Earth's Future

RESEARCH ARTICLE
10.1029/2024EF004715

Key Points:

- The average marsh soil carbon stock in the Venice Lagoon is 17,108 ton C km^{-2}, while carbon accumulation rate is 85 ton C km^{-2} yr^{-1}
- Flood regulation strategies, which reduce vertical accretion capacity, may decrease the annual marsh CO_2 sequestration by more than 30%
- Our results highlight the importance of considering local variability and methodological differences, complicating blue carbon assessments

Supporting Information:

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

Correspondence to:

A. Puppin,
alice.puppin@unipd.it

Citation:

Puppin, A., Tognin, D., Paccagnella, M., Zancato, M., Ghinassi, M., D'Alpaos, C., et al. (2024). Blue carbon assessment in the salt marshes of the Venice Lagoon: Dimensions, variability and influence of storm-surge regulation. *Earth's Future*, *12*, e2024EF004715. https://doi.org/10.1029/2024EF004715

Received 25 MAR 2024
Accepted 30 AUG 2024

Blue Carbon Assessment in the Salt Marshes of the Venice Lagoon: Dimensions, Variability and Influence of Storm-Surge Regulation

Alice Puppin[1,2], Davide Tognin[3], Michela Paccagnella[4], Mirella Zancato[4], Massimiliano Ghinassi[1], Chiara D'Alpaos[3], Marco Marani[3], and Andrea D'Alpaos[1]

[1]Department of Geosciences, University of Padova, Padova, Italy, [2]Department of Land, Environment, Agriculture and Forestry, University of Padova, Padova, Italy, [3]Department of Civil, Environmental and Architectural Engineering, University of Padova, Padova, Italy, [4]Department of Pharmaceutical and Pharmacological Sciences, University of Padova, Padova, Italy

Abstract Salt marshes are intertidal coastal ecosystems shaped by complex feedbacks between hydrodynamic, morphological, and biological processes. These crucial yet endangered environments provide a diverse range of ecosystem services but are globally subjected to high anthropogenic pressures, while being severely exposed to climate change impacts. The importance of salt marshes as "blue carbon" sinks, deriving from their primary production coupled with rapid surface accretion, has been increasingly recognized within the framework of climate mitigation strategies. However, large uncertainties remain in salt marsh carbon stock and sequestration estimation. In order to provide further knowledge in salt marsh carbon assessment and investigate marsh carbon pool response to management actions, we analyzed organic matter content in salt marsh soils of the Venice Lagoon (Italy) from 60 sediment cores to the depth of 1 m and estimated organic carbon stock and accumulation rates in different areas. Organic carbon stocks and accumulation rates were highly variable in different marshes, being affected by organic and inorganic inputs and preservation conditions. Our estimates suggest that the studied marshes store 17,108 ± 5,757 tons of carbon per square kilometer in top 1-m of soil and can accumulate 85 ± 25 tons of carbon per square kilometer per year. However, flood regulation may reduce the annual marsh CO_2 sequestration potential by more than 30%. Our results contribute valuable information for regional carbon assessments, reinforcing the need for integrated coastal management policies to preserve the ecosystem services of coastal environments, and underscore the importance of considering local variability and methodological variations.

Plain Language Summary Salt marshes are coastal ecosystems periodically inundated by tides. They offer crucial ecosystem services, including carbon storage, coastal protection, and biodiversity enhancement. The importance of salt marshes as "blue carbon" sinks has been increasingly recognized within the framework of climate mitigation strategies. Salt marsh vegetation captures and stores organic carbon, removing CO_2 from the atmosphere through photosynthesis. Vertical accretion, driven by the deposition of both organic matter and mineral sediments, promotes the burial and preservation of carbon content in plant tissues and organic litter in the soil. However, uncertainties persist in estimating salt marsh carbon storage and sequestration potential. To address this, we analyzed soil organic content in 10 salt marshes of the Venice Lagoon (Italy). Our estimates suggest that the studied marshes can accumulate the same amount of carbon absorbed by 130,000 trees and highlight the economic value associated with their protection and restoration. However, coastal management actions may impact the carbon storage function of coastal environments. We show that flood regulation may reduce the annual marsh CO_2 sequestration potential by more than 30%. Additionally, our results underscore the importance of considering local variability and methodological variations, which can significantly complicate blue carbon assessments.

1. Introduction

Vegetated coastal ecosystems, including salt marshes, mangrove forests, and seagrass meadows, have been termed "Blue Carbon ecosystems" for their increasingly recognized carbon (C) sequestration and storage potential (Chmura et al., 2003; Duarte et al., 2005; Macreadie et al., 2019; McLeod et al., 2011; Nellemann et al., 2009). Estimates show that the C burial rate per unit area in these ecosystems may be exceptionally high, exceeding that of terrestrial forests by 1–2 orders of magnitude (Chmura et al., 2003; Duarte et al., 2005;

Macreadie et al., 2019; McLeod et al., 2011). In light of this, tidal wetlands may provide a considerable contribution to global long-term C sequestration, despite their limited areal extension (Chmura et al., 2003; Duarte et al., 2005; Macreadie et al., 2019; McLeod et al., 2011). Additionally, tidal wetlands support many other ecosystem services, whose high value is often difficult to estimate (Barbier et al., 2011; Costanza et al., 1997). Tidal wetlands enhance biodiversity (Marani et al., 2013), protect coastal regions against erosion and storms (Fairchild et al., 2021; Möller et al., 2014; Temmerman et al., 2013), help maintaining commercial fisheries, filter nutrients and pollutants, support tourism and recreational activities (Barbier et al., 2011; Costanza et al., 1997).

The intertidal landscape of low-energy temperate coasts is characterized by salt marshes, which are colonized by grass and shrub halophytic vegetation adapted to regular or occasional submersion (Adam, 1990; Mudd et al., 2009). Marshes are intrinsically dynamic environments and their evolution is regulated by feedbacks between hydrodynamic, morphological, and biological processes, which have allowed them to accrete and keep pace with sea-level rise over thousands of years (Brückner et al., 2019; D'Alpaos et al., 2007; Fagherazzi et al., 2012; Marani et al., 2007; Mudd et al., 2009). Salt marsh vegetation captures and stores carbon removing CO_2 from the atmosphere through photosynthesis (Howard et al., 2017; Perillo et al., 2009). Thanks to the peculiar high rates of vertical accretion in tidal marshes, driven by the deposition of both organic matter and mineral sediments, plant tissues and organic litter are then buried into the soil, where up to 90% of marsh carbon stocks are found (Pendleton et al., 2012; Serrano et al., 2019). Moreover, by inhibiting microbial aerobic activity and slowing down decomposition (Puppin et al., 2023), tidal flooding further fosters soil organic carbon (SOC) preservation, thus locking away carbon from the atmosphere over centennial to millennial time scales (Duarte et al., 2005).

However, climate change and anthropogenic disturbances may dramatically alter salt marsh biomorphodynamic equilibrium, jeopardizing their survival (Barbier et al., 2011; Breda et al., 2022; M. L. Kirwan & Megonigal, 2013; McLeod et al., 2011), affecting carbon sequestration (Sandi et al., 2021), and even shifting marshes from net sinks to sources of carbon (McLeod et al., 2011; Pendleton et al., 2012). Global warming, increased carbon dioxide concentration, and sea-level rise have the potential to modify biomass production, organic soil decomposition and surface accretion (Kirwan & Megonigal, 2013; Puppin et al., 2023; Ratliff et al., 2015; Xie et al., 2020; Yang et al., 2023). Human activities directly and indirectly interfere with marsh dynamics through land use changes and alterations of nutrient inputs, sediment dynamics and subsidence rates (Kirwan et al., 2011; Kirwan & Megonigal, 2013). Moreover, to reduce flooding risk, coastal communities are increasingly adopting coastal flooding protection infrastructures (Mooyaart & Jonkman, 2017; Orton et al., 2023), which, however, may change sediment transport in coastal wetlands and reduce salt marsh sediment supply, thus further questioning their future (Tognin et al., 2022). For example, the sediment supply to the salt marshes in the Venice Lagoon (Italy) was shown to be importantly reduced by the operation of the recently-activated storm-surge barrier, known as the Mo.S.E. system, designed to protect the city of Venice from flooding (Tognin et al., 2021).

The adoption of storm-surge barriers to provide coastal flood protection is becoming increasingly common (Mooyaart & Jonkman, 2017; Orton et al., 2023) due to the growing density of human populations and socio-economic activities in coastal zones, which are particularly vulnerable to the effects of climate change. Important examples are found in the river Scheldt Estuary (the Netherlands), St. Petersburg (Russia), the River Thames (United Kingdom), New Orleans (United States) and Venice (Italy), and others are being proposed or planned, such as those in Galveston Bay (United States) (Orton et al., 2023). However, the possible impacts of flood regulation strategies (Tognin et al., 2021) on C dynamics in coastal environments have not been explored and should be considered a global concern.

In light of the increasing interest to include blue C ecosystems as greenhouse-gas-offsetting activities in climate policies and considering the high uncertainty of existing blue C estimates (e.g., Chmura et al., 2003; Sifleet et al., 2011) there is a need to quantify the magnitude of C stocks and fluxes in salt marsh ecosystems. In addition, it is crucial to estimate the potential spatial variability of C stocks and fluxes, especially in the soil where the majority of the long-term C pools persist, and to understand how marshes will be affected by management actions under different scenarios.

