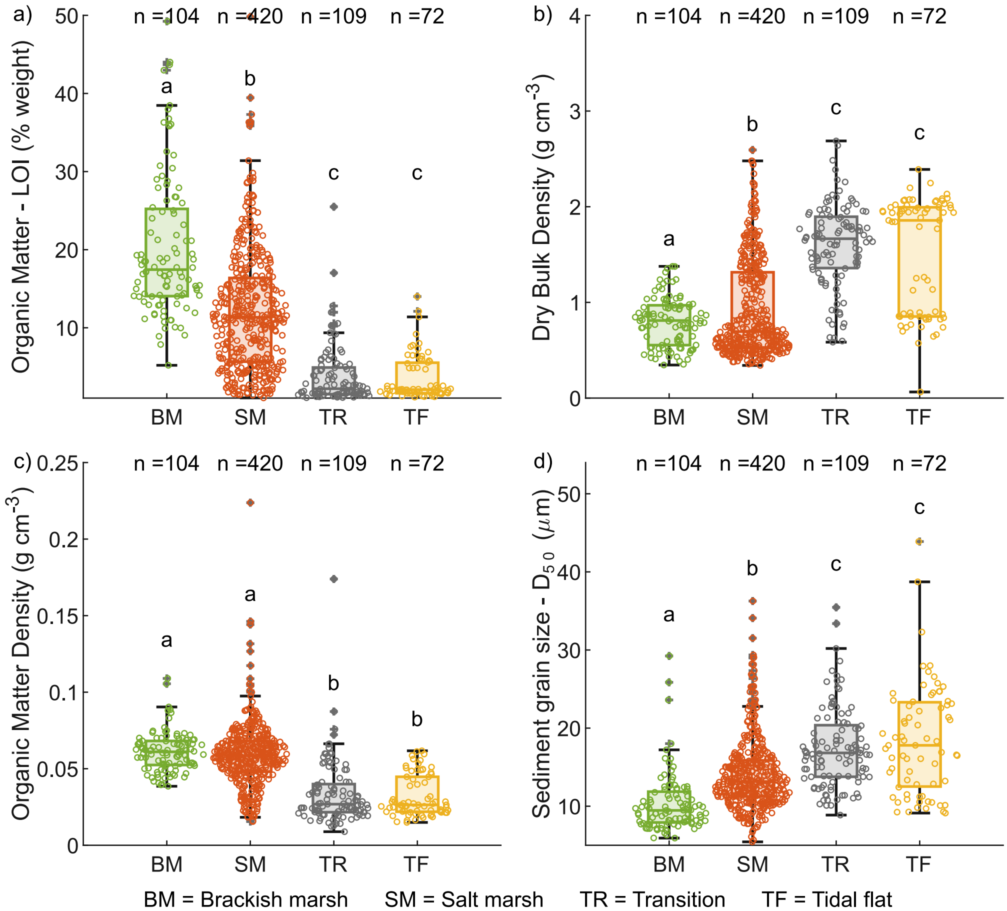


Figure 6. Sediment characteristic variations in different depositional environments: organic matter content (LOI—% weight) (a), Dry Bulk Density (g cm^{-3}) (D_{50}—μm) (b), organic matter density (g cm^{-3}) (c), grain size distribution (d). Box plots show median and quartiles, swarm plots show single values. Different letters above the box plots indicate significant difference on the basis of Kruskal-Wallis test and post hoc multiple comparison test.

contrast, coarser median grain size values are found in SF, SA, SE, VB, and CO sites (average D_{50} value between 17 and 20 μm). Furthermore, at SF, SA, and SE sites, a clear increase in grain size was observed below 30–40 cm depth with sand fractions reaching 20%.

Considering all our data, OM content showed a significant relationship with sediment median grain size (D_{50}) (Kendall's tau test, $\tau = -0.3843$ p-value < 0.0001), with organic content decreasing when sediments become coarser (Figure 8). Additionally, a correlation between organic matter content and the percentage of mud (grain size < 64 μm) was observed, albeit weaker (Kendall's tau test, $\tau = 0.0499$ p-value $= 0.0456$) (Figure 8).

3.5. Relationship Between OM Content and DBD

A clear relationship was observed between OM content and DBD, with soil density rapidly decreasing with increasing organic content (Figure 9). We tested an ideal mixing model against our data, accordingly to Morris et al. (2016): the model assumes that the bulk volume of soil approximates the summed self-packing volumes of the organic and mineral components, represented by the coefficients of the equation (Morris et al., 2016):

$$\mathrm{DBD} = \frac{1}{\frac{\mathrm{LOI}}{k_1} + \frac{(1-\mathrm{LOI})}{k_2}}$$