Here we estimate the C storage and sequestration potential of the salt marshes in the Venice Lagoon and the impact of flood regulation by storm-surge barriers on C accumulation dynamics. Toward this goal, we analyzed organic matter (OM) and organic carbon (OC) content in salt marsh soils in 720 samples from 60 sediment cores

10.1029/2024EF004715

to the depth of 1 m collected in 10 different areas of the Venice Lagoon, therefore estimating carbon stocks and carbon accumulation rates at the whole system scale, together with their spatial variability.

Our analyses contribute important information for regional carbon assessments and for the inclusion of coastal wetlands as carbon sinks in greenhouse gas (GHG) inventories and climate mitigation strategies. Additionally, we estimate the possible reduction in salt marsh carbon sequestration potential driven by anthropogenic disturbances, such as the reduction of sediment supply and accretion rates induced by flood-regulation strategies. Thus, the outcomes of the present study, paired with the assessment of other ecosystem services, can inform territorial management strategies and support decision makers in designing cost-effective protection policy and optimizing restoration efforts.

2. Materials and Methods

The Venice Lagoon, the largest tidal embayment of the Mediterranean basin with an area of about 550 km^2, is located on the northeastern coast of Italy and connected to the Adriatic Sea through three inlets: Lido, Malamocco and Chioggia (Figure 1a). The Venice Lagoon is a shallow back-barrier lagoon, characterized by a semi-diurnal microtidal regime with average and maximum tidal range of about 1.0 and 1.5 m, respectively. The present-day morphology of the lagoon is the result of the intertwined effects of natural (Holocene sea-level rise, natural subsidence, wind-wave erosion) and human-induced processes (river diversion and reduction in sediment supply, human-induced subsidence, construction of the jetties at the inlets, and excavation of navigable channels) over the last millennium (Carniello et al., 2009; D'Alpaos, 2010). In particular, the artificial diversion of all the major rivers flowing into the lagoon between the fifteenth and seventeenth century, together with more recent modifications of the inlets, strongly influenced the hydrodynamics and sediment supply within the lagoon, triggering a sediment-starved condition and a generalized deepening of the lagoon (Carniello et al., 2009; D'Alpaos, 2010; Finotello et al., 2022; Silvestri et al., 2018). As a result, salt marshes in the Venice Lagoon experienced a 70% surface reduction in the last century (Tommasini et al., 2019).

Ten salt marshes were selected in the whole Venice Lagoon (Figure 1a), in order to provide a spatially-explicit assessment of C stocks and accumulation rates. In the northern lagoon, the Sant'Erasmo (SE), San Felice (SF), and Saline (SA) salt marshes are located at the edges of large tidal channels originating from the Lido inlet. Conversely, the Pagliaga (PA) and Campalto (CA) sites are positioned at the lagoon-mainland boundary in the northern lagoon. PA is situated at the mouth of the spring-fed Dese River, whereas CA is located on continental ground (Bonometto, 2005). The salt marshes in the southern part of the Venice lagoon are known to have originated from pre-existing brackish environments or salinized freshwater areas, due to river diversions (Bonometto, 2005). This region was significantly influenced by the inputs from the Brenta River, which was repeatedly diverted and reintroduced into the lagoon (e.g., D'Alpaos, 2010; Roner et al., 2017). The Mira (MI) and Valle di Brenta (VB) sites are located near the landward boundary, while the Canale Virgilio (CV) and Fossei (FO) sites are situated within the marsh belt in front of the Malamocco and Chioggia inlets. The Conche (CO) salt marsh borders the mainland and faces the extensive subtidal flats that occupy the central-southern part of the Venice Lagoon.

Six uncompacted cores were collected in each of the 10 selected salt marshes, for a total of 60 cores. The core depth of 1 m was selected as international methodologies for SOC assessment are generally based on analyses over depths of 1 m (Howard et al., 2014; IPCC, 2013). For each core, soil samples were taken at 12 depths (0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 75 cm from the surface, see Howard et al., 2014) and subsamples were prepared for different analyses, including soil density, organic matter and carbon content.

Samples were dried at 60°C until a constant weight was achieved. The difference in weight between wet and dry samples was used to estimate the water content. Percent organic matter of each sample was determined through Loss On Ignition (LOI, at 375°C for 16 hr, Roner et al., 2016). Water content and organic matter content were used to estimate the dry bulk density (DBD [ML^{-3}]) (Kolker et al., 2009).

Being a relatively cheap and rapid method, LOI has been widely used to measure organic matter content in marsh soil (Craft et al., 1991; Howard et al., 2014; Ouyang & Lee, 2020). However, LOI does not provide a direct measure of organic carbon. Empirical relationship between organic matter from LOI and organic carbon have been proposed for different wetland systems worldwide (Craft et al., 1991; Holmquist et al., 2018; Howard et al., 2014; Maxwell et al., 2023; Ouyang & Lee, 2020). Nevertheless, caution should be used in the application

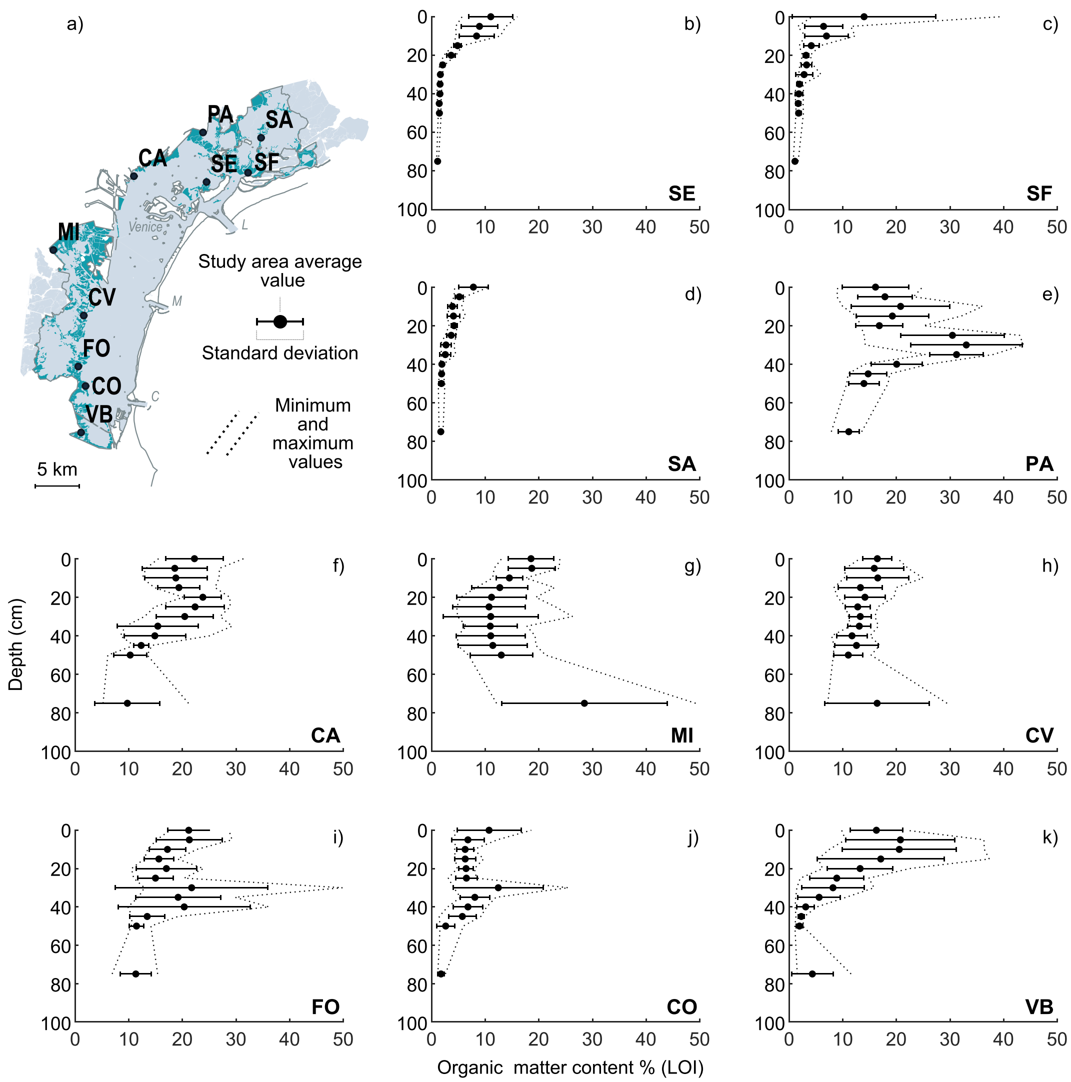

Figure 1. Organic matter content variability. (a) Map of the study sites in the Venice Lagoon (Italy). The Venice Lagoon is a shallow back-barrier lagoon located on the northeastern coast of Italy and connected to the Adriatic Sea through three inlets: Lido (*L*), Malamocco (*M*) and Chioggia (*C*); (b–k) Average of percent organic matter with respective standard deviation, minimum and maximum values at different depths for each of the 10 sites considered. Names of the sites as follows: Sant'Erasmo (SE), San Felice (SF), Saline (SA), Pagliaga (PA), Mira (MI), Canale Virgilio (CV), Fossei (FO), Conche (CO), Valle di Brenta (VB). Organic matter content was estimated using the loss-on-ignition procedure by combusting ground soil samples in a muffle furnace at 375°C for 16 hr (Roner et al., 2016).

of these relationships to systems different from those for which they were calibrated. Site-specific relationship might provide a more accurate estimate of OC content. For this reason, we selected a subset of 102 representative samples to directly determine C content using an elemental analyzer (varioMicro Cube V4.0.10 Elementar Analysensysteme GmbH). In order to correct organic carbon measurements performed through elemental analysis for the inorganic carbon content, ashed subsamples (previously obtained from the LOI procedure) were also analyzed. This procedure allowed us to determine the remaining inorganic carbon in each sample, which was then subtracted from the total carbon measurements. Directly determined C content data (from elemental analysis) were used to fit a regression equation and convert soil organic matter (from LOI) into organic carbon, following Craft et al. (1991) (Figure 2).

SOC stocks [ML^{-2}] in 1 m soil depth were calculated based on Howard et al. (2014) by summing the carbon content in each soil interval along the core:

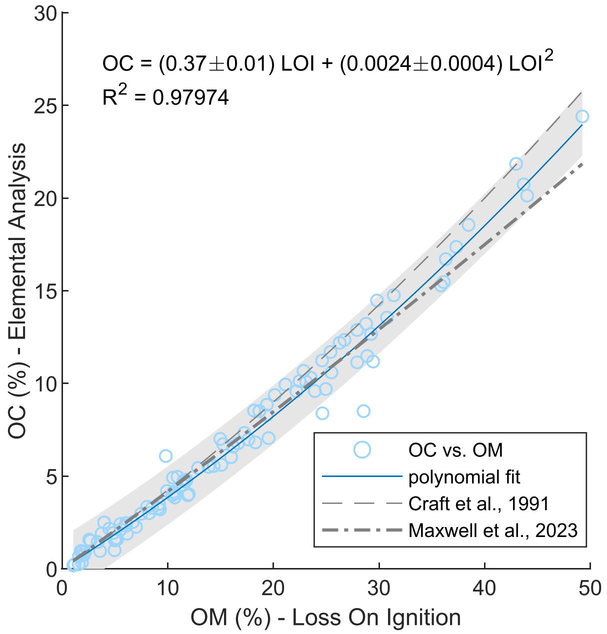

Figure 2. Relationship between Organic Carbon and Organic Matter. The relationship between organic carbon percentage, directly determined through elemental analysis and organic matter percentage measured through Loss On Ignition in marsh soils ($n = 102$).

$$OC\ stock = \sum SCD_i \times l_i$$

$$SCD = OC_i \times DBD_i$$

where SCD_i is soil carbon density (SCD) [ML^{-3}], l_i is the soil thickness [L], OC_i is the organic carbon content and DBD_i is Dry Bulk Density [ML^{-3}] of the ith interval. Carbon stocks within the cores collected in the same area were averaged and converted to ton C km^{-2} to estimate total OC stock down to 1 m depth for each location.

Carbon accumulation rates were estimated by multiplying the average SCD in a reference surface layer of 5 cm (average value for each location) by salt marsh accretion rates derived from measurements based on marker horizons (over a 2–20 years period) (Day et al., 1999; Saintilan et al., 2022; Tognin et al., 2021) (Table S2 in Supporting Information S1). The short-term estimate was chosen due to the availability of marker horizon data and because it was deemed more reasonable for future projections and comparisons, as it excludes the influence of past extensive modifications of the lagoon. However, using the OC content of a superficial reference layer may lead to an overestimation of the carbon accumulation by neglecting the effect of decomposition on longer timescales. Therefore, in order to provide a comparison, beside the short-term estimate, a long-term estimate is provided on the basis of the average SCD in the top-1-m reference interval and accretion rates determined from ^{210}Pb profiles by Bellucci et al. (2007) (to the depth of 50–60 cm, back to about 100 years ago) (Table S3 in Supporting Information S1).

Estimates of carbon accumulation rates (short-term) were used to assess CO_2 sequestration by salt marsh soils in the Venice Lagoon, converting the mass of carbon into CO_2 equivalent by multiplying by 44/12, that is, by the ratio between the weight of carbon dioxide (44 atomic mass units) and the atomic weight of carbon (12 atomic mass units). Despite the present study not delving into the origin of the OM found in the salt marsh soils, we consider it plausible that the majority of it originates internally within the lagoon system, as the Venice Lagoon is currently characterized by minimal inputs of sediment from both riverine and marine sources (Carniello et al., 2012; Tognin et al., 2021).

3. Results

3.1. OM Content in the Salt Marshes of the Venice Lagoon

Organic matter content of marsh soils of the Venice Lagoon, measured through LOI, ranged between 1% and 50%, with remarkable variations both among and within the 10 study areas (Figure 1). Vertical trends of organic matter content showed variable patterns at different sites. At the SE, SF and SA salt marshes (Figures 1b–1d) organic content rapidly decreased with depth, while PA, CA, MI, CV, FO, CO, and VB salt marshes (Figures 1e–1k) showed irregular distributions of organic content with depth, with organic-rich levels at different depths. The highest carbon contents were observed in the PA salt marsh (Figure 1e). Organic-rich fragments of reeds and peat were also observed at the bottom of the cores at CA, MI, CV, FO, and VB sites.

3.2. Relationship Between OC and LOI

To estimate the C content in the soil of Venice marshes based on the LOI measurements, we evaluated the relationship between OC determined through elemental analysis and OM measured through LOI on a representative set of subsamples ($n = 102$) (Figure 2).

Following Craft et al. (1991), we fitted a quadratic relationship (Equation 1) between OM and OC

$$OC = (0.37 \pm 0.01)\ LOI + (0.0024\ \pm 0.0004)\ LOI^2 \tag{1}$$

10.1029/2024EF004715

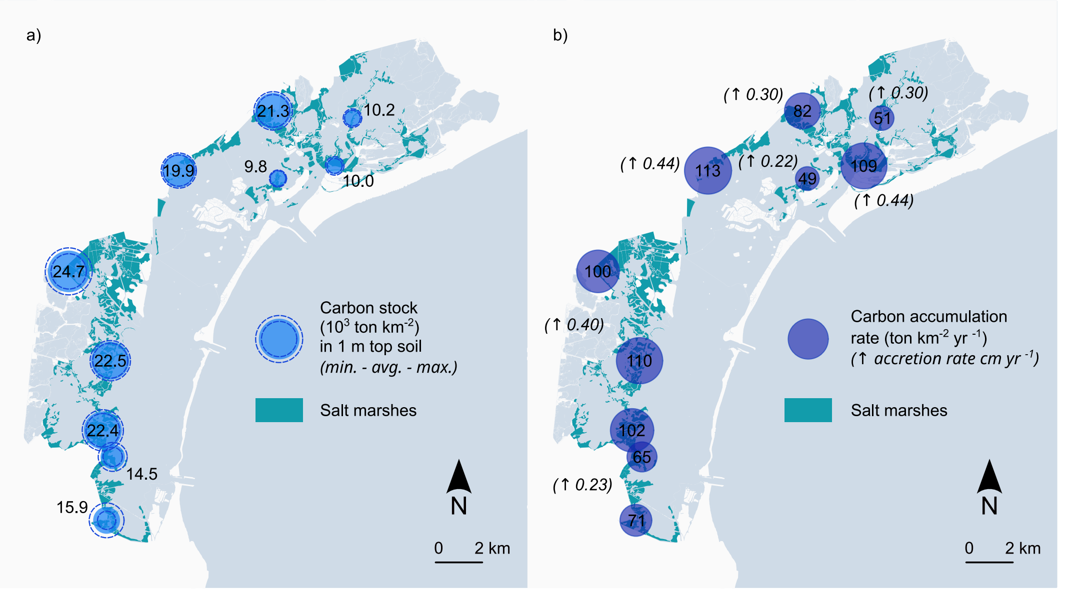

Figure 3. Carbon stock and accumulation in the salt marshes of the Venice Lagoon. (a) Carbon stock in 1 m top soil and (b) carbon accumulation rate estimates at each of the 10 salt marsh sites analyzed. Carbon stock is the sum of the organic carbon content in 1 m soil and carbon accumulation rate results from the product of carbon density in top 5-cm soil and vertical accretion rates derived from measurements from marker horizons (over a 2–20 years period) (Table S2 in Supporting Information S1).

finding a very high correlation ($R^2 = 0.979$, $p << 0.0001$).

3.3. Soil Carbon Stocks and Carbon Accumulation Rates

Using OC content and DBD data, we calculated SCD and then carbon stocks and carbon accumulation rates.

Soil carbon stock estimates ranged between 9,800 and 24,700 ton C km^{-2} (17,108 ± 5,757 ton C km^{-2}), with higher values generally occurring at the landward side of the lagoon boundaries (Figure 3a).

Carbon accumulation rates in salt marshes depend on carbon density and vertical accretion rate (Chmura et al., 2003). Carbon density within the top 5 cm soil layer displayed local mean values ranging between 0.017 and 0.031 g cm^{-3} (0.025 ± 0.004 g cm^{-3}) (Figure 4a). Accretion rates measured at the study sites, based on marker horizons over a 2–20 years period (Day et al., 1999; Saintilan et al., 2022; Tognin et al., 2021) (Table S2 in Supporting Information S1), ranged between 0.22 and 0.44 cm yr^{-1} (Figure 4b). As a result, estimates of carbon accumulation rates ranged from 49 to 113 ton C km^{-2} yr^{-1} (85 ± 25 ton C km^{-2} yr^{-1}) (Figure 3b).