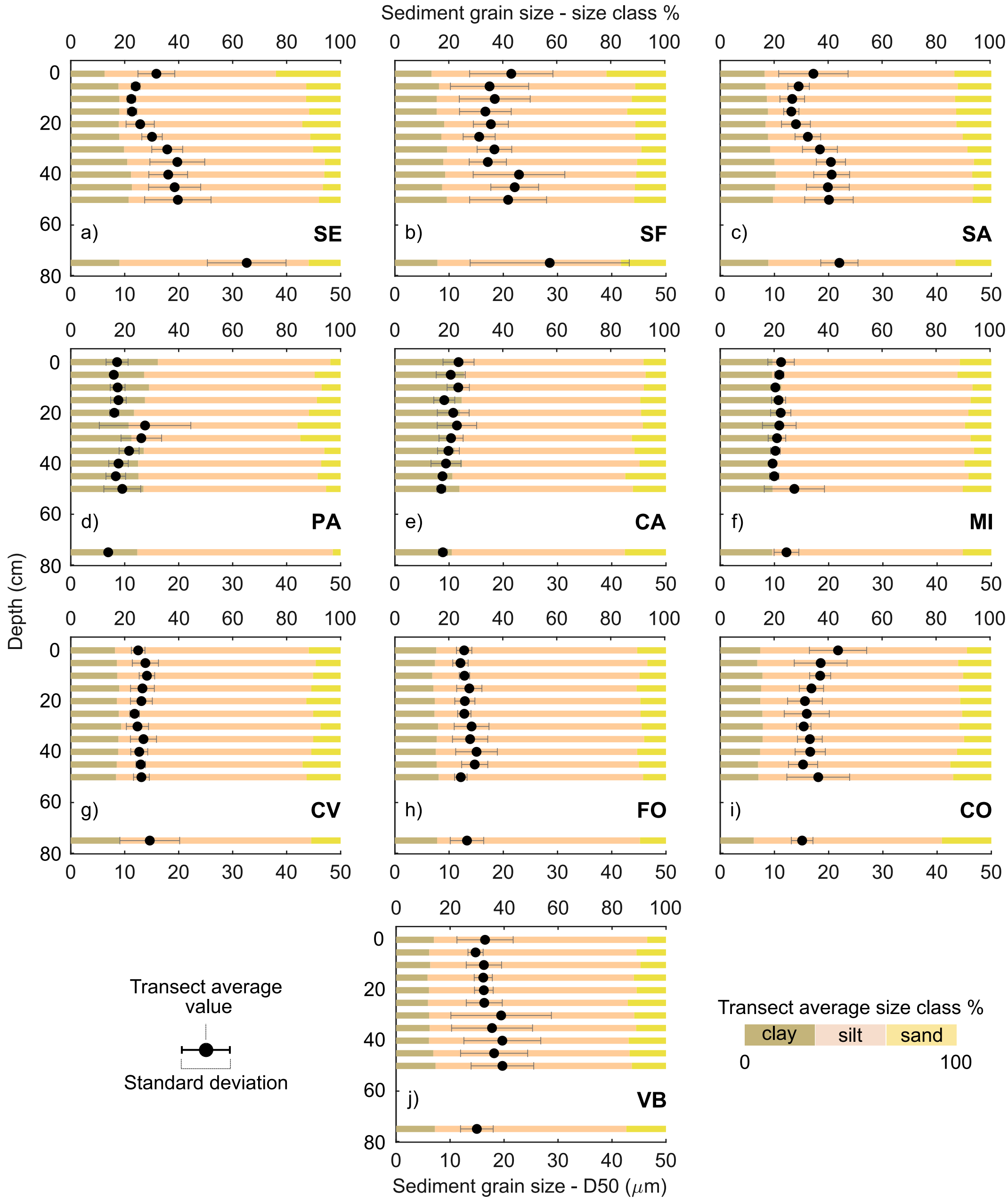


Figure 7. Depth-distribution of sediment grain size: average of median grain size (D_{50} - μm) with respective standard deviation and sand-silt-clay percentage at different depths at each of the 10 sites considered (a–j).

where DBD is the sediment Dry Bulk Density, LOI is the OM content resulting from LOI procedure, k_1 and k_2 are two coefficients.

The fit over all our samples gave k_1 and k_2 coefficients of 0.014 and 2.28 g cm^{-3}, respectively.

3.6. Soil Organic Matter Modeling With Depth

An exponential function (Equation 1) was fitted to SOM concentrations, in terms of percentage and density, of current salt marsh and transitional deposits in each soil profile down to 1 m depth. The fitted exponential functions showed highly variable R^2 values ranging between 0.011 and 0.94 (Figures 10 and 11). SE, VB and SF showed the highest mean R^2 values, 0.85, 0.81 and 0.75, respectively.

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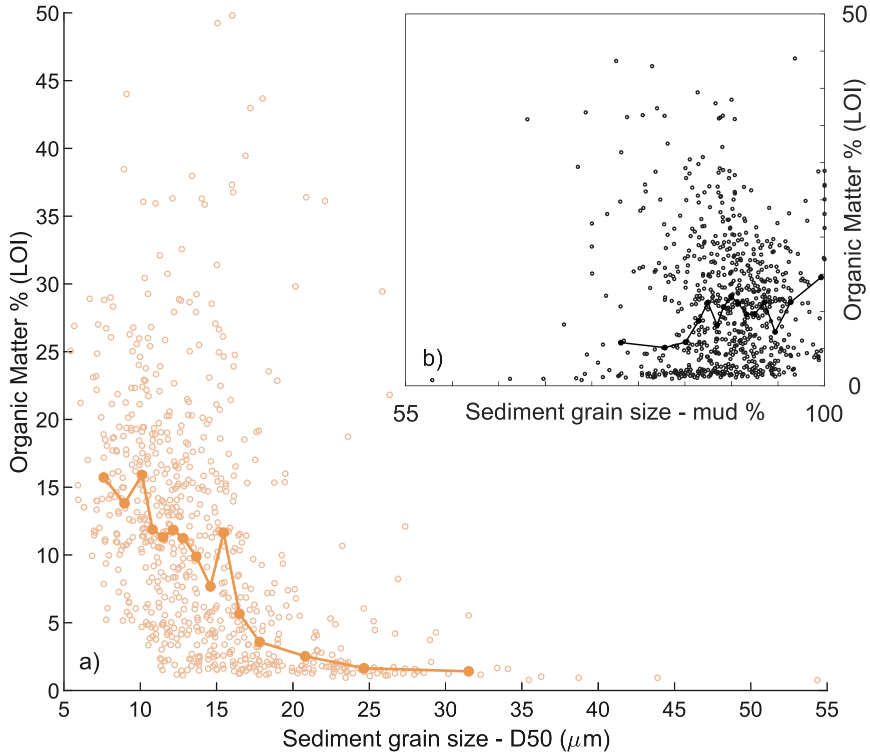

Figure 8. Organic matter content as a function of sediment grain size, as (a) sediment median grain size (D_{50}) and (b) percentage of mud (grain size <64 μm). Orange and gray open circles represent individual values. Binned averaged values obtained by averaging sets of 50 data points (orange and gray closed circles connected by lines) are shown to visually represent the relationships highlighted by Kendall's tau test, performed on the entire data set.

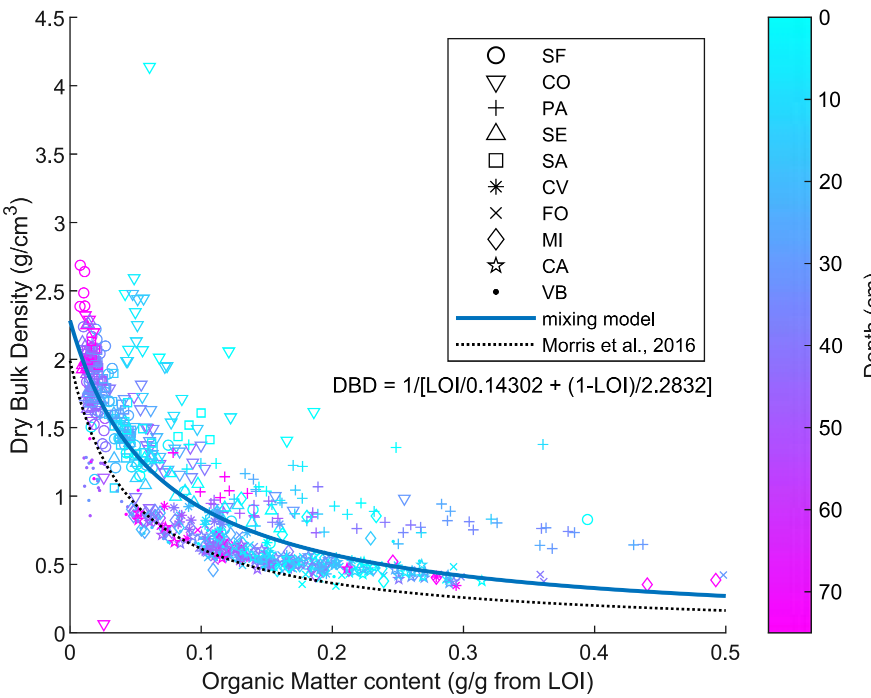

Figure 9. Relationship between soil density and organic content. The relationship between soil Dry Bulk Density, determined through the ratio between dry weight and estimated wet volume, and soil organic matter percentage measured through loss on ignition (LOI) in marsh soil samples ($n = 706$) and best fit of the ideal mixing model to our data (blue line) following Morris et al. (2016). The dashed line represents the best fit of the ideal mixing model to the data from Morris et al. (2016).