To examine the range of variability between estimates of carbon accumulation rates using different time scales and reference intervals, we provided a long-term estimate in addition to the short-term estimate based on top-5-cm reference interval. The long term estimate was derived from the average SCD in the top-1-m reference interval and accretion rates determined from ^{210}Pb profiles by Bellucci et al. (2007) (to a depth of 50–60 cm, dating back to about 100 years ago) (Table S3 in Supporting Information S1). SCD in the top-1-m reference interval ranged between 0.012 and 0.024 g cm^{-3} (0.019 ± 0.005 g cm^{-3}) (Figure 4a). Accretion rates from ^{210}Pb-based dating methods ranged between 0.13 and 0.47 cm yr^{-1} (Figure 4b). Long-term estimates of carbon accumulation rates ranged from 16 to 110 ton C km^{-2} yr^{-1} (68 ± 38 ton C km^{-2} yr^{-1}) (Figure 4c).

By multiplying the mean C accumulation rate (based on top-5-cm reference interval, 85 ± 25 ton C km^{-2} yr^{-1}) by the total salt marsh area (43 km^2, Carniello et al., 2009), and converting the mass of carbon into CO_2 equivalents, we estimated that the salt marsh soils of the Venice Lagoon may sequester about 13,436 tons of CO_2 per year.

Because the carbon accumulation rate is directly affected by changes in SCD and vertical accretion rate, we investigated the potential effects of changes in these two quantities. In particular, vertical accretion rate has been shown to be reduced by flood regulation (Tognin et al., 2021), because storm-surge barriers hinder sediment

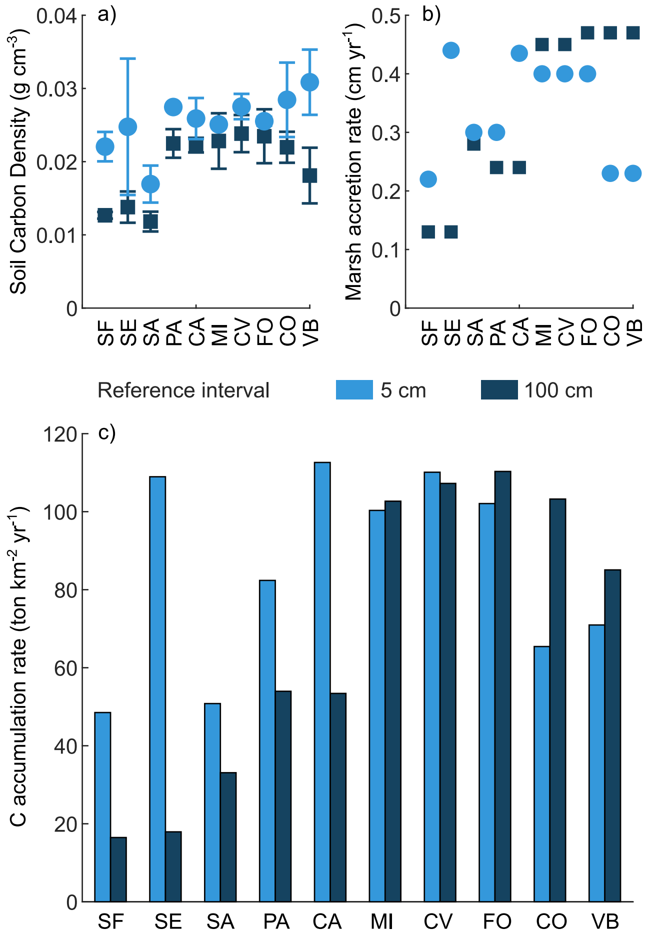

Figure 4. Comparison between short-term and long-term carbon accumulation rate estimates. (a) Mean soil carbon density (error bars represent standard deviation), (b) marsh accretion rate estimate, and (c) carbon accumulation rate estimate in 10 salt marsh study sites on a short-term (5-cm reference interval and marker-horizon accretion rate estimates) and long-term scale (1-m reference interval and ^{210}Pb-based dating methods) (Tables S2 and S3 in Supporting Information S1).

accumulation during storm surges, which account for more than 70% of the annual sediment accumulation on the marshes in the Venice Lagoon. Based on deposition measurements under non-regulated conditions and concurrent water-levels, Tognin et al. (2021) proposed site-specific exponential relationships between sedimentation rates and inundation depth over the marsh surface. By combining water levels in the lagoon, computed through a numerical hydrodynamic model as they would have been modified by Mo.S.E. operations, and site-specific exponential relationships between sedimentation rate and inundation depth, Tognin et al. (2021) calculated the sediment accumulation rate and vertical accretion in the flood-regulated scenario. They estimated an average annual reduction in sediment accumulation on marsh platforms of 28% (ranging from 20% to 60%), which resulted in a vertical accretion reduction of 1.1 mm yr^{-1}. These observations were further supported by the results of numerical hydrodynamic and sediment transport simulations for the first 15 Mo.S.E. closures (Tognin et al., 2022).

Considering the reduction in the accretion rate attributed to the current flooding-regulated scenario (decrease of 1.1 mm yr^{-1} in vertical accretion), we estimated a reduction in carbon accumulation rates ranging between 25% and 50% (Figure 5a), assuming SCD values remain constant. Based on this data, we estimated that storm-surge barrier operations may reduce the annual marsh CO_2 sequestration potential in the Venice Lagoon to approximately 9,022 tons of CO_2 per year, resulting in a 33% reduction compared to the non-regulated scenario (13,436 tons of CO_2 per year).

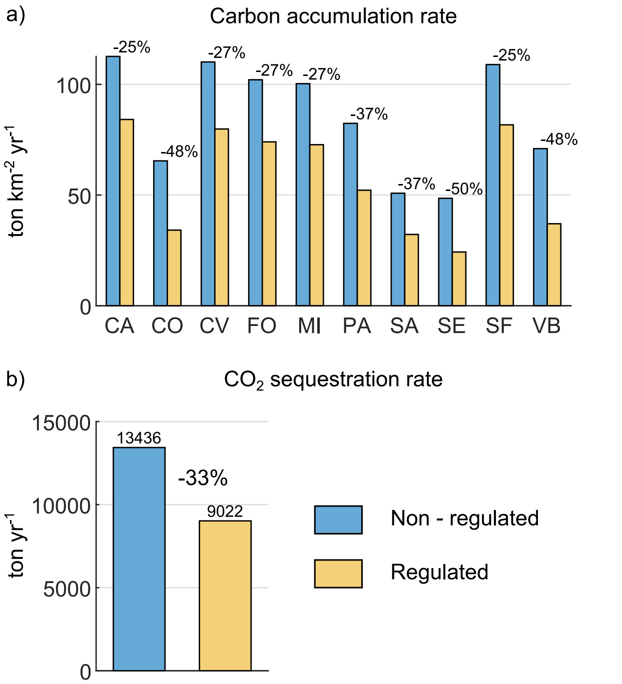

Figure 5. Effect of storm surge barriers on the carbon sink potential of the salt marsh environment. (a) Comparison between non-regulated and regulated scenarios of carbon accumulation rate estimates in 10 salt marsh study sites, considering a 1.1 mm per year reduction in salt marsh accretion rates, due to barrier closures. (b) Comparison between non-regulated and regulated scenarios of total CO_2 sequestration potential of the salt marshes of the Venice Lagoon (total area of 43 km^2).

4. Discussion

4.1. Local Variability of the OM Content in the Salt Marshes of the Venice Lagoon

Organic matter content of marsh soils of the Venice Lagoon showed remarkable variations both among and within the study areas (Figure 1). The widely variable depth-distribution patterns of organic matter content suggest how stratigraphy records the signatures of past depositional and environmental conditions, which evolved differently in different areas of the lagoon. These variations in organic carbon content, determined by organic inputs and preservation conditions, are affected by vegetation characteristics as well as sedimentary conditions. Both these factors are highly variable in space and time, due to shifting environmental characteristics.