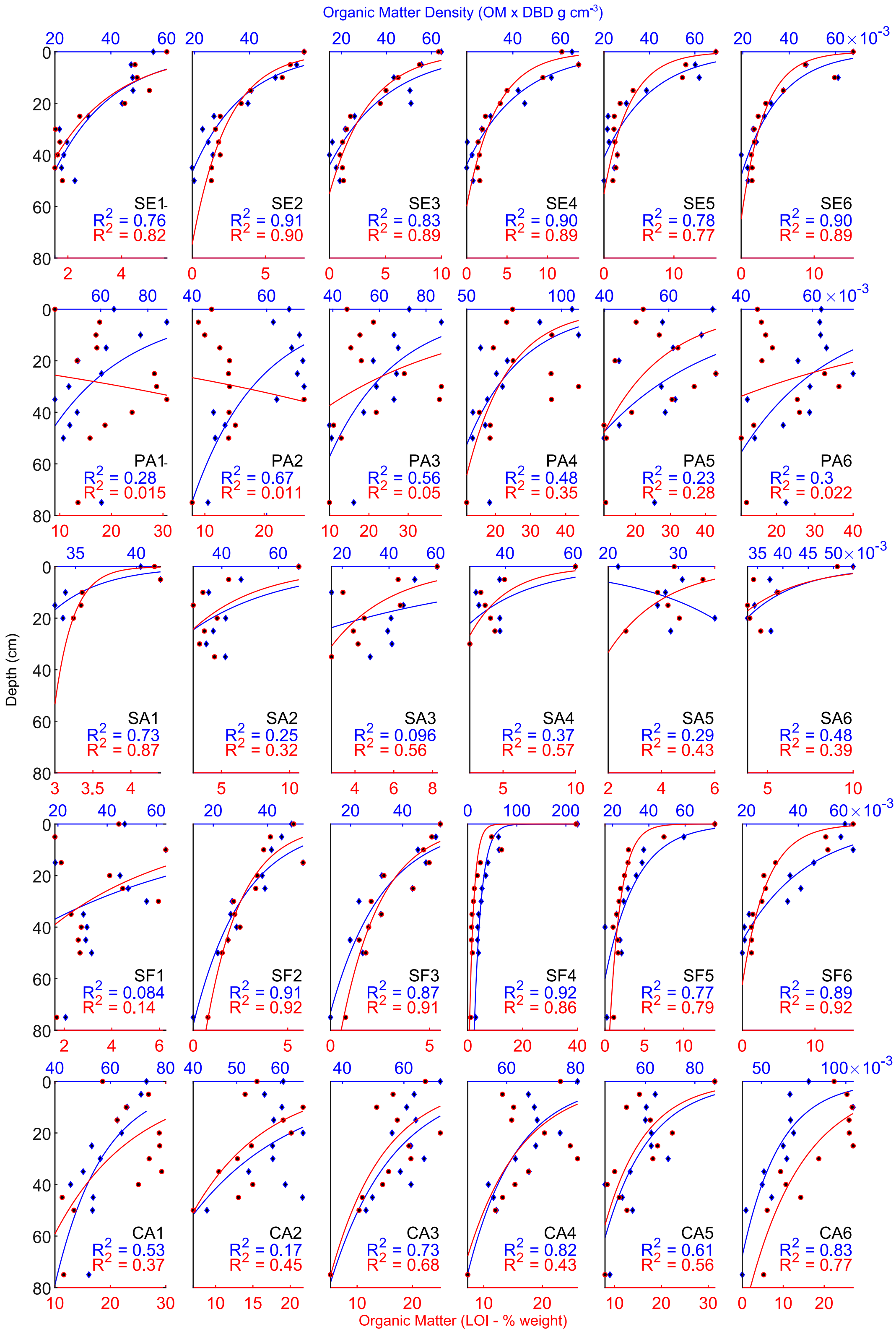

Figure 10. Exponential fitting of OM depth-distribution (northern lagoon). Fitting curves of vertical distribution of organic matter content (LOI - % weight) (red) and organic matter density (g cm^{-3}) (blue) in current salt marsh deposits using an exponential function (LOI = a exp (−bD)) at SE, SF, SA, PA, CA. Current marsh deposits were considered, including related transition zone, if present.

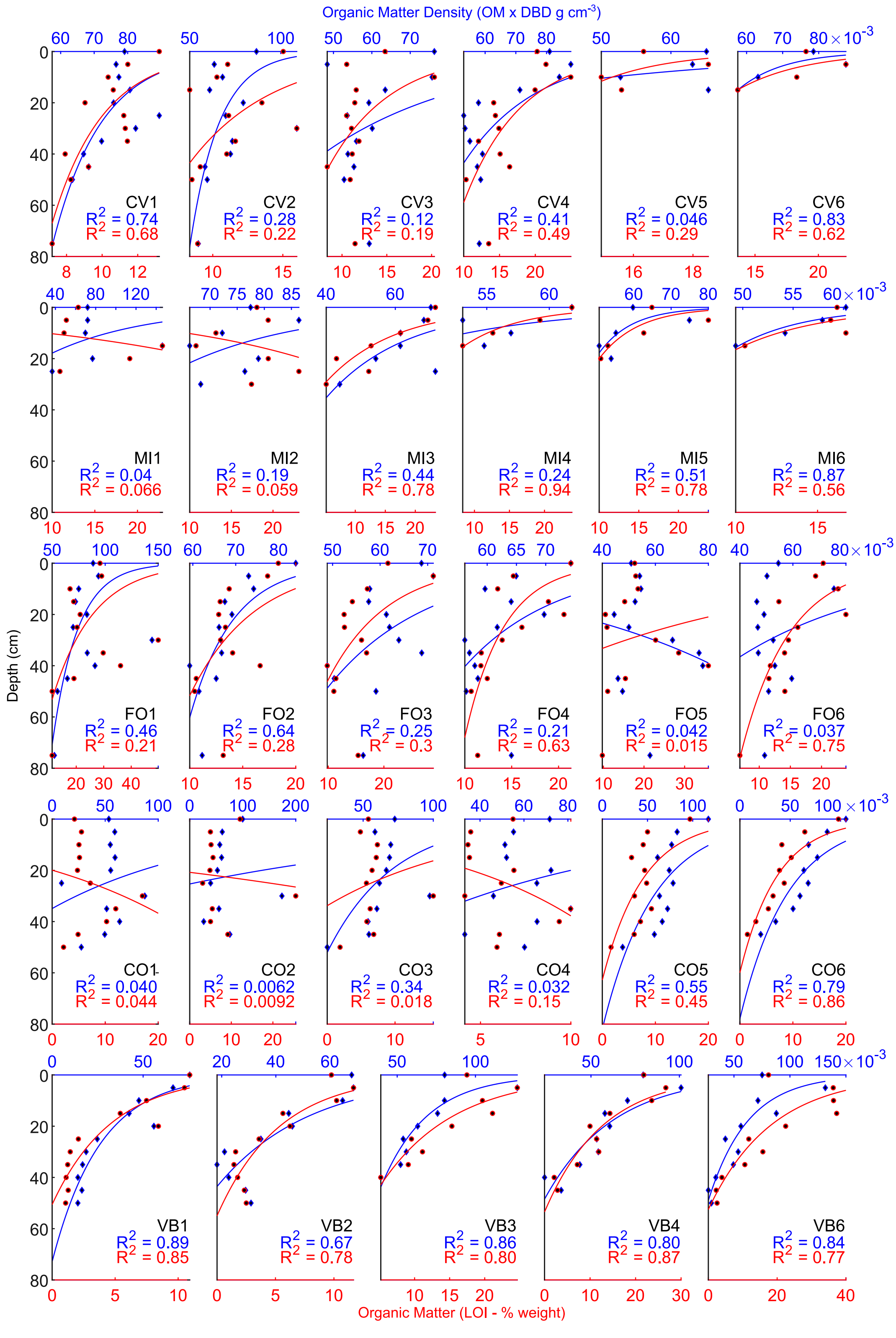

Figure 11. Exponential fitting of OM depth-distribution (southern lagoon). Fitting curves of vertical distribution of organic matter content (LOI - % weight) (red) and organic matter density (g cm^{-3}) (blue) in current salt marsh deposits using an exponential function (LOI = a exp (−bD)) at MI, CV, FO, CO, VB, including related transition zone, if present.

4. Discussion

4.1. SOM Depth-Variability Patterns: Sedimentological Interpretation and Differences Among Depositional Environments

The depth distribution of OM observed in the 1 m analyzed cores varies considerably between sites. OM content decreases rapidly with depth, following a classical exponential trend at sites SE, SF, and SA. Despite a more irregular pattern, characterized by some peaks, a marked decrease in OM content is also observed in the inner marsh at the MI site (cores 4, 5, and 6), as well as at the CO and VB sites. The stratigraphy at these locations reveals a gradual transition from a tidal flat to a vegetated salt marsh depositional environment. Some central and southern lagoon sites, such as CA, CV, and FO, are characterized by thick marsh layers occupying a large portion of the stratigraphic profile. Some sites, like FO and MI, show evidence of local evolution in pond areas. Higher OM content was observed at the PA site, currently dominated by near-freshwater vegetation, particularly *Phragmites australis*, a reed that forms a dense, deep network of tough stems, roots, and rhizomes (Moore et al., 2012; Scarton et al., 2002). The dominance of *Phragmites australis* in both present-day and buried deposits is considered a diagnostic sign of brackish marsh deposits. The remains of these organic substrates, forming peaty layers, are easily recognizable in the buried brackish marsh deposits at the bottom of some cores, such as at CA and the edge cores of MI, or in the inner cores at CV, where an increase in OM content is observed. The stratigraphy at these sites indicates a transition from a brackish, pre-existing bottom layer to a salt marsh depositional environment in the upper layers. This transition marks a shift in salinity, likely driven by river diversions, which would have impacted vegetation characteristics, leading from reed-dominated to halophytic vegetation as the environment shifted to a salt marsh. This aligns with previous studies suggesting that fluvially-influenced tidal marshes tend to have higher OC stocks (Kelleway et al., 2016; Macreadie et al., 2017; Saintilan et al., 2013).

Stratigraphic analysis suggests that changes in deposit types may substantially influence the depth distribution of OM content in salt marsh soils. Statistical analysis confirmed that marsh deposits exhibit significantly higher OM content than tidal flat and transitional deposits (Figure 6a), with brackish marsh deposits showing notably higher OM content than salt marsh deposits. Our findings attribute higher carbon storage potential to tidal marsh environments, directly dependent on OM density, when compared to transition zones and tidal flats, with a twofold higher median OM density. The sedimentary features of tidal flat deposits prevented us from determining whether they were vegetated. However, our results align with previous studies reporting lower OM content in both bare tidal flats (Brevik & Homburg, 2004; Lee et al., 2021; Mao et al., 2021) and seagrass meadows (Duarte et al., 2013) compared to salt marshes. Tidal marsh deposits influenced by freshwater inputs, classified as brackish marsh deposits, showed higher OM content than salt marshes, although OM density was not significantly different, likely due to the low density of organic-rich deposits.

4.2. Relationship Between OM Content and Sediment Grain Size

OM content showed a significant relationship with sediment grain size, decreasing as sediments became coarser (Figure 8). Several mechanisms may explain this negative relationship between OM content and sediment grain size (Kelleway et al., 2016). One key explanation is the variation in OM content across depositional environments, which differ in their sediment grain size characteristics. Coarser sediments are typically found in tidal flats and transition zones, where increased exposure to wave action promotes mud resuspension and the concentration of coarser deposits, whereas finer sediments are more prevalent in brackish marshes. Moreover, on a catchment scale, coarser sediments are more commonly found at the seaward boundary of the lagoon (e.g., SF, SA, SE, VB, and CO), whereas finer sediments dominate the landward side (i.e., PA, CA, and MI). This pattern is consistent with the general grain-size distribution observed in the Venice Lagoon, which reflects decreasing hydrodynamic energy from the inlets to the landward shore, with sandy sediments delivered from the sea and finer sediments supplied from the mainland (Zonta et al., 2018). Concurrently, higher organic content is observed at fluvially influenced sites compared to marine-influenced locations, likely due to the interplay of physical and biological factors (Kelleway et al., 2016; Macreadie et al., 2017; Van de Broek et al., 2016). Fine sediments, with larger specific surface area and higher cation exchange capacity compared to coarser sediments, have a greater potential to protect OM from decay through organic-mineral interactions and the formation of micro- or macro-aggregates (Bader et al., 1960; Baldock & Skjemstad, 2000; De Gryze et al., 2006). Fine sediments may bind to OM in situ, thereby preventing its decomposition, or contribute allochthonous, organic-rich fine particles that are already stabilized, enhancing carbon accretion. Moreover, fine sediments enhance carbon preservation by reducing oxygen exchange, due to lower porosity and drainage capacity. This promotes anoxic conditions, which slow down decomposition rates (Arnarson & Keil, 2007; Hartnett et al., 1998).