At the SE, SF and SA salt marshes (Figures 1b–1d), which are adjacent to large tidal channels departing from the Lido inlet, we observed that organic carbon content decreases rapidly with depth. This decrease is attributed to organic matter decomposition (Van de Broek et al., 2016; Zhou et al., 2006) and a transition from salt marsh to tidal-flat deposits in the deepest layers. In contrast, sites located on the landward side of the lagoon (e.g., PA, CA, MI, Figures 1e–1g) and in the southern lagoon (e.g., CV, FO, CO, VB, Figures 1h–1k) exhibited irregular distributions of carbon content with depth. Organic-rich layers were found at various depths (e.g., 20–40 cm at PA site, 30–40 cm at FO site, 75 cm at MI site), likely corresponding to different episodes of abundant organic inputs. The PA salt marsh (Figure 1e), which exhibited the highest carbon content, is located near the estuary of the springwater Dese River. The lower salinity in this area has facilitated the encroachment of a brackish plant community dominated by *Phragmites australis*, forming a dense and deep network of roots and rhizomes (Moore et al., 2012) that significantly increases soil organic matter content. Carbon-rich fragments of reeds and peat were also observed at the bottom of the cores at some sites close to the lagoon-mainland boundary (CA, 75 cm) and in the southern lagoon (CV, 75 cm; MI, 75 cm) (Figures 1f–1h), indicating traces of pre-existing brackish environments that temporarily occurred over time (Roner et al., 2021). Past and present fluvial inputs crucially affected organic carbon storage at these sites by influencing hydrology, salinity, nutrient status, vegetation characteristics, sediment type, and supply (Ewers Lewis et al., 2020; Howe et al., 2009; Kelleway et al., 2016; Roner et al., 2021; Saintilan et al., 2013). Freshwater inputs impact marsh vegetation, by promoting the growth of reeds (*Phragmites australis*), which are characterized by higher biomass and deeper roots (Moore et al., 2012; Scarton et al., 2002). Additionally, fluvial inputs contribute more terrestrial sediments, which may enhance accretion rates and carbon accumulation. River-fed sediments mainly consist of mud, which can enhance C preservation by reducing sediment aeration compared to sandy sediments (Kelleway et al., 2016), and have higher concentration of suspended particulate OC (Van de Broek et al., 2016).

4.2. Relationship Between OM and OC

To transition from organic matter data to blue carbon assessment, we derived a site-specific quadratic relationship between OM and OC (Figure 2, Equation 1).

This quadratic form indicates that the proportion of OC in soil OM increases with soil OM content. Craft et al. (1991) suggested that this could be explained by the varying ages of OM content. Over time, the anaerobic decomposition of soil organic matter accumulating in organic-rich soils produces reduced compounds, such as refractory organic compounds, which contain a higher C content than fresh plant tissues (Craft et al., 1991).

The parameter values obtained from our data are in close agreement with those reported by Craft et al. (1991), who analyzed 250 soil samples from marshes in North Carolina, USA ($OC = (0.40 \pm 0.01)\,LOI + (0.0025 \pm 0.0003)\,LOI^2$). They are also consistent with those obtained by Maxwell et al. (2023), who developed a general best fitting model using a comprehensive database from various studies capturing a range of

10.1029/2024EF004715

coastal tidal marsh types distributed across the world (OC = (0.41 ± 0) LOI + (0.000683 ± 0.00563) LOI^2). Although in our case the use of conversion equations from the literature (Craft et al., 1991; Maxwell et al., 2023) results in a limited error (see Table S1 in Supporting Information S1), Maxwell et al. (2023) demonstrated considerable variability in the OM-OC relationship across different studies. Thus, site-specific conversion equations are always preferable when feasible. Our site-specific relationship provides a more accurate estimate, especially for larger OM values, where differences between the equations are more pronounced.

4.3. Soil Carbon Stock in the Venice Lagoon Salt Marshes

Consistently with organic matter content variability, soil carbon stock estimates from our study were highly variable across different marshes (17,108 ± 5,757 ton C km^{-2}), with higher values generally occurring at the landward side of the lagoon boundaries (Figure 3a). The average value from our study falls within previous global estimates of salt marsh SOC stock. Global estimates are reported by Duarte et al. (2013), with an average value of 16,200 ton C km^{-2} and a maximum value of 25,900, by Pendleton et al. (2012) with an average value of 25,000 ton C km^{-2}, by van Ardenne et al. (2018) with 26,130 ton C km^{-2} and by Macreadie et al. (2017) with 16,541 ton C km^{-2}. Although some of the variability among global compilations may be due to methodological differences, our results suggest that the sedimentary history and the environmental conditions within a tidal system may generate variable and site-specific carbon accumulation patterns, enhancing blue carbon assessment complexity. Importantly, the values estimated in our study are comparable to carbon stock estimates attributed to temperate and tropical forests (24,300 and 15,300 ton C km^{-2}, respectively, (Watson et al., 2000)) and support the great potential of salt marshes as efficient carbon sinks. High content of organic carbon found deep in salt marsh soils, with well-preserved plant debris dating back hundreds of years (Roner et al., 2021), further confirms salt marsh potential to store carbon over long temporal scales and thus the eligibility of their carbon offsets for greenhouse gas markets. Furthermore, our results on near-surface carbon stocks provide important information to estimate the amount of carbon which is mobilized and potentially lost after salt marsh erosion, degradation or conversion to tidal flats. Although further research is needed to quantitatively investigate the fate of carbon after salt marsh conversion or degradation, once sediment is reworked and exposed to oxygen, some studies suggest that the subsequent increased microbial activity may release large amounts of C to the atmosphere or water column (Kelleway et al., 2016; McTigue et al., 2021; Pendleton et al., 2012).

4.4. Assessing Carbon Accumulation Potential: Variability in Global and Local Data

The average carbon accumulation rate estimate from our study (85 ± 25 ton C km^{-2} yr^{-1}) is lower than current global means (McLeod et al., 2011; Nellemann et al., 2009), although it falls within the broad range defined by previous estimates, which span from 27 to 273 ton C km^{-2} yr^{-1} (Sifleet et al., 2011). For example, our values are consistent with results from Macreadie et al. (2017), who compiled all available data on SOC storage in Australia's tidal marshes (323 cores), reporting a mean carbon accumulation rate of 54.52 ± 2.34 ton C km^{-2} yr^{-1}. However, they are lower than the 218 ± 24 ton C km^{-2} yr^{-1} reported by Chmura et al. (2003) and the 151 ton C km^{-2} yr^{-1} reported by Nellemann et al. (2009).

To understand the reasons behind such high uncertainty in carbon accumulation rate estimates in salt marsh soils, we need to consider multiple sources of variability. These estimates are influenced by the product of SCD and accretion rate, both of which can vary due to methodological differences and the intrinsic variability of these parameters across different scales. Furthermore, comparing carbon accumulation rates in salt marsh soils is challenging due to the differences in temporal scales, reference soil layer thickness, and methods for calculating accretion rates (Chmura et al., 2003; Sifleet et al., 2011).

Chmura et al. (2003) presented data from 154 sites across the western and eastern Atlantic and Pacific coasts, as well as the Indian Ocean, Mediterranean and Gulf of Mexico. Their study summarized information on organic carbon density and carbon accumulation rates within salt-marsh (75%) and mangrove soils. Most soil carbon densities were reported based on LOI, although Walkley Black and dichromate digestion methods, as well as elemental analysis, were also used. LOI measurements were converted through the relationship reported by Craft et al. (1991). Vertical soil accumulation rates, representing averages over periods ranging from 1 to 100 years, were determined through ^{137}Cs and ^{210}Pb dating or marker horizons methods. The average SCD for salt marshes reported by Chmura et al. (2003) is 0.039 ± 0.003 g cm^{-3}, which is higher than the mean value measured in our study (0.025 ± 0.004 g cm^{-3}) (Figure 5a). Larger SCD values were found in the Mississippi Delta by Bryant and

Chabreck (1998) who measured values ranging between 0.093 and 0.19 g C cm^{-3}. Values from our study are similar to those from the global database collected by Maxwell et al. (2023), who reported an average SCD of 0.027 g cm^{-3} (Figure 5a). Maxwell et al. (2023)'s database, which includes 14,493 SCD values, shows high variability (standard deviation of 0.023) and encompasses values from various regions worldwide, different depths, and analytical methodologies.

Thus, apart from the Mississippi Delta data, soil carbon densities measured in our study are consistent with global data. The higher mean global estimate of carbon accumulation rate reported by Chmura et al. (2003) for salt marshes (218 ± 24 ton C km^{-2} yr^{-1}), compared to our estimates is partially explained by the presence of locally larger carbon density values. In addition, variability in accretion rates strongly affects carbon accumulation rate estimates. Some of the highest carbon accumulation rates were indeed reported by Oenema and DeLaune (1988) from the Eastern Scheldt, South-western Netherlands, where observed mean accretion rates ranged from 0.4–0.9 cm yr^{-1} to 1.0–1.5 cm yr^{-1}, significantly higher than those measured at our study site (0.22–0.44 cm yr^{-1}). Therefore, our carbon accumulation estimates are generally consistent with previous findings (Figure 5).

Comparisons among carbon accumulation rate estimates are further complicated by their dependence on the time scale and reference soil layer depth considered (DeLaune et al., 2018). Short time scales and thinner soil layers typically produce larger estimates of C sequestration and OC stocks in blue carbon ecosystems, due to the common decline in OC density with soil depth (Mueller et al., 2019).

To better contextualize our results, we examined the difference between estimates of carbon accumulation rate estimates using various time scales and reference intervals in the Venice Lagoon. As expected, we found higher SCD values in the topsoil (5 cm). However, minor differences were observed at sites at the landward side of the lagoon (e.g., PA, CA, MI, CV, FO) (Figure 6a), which show irregular depth-distributions of carbon content, with organic-rich levels at deeper soil layers.

Marsh accretion rate estimates show a contrasting behavior between the northern and southern lagoon sites, with higher short-term estimates in the northern lagoon and higher long-term estimates in the southern lagoon (Figure 6b). The latter may be attributed to changes in the accretion rate due to variations in sediment supply as a consequence of the repeated diversions of the Brenta River in the southern Venice Lagoon (Roner et al., 2017).

Consequently, the relationship between short-term (SCD 5-cm-topsoil mean, 2–20 years marker-horizon accretion rate estimates) and long-term (SCD 1-m mean, ^{210}Pb-based dating methods back to about 100 years ago) carbon accumulation rate estimates at our study sites is variable. Short-term estimates are higher in the northern lagoon, where recent accretion rates are higher, whereas long-term estimates are generally slightly higher in the southern lagoon, where accretion rates have decreased over time.

This highlights time scale and reference interval as key factors in comparing C stock and accumulation rate estimates in wetland environments. It also underscores the need to consider the local variability and the historical evolution of the study system, to improve blue C assessments.

Moreover, although our results suggest that using a superficial reference interval may lead to an overestimation of the carbon accumulation rate over longer periods, accounting for decomposition processes remains challenging. Varying environmental conditions, such as vegetation quality and substrate characteristics, can significantly affect the preservation of organic material.

4.5. The Value of Salt Marsh Carbon Sequestration and the Effect of Flood-Regulation Strategies

Although the carbon accumulation rates in the salt marshes of the Venice Lagoon are lower than global estimates, they still provide significant ecosystem services. These marshes sequester approximately 13,436 tons of CO_2 per year, which is equivalent to about 20% of the annual emissions from waterborne navigation in the city of Venice (66,000 ton CO_2e yr^{-1}) or about 17% of the annual local emissions from the aviation system at the Venice Marco Polo Airport (77,000 ton CO_2e yr^{-1}) (CIRIS–City Inventory Reporting and Information System–2018). This highlights the crucial role of salt marsh ecosystems in mitigating GHG effects.

Carbon sequestration has a monetary value, which can be assessed through the market price of carbon set in carbon offset markets. In the European Emission Trading System (EU ETS), the first-established and largest carbon market globally, the average spot price of emission allowances (EUA) was about 80 euros per ton of CO_2e in 2022, whereas it was about 84 euros per ton of CO_2e in 2023 (https://www.eex.com/en/market-data/

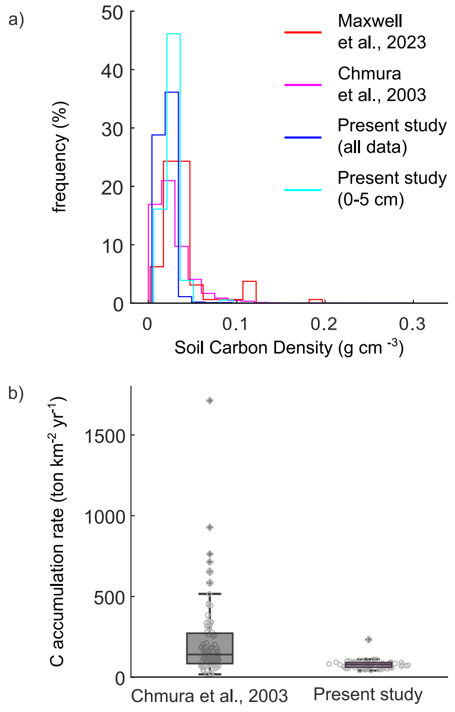

Figure 6. Carbon density and accumulation observations in relation to previous findings. (a) Comparison of Soil Carbon Density and (b) comparison of C accumulation rate values obtained from our study with literature data from Chmura et al. (2003) and Maxwell et al. (2023). In the box plots the central 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 "+" marker. Swarm plots show single values (circles).

environmental-markets/auction-market). Based on the average 2022 spot price, the annual CO_2 sequestration value from the salt marshes of the Venice Lagoon (13,436 tons of CO_2e per year) amounts to approximately 1.08 million euros per year, whereas it amounts to approximately to 1.12 million euros per year at the 2023 average spot price.

It is important to note that EU carbon prices are highly volatile and have rapidly increased since the reform of the EU ETS in 2018 (Directive 2018/410/EU, see Figure S1 in Supporting Information S1). EUA spot prices undergone a further skyrocket growth starting in 2021, reaching a record high of about 100 euros per ton of CO_2e in February 2023 (Figure S1 in Supporting Information S1), and they are currently undergoing a slight decrease. The observed increase in EU carbon prices might continue in the future, as a result of the ever-growing challenge of meeting emission reduction targets. As a result, the monetary values of the annual CO_2 sequestration in the salt marshes of the Venice Lagoon might similarly increase, making polices for marsh preservation and restoration increasingly appealing.

As previously highlighted, vertical accretion plays a crucial role in determining carbon accumulation rates in salt marsh soils. In sediment starved systems like the Venice Lagoon, where riverine and marine sediment inputs are now negligible (Carniello et al., 2012; Tognin et al., 2021), vertical accretion rate may be particularly low. Furthermore, the operation of the Mo.S.E. storm-surge barriers can further reduce salt marsh vertical accretion by lowering water levels within the lagoon during storm surges, which are fundamental suppliers of sediment to salt marshes (Tognin et al., 2021).

In the current flooding-regulated scenario, we estimate a reduction in carbon accumulation rates ranging between 25% and 50%, based on the decreased accretion rates observed by Tognin et al. (2021), assuming soil SCD values remain constant. Because the decrease in vertical accretion is spatially uniform (Tognin et al., 2021), the relative reduction in carbon accumulation rates is larger at sites with lower accretion rates (e.g., SE).

Our data suggest that the operation of storm-surge barriers could potentially reduce the annual CO_2 sequestration capacity of the Venice Lagoon's marshes to approximately 9,022 tons of CO_2 per year, resulting in a 33% reduction compared to the non-regulated scenario (13,436 tons of CO_2 per year). This highlights the crucial role of vertical accretion in determining CO_2 sequestration potential of tidal environments, in addition to its importance for salt-marsh survival and associated ecosystem services. For a more comprehensive understanding, further research is needed to access how reduced sediment inputs affect vegetation growth, and organic contribution to marsh accretion, and, consequently, SCD.

According to our estimates, the reduction in annual marsh CO_2 sequestration potential due to storm-surge barrier operations may indeed generate a loss of approximately 354,000 euros per year at the 2022 average EUA spot price (i.e., about 33% of 1.08 million euros). In the medium-long run, on the basis of the conservative assumption that the EUA average spot price does not increase and remain constant at the 2022 average price, the present value of future monetary losses for the period 2024–2050 would be about 6.12 million euros, assuming a discount rate of 3.5% (Social Time Preference Rate—STPR), which is usually adopted in cost-benefit analysis (Treasury, 2022). However, if we assume, as a conservative scenario, the 2020 EUA average spot price (i.e., about 25 euros per ton of CO_2e), which was registered before the further 2021 skyrocket price growth, the present value of the above monetary losses for the period 2024–2050 would be equal to about 1.87 million euros, assuming all other factors remain the same. In light of the above considerations on the EUA price trend, the latter monetary value reasonably represents a lower bound of the CO_2 sequestration present value, thus suggesting that the role of the marsh environment must not be underestimated in cost-benefit analyses and decision-making processes.

As a part of a comprehensive strategy to achieve emission reduction targets, our projection supports the usefulness of including blue C ecosystems in climate policies, starting from the local and regional scale. Moreover, our results reveal that flood regulation through storm-surge barriers in the Venice Lagoon may crucially decrease marsh C sequestration potential, reinforcing the need for integrated coastal management policies to enhance salt marsh resilience and to pursue the preservation of related ecosystem services, including C accumulation (Orton et al., 2023).

5. Conclusions

In this study, we assessed the carbon stocks and accumulation rates of salt marshes in the Venice Lagoon, investigating their variability and the influence of flood regulation by storm-surge barriers on carbon accumulation dynamics. Our estimates underscore the significant potential of salt marshes as efficient carbon sinks. The SOC stock estimates obtained align with previous global estimates and are comparable to those of temperate and tropical forests. Furthermore, our findings on carbon stocks provide critical insights into estimating the carbon mobilized and potentially lost after salt marsh erosion or degradation. While our carbon accumulation estimates fall within the wide range defined by previous studies, they are below current global means. As our analysis reveals the consistency of SCD values with global data sets, this discrepancy may be mainly attributed to the relatively low accretion rates characterizing the Venice Lagoon. Our findings suggest that flood regulation strategies, further reducing the vertical accretion capacity of marshes, may significantly impact their carbon accumulation potential. Additionally, our results underscore the importance of considering local variability and methodological variations, which can significantly complicate blue carbon assessments and comparisons between different sites.

In conclusion, our analyses contribute valuable information for regional carbon assessments and highlight the need for further research efforts to address uncertainties in blue carbon assessment for the inclusion of coastal wetlands in greenhouse gas inventories and climate mitigation strategies. Moreover, they reveal possible impacts of flood regulation strategies on marsh carbon sequestration potential, thereby reinforcing the need for integrated coastal management policies to preserve the ecosystem services of coastal environments. Building interest in the recently-recognised value of tidal marshes in carbon offset markets and nature-based climate change mitigation may be an opportunity to promote their protection and restoration, contributing to the preservation of a multitude of naturally co-occurring ecosystem services.