4.3. Relationship Between OM Content and DBD

A clear relationship was observed between OM content and DBD, with soil density decreasing rapidly as organic content increased (Figure 9). This relationship aligns with the ideal mixing model and is consistent with the findings of Morris et al. (2016). However, it is important to note that our data do not encompass the full spectrum of DBD and LOI values. Additionally, we emphasize that a non-negligible source of variability arises from the low accuracy of wet sample volume estimates. For example, PA samples noticeably deviate from the fitting curve, likely due to the difficulties in estimating the volume of irregular samples rich in plant debris. In contrast, sample depth does not appear to influence the relationship between OM content and DBD (Figure 9). This is consistent with the presence of organic-rich, low-density sediments at various depths, depending on the evolution of the depositional environment. Our analyses do not account for the contribution of different sediment components to DBD. Mariotti et al. (2020) proposed an alternative model that includes mud OM, distinguishing sand as a separate constituent with its inherently high dry bulk density. This model accounts for the lower bulk density observed in muddy sediments. However, regardless of the contribution of sand and mud components to DBD, it is worth noting that the relationship shown in Figure 9 holds across different sites and geographic contexts. This consistency is deemed to be useful for predicting OM content based on DBD, particularly given some existing studies on using remote sensing to estimate DBD (Salehi Hikouei et al., 2021).

4.4. Soil Organic Matter Depth Distribution Modeling: Outlining a Conceptual Framework

After identifying significant differences between the various tidal deposits, we tested the fit of an exponential function to OM content and OMD in the current salt marsh and transitional deposits. We observed that in many cases, the exponential function did not adequately represent SOM depth distribution in our study area. Even after excluding major changes caused by shifts in depositional environments (e.g., tidal flat deposits or pre-existing brackish environments), the SOM depth distribution in marsh deposits remained highly variable. This suggests the presence of additional, complex drivers of OM variability beyond decomposition, which are difficult to predict.

Direct measurements of OM content, combined with dating analyses, are commonly used to develop age-depth models that estimate OM and OC accumulation rates. However, these methods can be expensive, and local variability may complicate the upscaling of results. Our results suggest the need for caution when using vertical distribution models to predict SOM at unsampled soil depths, as unknown past conditions may result in inaccurate SOC stock estimates. Therefore, developing alternative modeling approaches that better describe and predict SOM patterns within tidal deposits by identifying well-defined, globally relevant patterns is essential. These improvements are critical to providing accurate representations of SOM and SOC distributions, which underpin carbon assessments, greenhouse gas offset planning, and conservation strategies. Maxwell et al. (2024) proposed a spatially explicit model that captured 59% of the variability in SOC density at the global scale. Using a machine-learning approach, they integrated SOC measurements with a set of environmental covariates identified through expert consultation. Their results identified soil depth and elevation as the strongest drivers. However, consistent with our findings, they emphasized the importance of accounting for sea-level rise history at a finer scale and incorporating more detailed geomorphic information.

The drivers we observed and analyzed at the lagoon scale at our study site are common to tidal systems globally and also vary on larger scales. Thus, our findings may offer useful insights for developing alternative modeling approaches that can better account for the complexities we observed. While building an alternative quantitative model is beyond the scope of this study, our work helps to generalize and outline a conceptual framework.

As the principal components of marsh deposits, organic inputs—whether autochthonous or allochthonous—and inorganic sediment inputs are the primary drivers of OM content in marsh soils (Mueller et al., 2019). Both factors can vary significantly across space and time and interact through ecogeomorphological feedbacks that contribute to marsh accretion.

Changes in organic inputs may be driven by shifts in plant species composition, which in turn affect both the amount and the decomposition resistance of OM. We clearly observed that higher OM content is associated with *Phragmites australis*, suggesting that brackish marshes dominated by reed vegetation, with its high biomass, may produce higher SOM content. However, quantitative relationships between vegetation and OM content in surface marsh soils were not found by analyzing species composition and vegetation cover at the analyzed sites (Puppin, Tognin, Ghinassi, et al., 2024). Different species produce varying amounts of belowground biomass and have distinct root systems that could affect OM depth distribution, particularly in the upper 20–30 cm of soil. However, complex feedback between halophytic species distribution and the micromorphology of marsh surfaces prevents us from drawing general conclusions at the spatial and temporal scales considered. Additionally, we lack information on vegetation evolution over time, which limits our ability to describe its influence beyond the present-day rhizosphere. In addition, OM peaks may result from the input of allochthonous organic material, which affects both the quantity of organic matter and its resistance to decomposition. This is likely the case for the OM peaks observed at the wave-exposed CO site, attributed to beach-cast seagrass wracks periodically deposited on tidal flats or pioneer salt marshes during storms and subsequently covered by sediment (Figure 5 insert d and e). Fluvial sediments are also observed to be richer in particulate organic matter than marine-derived sediments (Van de Broek et al., 2016). Van de Broek et al. (2018) suggest that stabilized allochthonous mainland-sourced OC is a major component of the OC preserved in deeper sediments, potentially contributing to the higher OM content observed at sites further from the inlets.

Fluctuations in inorganic inputs, and consequently sedimentation rates on marsh surfaces, may also influence OM content. Sedimentation rates, in turn, depend on various factors, including sediment availability and accommodation space. Sediment availability is influenced by sources such as fluvial inputs, marine sediments, and tidal flat sediment resuspension. Accommodation space is affected by water level variations driven by factors such as relative sea-level rise (RSLR), subsidence, tides, and waves, operating across different timescales.