Acknowledgments

This scientific activity was performed in the Research Programme Venezia2021, coordinated by CORILA, with the contribution of the Provveditorato for the Public Works of Veneto, Trentino Alto Adige and Friuli Venezia Giulia, Research Line 3.2 (PI A.D.). The University of Padova SID2021 project, "Unraveling Carbon Sequestration Potential by Salt marsh Ecosystems" is also acknowledged (PI A. D.). This study was funded within the RETURN Extended Partnership and received funding from the European Union Next-GenerationEU (National Recovery and Resilience Plan – NRRP, Mission 4, Component 2, Investment 1.3 – D.D. 1243 2/8/2022, PE0000005) and within the PRIN 2022 project "Eco-geomorphic CArbon Pumping from rivers To blUe caRbon Ecosystems." This study was supported by the Italian Ministry of University and Research (MUR) through the project titled "The Geosciences for Sustainable Development" (Budget MUR – Dipartimenti di Eccellenza, 2023–2027; Project ID C93C23002690001). The authors thank the colleagues and technical staff of the Department of Biology, the Department of Pharmaceutical and Pharmacological Sciences and the Department of Geosciences, University of Padova, for fieldwork and laboratory analysis support. Open access publishing facilitated by Universita degli Studi di Padova, as part of the Wiley - CRUI-CARE agreement.

Data Availability Statement

The data sets generated during and/or analyzed during the current study are available in the Research Data Unipd repository, https://researchdata.cab.unipd.it/id/eprint/709 (Puppin et al., 2022).

References

Adam, P. (1990). *Saltmarsh ecology*. Cambridge University Press. https://doi.org/10.1017/CBO9780511565328

Barbier, E. B., Hacker, S. D., Kennedy, C., Koch, E. W., Stier, A. C., & Silliman, B. R. (2011). The value of estuarine and coastal ecosystem services. *Ecological Monographs*, *81*(2), 169–193. https://doi.org/10.1890/10-1510.1

Bellucci, L. G., Frignani, M., Cochran, J. K., Albertazzi, S., Zaggia, L., Cecconi, G., & Hopkins, H. (2007). 210Pb and 137Cs as chronometers for salt marsh accretion in the Venice Lagoon - Links to flooding frequency and climate change. *Journal of Environmental Radioactivity*, *97*(2–3), 85–102. https://doi.org/10.1016/j.jenvrad.2007.03.005

Bonometto, L. (2005). Functional characteristics of salt marshes (barene) in the Venice Lagoon, and environmental restoration scenarios. Workshop on Venice lagoon. In C. A. Fletcher & T. Spencer (Eds.), *Flooding and environmental challenges for Venice and its lagoon: State of knowledge* (pp. 473–486). Cambridge University Press.

Breda, A., Saco, P. M., Rodríguez, J. F., Sandi, S. G., & Riccardi, G. (2022). Assessing the effects of sediment and tidal level variability on coastal wetland evolution. *Journal of Hydrology*, *613*, 128387. https://doi.org/10.1016/j.jhydrol.2022.128387

Brückner, M. Z. M., Schwarz, C., van Dijk, W. M., van Oorschot, M., Douma, H., & Kleinhans, M. G. (2019). Salt marsh establishment and eco-engineering effects in dynamic estuaries determined by species growth and mortality. *Journal of Geophysical Research: Earth Surface*, *124*(12), 2962–2986. https://doi.org/10.1029/2019JF005092

Bryant, J. C., & Chabreck, R. H. (1998). Effects of impoundment on vertical accretion of coastal marsh. *Estuaries*, *21*(3), 416–422. https://doi.org/10.2307/1352840

Carniello, L., Defina, A., & D'Alpaos, L. (2009). Morphological evolution of the Venice Lagoon: Evidence from the past and trend for the future. *Journal of Geophysical Research*, *114*(F4), F04002. https://doi.org/10.1029/2008JF001157

Carniello, L., Defina, A., & D'Alpaos, L. (2012). Modeling sand-mud transport induced by tidal currents and wind waves in shallow microtidal basins: Application to the Venice Lagoon (Italy). *Estuarine, Coastal and Shelf Science*, *102–103*, 105–115. https://doi.org/10.1016/j.ecss.2012.03.016

Chmura, G. L., Anisfeld, S. C., Cahoon, D. R. D. R., & Lynch, J. C. J. C. (2003). Global carbon sequestration in tidal, saline wetland soils. *Global Biogeochemical Cycles*, *17*(4), 22–31. https://doi.org/10.1029/2002GB001917

Costanza, R., D'Arge, R., De Groot, R., Farber, S., Grasso, M., Hannon, B., et al. (1997). The value of the world's ecosystem services and natural capital. *Nature*, *387*(6630), 253–260. https://doi.org/10.1038/387253a0

Craft, C. B., Seneca, E. D., & Broome, S. W. (1991). Loss on ignition and kjeldahl digestion for estimating organic carbon and total nitrogen in estuarine marsh soils: Calibration with dry combustion. *Estuaries*, *14*(2), 175–179. https://doi.org/10.2307/1351691

D'Alpaos, A., Lanzoni, S., Marani, M., & Rinaldo, A. (2007). Landscape evolution in tidal embayments: Modeling the interplay of erosion, sedimentation, and vegetation dynamics. *Journal of Geophysical Research*, *112*(F1), F01008. https://doi.org/10.1029/2006JF000537

D'Alpaos, L. (2010). Fatti e misfatti di idraulica lagunare. La laguna di Venezia dalla diversione dei fiumi alle nuove opere delle bocche di porto. In Lettere e Arti Istituto Veneto di Scienze (Ed.), *La laguna di Venezia dalla diversione dei fiumi alle nuove opere delle bocche di porto*.

Day, J. W., Rybczyk, J., Scarton, F., Rismondo, A., Are, D., & Cecconi, G. (1999). Soil accretionary dynamics, sea-level rise and the survival of wetlands in Venice Lagoon: A field and modelling approach. *Estuarine, Coastal and Shelf Science*, *49*(5), 607–628. https://doi.org/10.1006/ecss.1999.0522

DeLaune, R. D., White, J. R., Elsey-Quirk, T., Roberts, H. H., & Wang, D. Q. (2018). Differences in long-term vs short-term carbon and nitrogen sequestration in a coastal river delta wetland: Implications for global budgets. *Organic Geochemistry*, *123*, 67–73. https://doi.org/10.1016/j.orggeochem.2018.06.007

Duarte, C. M., Losada, I. J., Hendriks, I. E., Mazarrasa, I., & Marbà, N. (2013). The role of coastal plant communities for climate change mitigation and adaptation. *Nature Climate Change*, *3*(11), 961–968. https://doi.org/10.1038/nclimate1970

Duarte, C. M., Middelburg, J. J., & Caraco, N. (2005). Major role of marine vegetation on the oceanic carbon cycle. *Biogeosciences*, *2*(1), 1–8. https://doi.org/10.5194/bg-2-1-2005

Ewers Lewis, C. J., Young, M. A., Ierodiaconou, D., Baldock, J. A., Hawke, B., Sanderman, J., et al. (2020). Drivers and modelling of blue carbon stock variability in sediments of southeastern Australia. *Biogeosciences*, *17*(7), 2041–2059. https://doi.org/10.5194/bg-17-2041-2020

Fagherazzi, S., Kirwan, M. L., Mudd, S. M., Guntenspergen, G. R. G. R., Temmerman, S., D'Alpaos, A., et al. (2012). Numerical models of salt marsh evolution: Ecological, geomorphic, and climatic factors. *Reviews of Geophysics*, *50*(1), RG1002. https://doi.org/10.1029/2011RG000359

Fairchild, T. P., Bennett, W. G., Smith, G., Day, B., Skov, M. W., Möller, I., et al. (2021). Coastal wetlands mitigate storm flooding and associated costs in estuaries. *Environmental Research Letters*, *16*(7), 74034. https://doi.org/10.1088/1748-9326/ac0c45

Finotello, A., Tognin, D., Carniello, L., Ghinassi, M., Bertuzzo, E., & D'Alpaos, A. (2022). Hydrodynamic feedbacks of salt-marsh loss in shallow microtidal back-barrier systems. *Earth and Space Science Open Archive*, *32*. https://doi.org/10.1002/essoar.10511787.2

Holmquist, J. R., Windham-Myers, L., Bliss, N., Crooks, S., Morris, J. T., Megonigal, J. P., et al. (2018). Accuracy and precision of tidal wetland soil carbon mapping in the conterminous United States. *Scientific Reports*, *8*(1), 9478. https://doi.org/10.1038/s41598-018-26948-7

Howard, J., Hoyt, S., Isensee, K., Telszewski, M., & Pidgeon, E. (2014). Coastal blue carbon: Methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrasses. In J. Howard, S. Hoyt, K. Isensee, M. Telszewski, & E. Pidgeon (Eds.), *Arlington, Virginia, USA: Conservation international, intergovernmental oceanographic commission of UNESCO*. International Union for Conservation of Nature.

Howard, J., Sutton-Grier, A., Herr, D., Kleypas, J., Landis, E., Mcleod, E., et al. (2017). Clarifying the role of coastal and marine systems in climate mitigation. *Frontiers in Ecology and the Environment*, *15*(1), 42–50. https://doi.org/10.1002/fee.1451

Howe, A. J. J., Rodríguez, J. F. F., & Saco, P. M. M. (2009). Surface evolution and carbon sequestration in disturbed and undisturbed wetland soils of the Hunter estuary, southeast Australia. *Estuarine, Coastal and Shelf Science*, *84*(1), 75–83. https://doi.org/10.1016/j.ecss.2009.06.006

IPCC. (2013). In K. T. Hiraishi, T. Tanabe, K. Srivastava, N. Baasansuren, M. J. Fukuda, et al. (Eds.), *Supplement to the 2006 IPCC guidelines for national greenhouse gas inventories: Wetlands*. IPCC.