Sedimentation rates are often higher during the early stages of marsh development, when surface elevation is lower relative to water level and accommodation space is greater. These rates tend to slow down over time, leading to a decreasing dilution of autochthonous organic carbon by mineral sediments upward in the core (Mueller et al., 2019). This trend aligns with the observed increase in OM content from transitional deposits, which often represent the pioneer marsh phase, to fully developed marsh deposits.

Moreover, we observed significantly varying thickness in salt marsh deposits across different sites, indicating that each site has experienced distinct evolutionary trajectories and accretion rates, which are not homogeneous within the lagoon. Bellucci et al. (2007) determined salt marsh accretion rates using ^{210}Pb and ^{137}Cs profiles from five cores across different areas of the Venice Lagoon, showing faster rates in the southern lagoon compared to the northern sector, likely driven by differences in hydrodynamics and sediment transport. Sediment supply in the southern lagoon varied over time due to repeated human-driven diversions of the Brenta River, up until relatively recent times, with the last intervention in 1896 (L. D'Alpaos, 2010). Additionally, pulses of local subsidence caused by the emplacement of deltaic lobes of the Brenta River, and later by the exploitation of underground water, caused an increase in relative water levels and thus in the accommodation space (Roner et al., 2017, 2021). Some studies suggest that OM burial in salt marshes may be enhanced, at least temporarily, by RSLR (e.g., Kirwan & Murray, 2007; McTigue et al., 2019; Miller et al., 2022; Mudd et al., 2009). Rising sea levels may increase OM production by directly enhancing plant productivity due to increased flooding (Gore et al., 2024) or by boosting inorganic sediment supply, which in turn stimulates belowground biomass production (Boorman et al., 2001; Song et al., 2022). Therefore, we hypothesize that short-term dynamics of sediment supply and RSLR may explain the higher OM content, irregular OM depth distributions, and deviations from the exponential function observed at some sites in the southern lagoon (e.g., FO, CV, MI) or near current fluvial inputs into the lagoon (PA). In the northern lagoon, where sediment supply and RSLR are lower and more constant, the SF and SE sites exhibit more regular OM depth distributions that fit the exponential model. In contrast, we hypothesize that the SA site significantly deviates from the exponential model due to the reduced thickness of salt marsh deposits. This is caused by tide dissipation, which increases with distance from the inlet, resulting in limited marsh accommodation space.

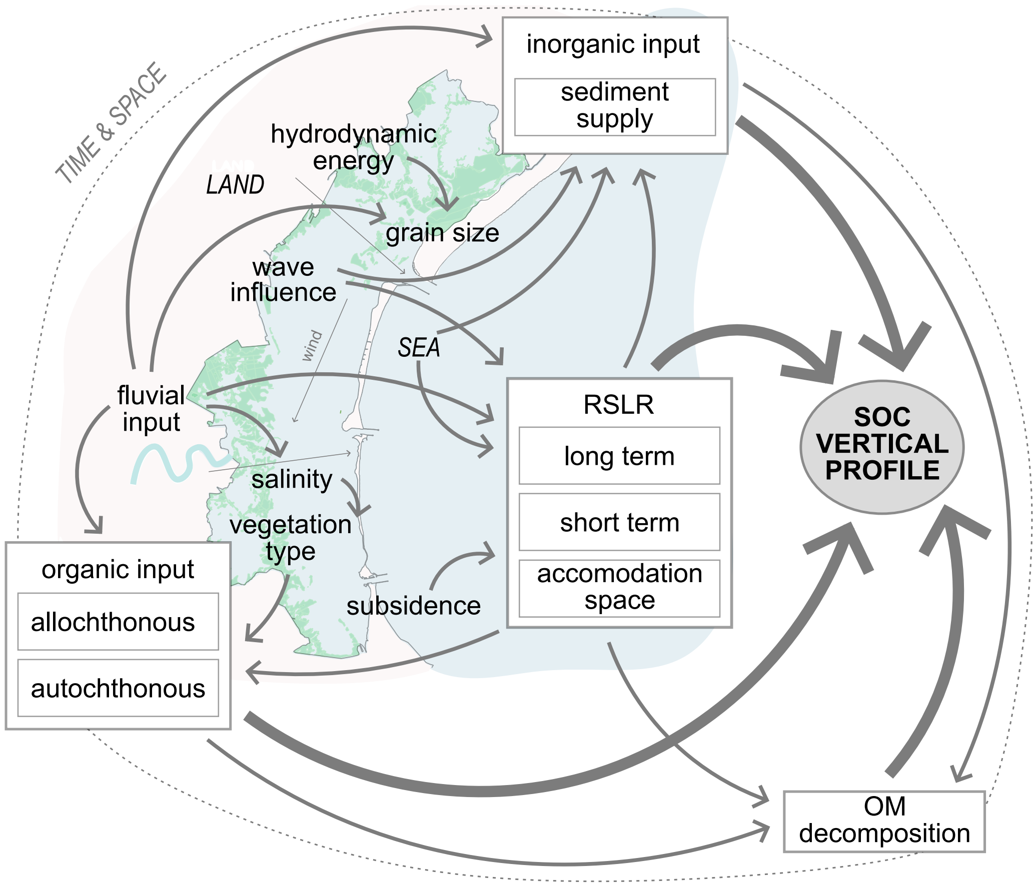

Figure 12. Conceptual framework of the main drivers shaping SOM and SOC vertical patterns in tidal marsh environments. The main drivers are represented within boxes. Arrows indicate the influence of one variable on another, with bold arrows highlighting the connection between the main drivers and the SOC vertical profile. All variables can vary over time and space across different scales, ranging from basin-wide (as in this example) to a global scale.

Additionally, salt marshes bordering the extensive subtidal flats in the central-southern Venice Lagoon are exposed to strong wind waves generated by the northeasterly Bora wind, the most intense and geomorphologically significant wind in the Venice Lagoon (A. D'Alpaos et al., 2024). During storms, wind waves resuspend tidal flat sediments (Tognin et al., 2024), which are then deposited on the marshes. We hypothesize that at sites exposed to wide fetches subject to storm-driven deposition (CO, FO, CV, CA), variations in storm frequency may be reflected in fluctuations in accretion rates (Bellucci et al., 2007; Kolker et al., 2009), contributing to the observed peaks in OM content. While some suggest that increased inorganic sediment supply associated with wave resuspension stimulate biomass production (Boorman et al., 2001; Song et al., 2022), others argue that OM peaks occur when sediment supply decreases, reducing inorganic input relative to organic contributions from plant biomass (Cassaway et al., 2024; Mudd et al., 2009). Moreover, waves may provide an input of allochthonous organic material (e.g., seagrass wracks) to the marsh surface. Wave effect is detectable also at the marsh scale. At CO and CA, facing tidal flats with important wave activity (Puppin, Tognin, Ghinassi, et al., 2024), R^2 values for the exponential model fit increase with distance from the edge, likely due to the decreasing impact of wave action at inner marsh locations (Tognin et al., 2025).

These observations can be used to generalize and outline a general framework to explain SOM depth distribution in tidal marshes (Figure 12). The primary driver of soil organic carbon profiles in tidal marsh soils is inevitably the organic inputs. Inorganic inputs also play a crucial role, as both components collectively build marsh deposits. The history of RSLR and fluctuations in water levels at various temporal and spatial scales critically affect the accumulation of organic and inorganic inputs—which determines surface accretion rate—by influencing accommodation space, promoting sediment supply through increased flooding, and impacting biomass production. These three primary factors interact with one another and are themselves influenced by a complex network of variables. The impact of RSLR and water level variations is closely linked to sediment availability and supply, which, in turn, affect marsh surface evolution through biogeomorphodynamic feedback. Water levels and sediment supply are influenced by tidal currents, fluvial inputs, and hydrodynamic conditions, which also affect vegetation characteristics and the contribution of both autochthonous and allochthonous organic inputs. Furthermore, factors such as water levels and sediment properties (e.g., grain size)—closely tied to hydromorphodynamic processes and the surrounding geomorphic context—also play a critical role in OM decomposition. Higher OM content is typically associated with relatively high sea level rise and sites influenced by fluvial processes. However, in areas with fluctuating water levels and sediment supply, such as those influenced by fluvial inputs and wave action, the SOM depth distribution tends to be more variable compared to sheltered areas. Stratigraphic analyses are essential for predicting SOM and SOC content in dynamic environments such as tidal systems, as they provide valuable insights into environmental evolution and the temporal dynamics of these drivers. In the absence of direct stratigraphic analyses, geomorphic data can help categorize tidal marshes based on their depositional history (e.g., origin, age, and depth). Despite the variability observed at the scale of individual marshes, it is important to recognize that all these drivers operate across multiple scales, from basin-wide to global, and over various timeframes.

We acknowledge that our enumeration of SOM drivers is incomplete and does not include many biological factors (e.g., OM composition, microbial activity, and soil conditions), which remain critical areas for future research. Additionally, further investigations are needed to better understand and quantify the causal relationships between these drivers and the observed SOM peaks in vertical profiles.

Coupling of data analyzed in our study with the latest ecomorphodynamic models, which align long-term marsh evolution with the stratigraphic record (Mariotti, 2024; Mudd et al., 2009), would significantly enhance our ability to model OM distribution in marsh environments, offering tools for upscaling measurements and enhancing our capacity to predict how these environments respond to climate change and anthropogenic pressures, in terms of both resilience and blue carbon potential.

5. Conclusions

Our study highlights the complex interplay of factors influencing SOM dynamics and carbon storage in intertidal environments. Variability in SOM depth distribution is primarily driven by stratigraphic shifts and the depositional history of individual sites. We found that tidal marsh environments have a carbon storage potential approximately twice as high as that of transitional zones and tidal flats. Additionally, tidal marsh deposits influenced by freshwater inputs and reed-dominated vegetation showed higher OM content than salt marshes. However, OM density remained similar, likely due to the low density of organic-rich deposits.

Even within tidal marsh deposits, SOM and SOC vertical patterns often diverge from the classical exponential model. Our data show that OM patterns in these environments are shaped by multiple factors, including sediment supply and organic inputs contributing to marsh deposit formation. These factors are further modulated by relative sea-level rise, river input, wave exposure, and vegetation characteristics, all of which depend on geomorphic conditions.

These findings highlight the importance of site-specific assessments that consider local geomorphology, relative sea-level history, and storm exposure when estimating SOC stocks. Additionally, they emphasize the need for predictive models in tidal environments that can integrate these drivers. Such models would better capture OM variability, enabling more accurate carbon assessments and supporting effective management strategies for coastal wetlands under climate change and anthropogenic pressures. This study provides a conceptual framework for such models, underscoring the potential for enhanced, spatially explicit approaches to predict SOM in diverse coastal landscapes.

Data Availability Statement

The data sets needed to evaluate the conclusions in the paper are available at https://doi.org/10.25430/researchdata.cab.unipd.it.00001316 (Puppin, Tognin, & D'Alpaos, 2024).

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