Kelleway, J. J., Saintilan, N., Macreadie, P. I., & Ralph, P. J. (2016). Sedimentary factors are key predictors of carbon storage in SE Australian saltmarshes. *Ecosystems*, *19*(5), 865–880. https://doi.org/10.1007/s10021-016-9972-3

Kirwan, M. L., & Megonigal, J. P. (2013). Tidal wetland stability in the face of human impacts and sea-level rise. *Nature*, *504*(7478), 53–60. https://doi.org/10.1038/nature12856

Kirwan, M. L., Murray, A. B., Donnelly, J. P., & Corbett, D. R. (2011). Rapid wetland expansion during European settlement and its implication for marsh survival under modern sediment delivery rates. *Geology*, *39*(5), 507–510. https://doi.org/10.1130/G31789.1

Kolker, A. S., Goodbred, S. L., Hameed, S., & Cochran, J. K. (2009). High-resolution records of the response of coastal wetland systems to long-term and short-term sea-level variability. *Estuarine, Coastal and Shelf Science*, *84*(4), 493–508. https://doi.org/10.1016/j.ecss.2009.06.030

Macreadie, P. I., Anton, A., Raven, J. A., Beaumont, N., Connolly, R. M., Friess, D. A., et al. (2019). The future of Blue Carbon science. *Nature Communications*, *10*(1), 1–13. https://doi.org/10.1038/s41467-019-11693-w

Macreadie, P. I., Ollivier, Q. R., Kelleway, J. J., Serrano, O., Carnell, P. E., Ewers Lewis, C. J., et al. (2017). Carbon sequestration by Australian tidal marshes. *Scientific Reports*, *7*(1), 44071. https://doi.org/10.1038/srep44071

Marani, M., Da Lio, C., & D'Alpaos, A. (2013). Vegetation engineers marsh morphology through multiple competing stable states. *Proceedings of the National Academy of Sciences of the United States of America*, *110*(9), 3259–3263. https://doi.org/10.1073/pnas.1218327110

Marani, M., D'Alpaos, A., Lanzoni, S., Carniello, L., & Rinaldo, A. (2007). Biologically-controlled multiple equilibria of tidal landforms and the fate of the Venice lagoon. *Geophysical Research Letters*, *34*(11), L11402. https://doi.org/10.1029/2007GL030178

Maxwell, T. L., Rovai, A. S., Adame, M. F., Adams, J. B., Álvarez-Rogel, J., Austin, W. E. N., et al. (2023). Global dataset of soil organic carbon in tidal marshes. *Scientific Data*, *10*(1), 797. https://doi.org/10.1038/s41597-023-02633-x

McLeod, E., Chmura, G. L., Bouillon, S., Salm, R., Björk, M., Duarte, C. M., et al. (2011). A blueprint for blue carbon: Toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. *Frontiers in Ecology and the Environment*, *9*(10), 552–560. https://doi.org/10.1890/110004

McTigue, N. D., Walker, Q. A., & Currin, C. A. (2021). Refining estimates of greenhouse gas emissions from salt marsh "blue carbon" erosion and decomposition. *Frontiers in Marine Science*, *8*. https://doi.org/10.3389/fmars.2021.661442

Möller, I., Kudella, M., Rupprecht, F., Spencer, T., Paul, M., Van Wesenbeeck, B. K., et al. (2014). Wave attenuation over coastal salt marshes under storm surge conditions. *Nature Geoscience*, *7*(10), 727–731. https://doi.org/10.1038/NGEO2251

Moore, G. E., Burdick, D. M., Peter, C. R., & Keirstead, D. R. (2012). Belowground biomass of Phragmites australis in coastal marshes. *Northeastern Naturalist*, *19*(4), 611–626. https://doi.org/10.1656/045.019.0406

Mooyaart, L., & Jonkman, S. N. (2017). Overview and design considerations of storm surge barriers. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, *143*(4), 6017001. https://doi.org/10.1061/(ASCE)WW.1943-5460.0000383

Mudd, S. M., Howell, S. M., & Morris, J. T. (2009). Impact of dynamic feedbacks between sedimentation, sea-level rise, and biomass production on near-surface marsh stratigraphy and carbon accumulation. *Estuarine, Coastal and Shelf Science*, *82*(3), 377–389. https://doi.org/10.1016/j.ecss.2009.01.028

Mueller, P., Ladiges, N., Jack, A., Schmiedl, G., Kutzbach, L., Jensen, K., & Nolte, S. (2019). Assessing the long-term carbon-sequestration potential of the semi-natural salt marshes in the European Wadden Sea. *Ecosphere*, *10*(1), e02556. https://doi.org/10.1002/ecs2.2556

Nellemann, C., Corcoran, E., Duarte, C. M., Valdés, L., De Young, C., Fonseca, L., & Grimsditch, G. (2009). Blue carbon: A rapid response assessment. In C. Nellemann, E. Corcoran, C. M. Duarte, L. Valdés, C. De Young, L. Fonseca, et al. (Eds.), *Environment. UN environment, GRID-Arendal*. Retrieved from http://www.grida.no/files/publications/blue-carbon/BlueCarbon_screen.pdf
Oenema, O., & DeLaune, R. D. (1988). Accretion rates in salt marshes in the eastern Scheldt, South-west Netherlands. *Estuarine, Coastal and Shelf Science*, *26*(4), 379–394. https://doi.org/10.1016/0272-7714(88)90019-4
Orton, P., Ralston, D., van Prooijen, B., Secor, D., Ganju, N., Chen, Z., et al. (2023). Increased utilization of storm surge barriers: A research agenda on estuary impacts. *Earth's Future*, *11*(3), e2022EF002991. https://doi.org/10.1029/2022EF002991
Ouyang, X., & Lee, S. Y. (2020). Improved estimates on global carbon stock and carbon pools in tidal wetlands. *Nature Communications*, *11*(1), 1–7. https://doi.org/10.1038/s41467-019-14120-2
Pendleton, L., Donato, D. C., Murray, B. C., Crooks, S., Jenkins, W. A., Sifleet, S., et al. (2012). Estimating global "blue carbon" emissions from conversion and degradation of vegetated coastal ecosystems. *PLoS One*, *7*(9), e43542. https://doi.org/10.1371/journal.pone.0043542
Perillo, G. M. E., Wolanski, E., Cahoon, D. R., & Hopkinson, C. S. (2009). Coastal wetlands: An integrated ecosystem approach. In E. Perillo, G. M. E. Wolanski, D. R. Cahoon, & C. S. Hopkinson (Eds.), *(II)*. Elsevier.
Puppin, A., Roner, M., Finotello, A., Ghinassi, M., Tommasini, L., Marani, M., & D'Alpaos, A. (2023). Analysis of organic matter decomposition in the salt marshes of the Venice lagoon (Italy) using standard litter bags. *Journal of Geophysical Research: Biogeosciences*, *128*(6), e2022JG007289. https://doi.org/10.1029/2022JG007289
Puppin, A., Tognin, D., & D'Alpaos, A. (2022). Blue carbon assessment of the salt marshes of the Venice lagoon, Italy. *Research Data Unipd*. https://doi.org/10.25430/researchdata.cab.unipd.it.00000709
Ratliff, K. M., Braswell, A. E., & Marani, M. (2015). Spatial response of coastal marshes to increased atmospheric CO_2. *Proceedings of the National Academy of Sciences*, *112*(51), 15580–15584. https://doi.org/10.1073/pnas.1516286112
Roner, M., D'Alpaos, A., Ghinassi, M., Marani, M., Silvestri, S., Franceschinis, E., & Realdon, N. (2016). Spatial variation of salt-marsh organic and inorganic deposition and organic carbon accumulation: Inferences from the Venice lagoon, Italy. *Advances in Water Resources*, *93*, 276–287. https://doi.org/10.1016/j.advwatres.2015.11.011
Roner, M., Ghinassi, M., Fedi, M., Liccioli, L., Bellucci, L. G., Brivio, L., & D'Alpaos, A. (2017). Latest holocene depositional history of the southern Venice lagoon, Italy. *The Holocene*, *27*(11), 1731–1744. https://doi.org/10.1177/0959683617708450
Roner, M., Ghinassi, M., Finotello, A., Bertini, A., Combourieu-Nebout, N., Donnici, S., et al. (2021). Detecting the delayed signatures of changing sediment supply in salt-marsh landscapes: The case of the Venice lagoon (Italy). *Frontiers in Marine Science*, *8*. https://doi.org/10.3389/fmars.2021.742603
Saintilan, N., Kovalenko, K. E., Guntenspergen, G., Rogers, K., Lynch, J. C., Cahoon, D. R., et al. (2022). Constraints on the adjustment of tidal marshes to accelerating sea level rise. *Science*, *377*(6605), 523–527. https://doi.org/10.1126/science.abo7872
Saintilan, N., Rogers, K., Mazumder, D., & Woodroffe, C. (2013). Allochthonous and autochthonous contributions to carbon accumulation and carbon store in southeastern Australian coastal wetlands. *Estuarine, Coastal and Shelf Science*, *128*, 84–92. https://doi.org/10.1016/j.ecss.2013.05.010
Sandi, S. G., Rodriguez, J. F., Saco, P. M., Saintilan, N., & Riccardi, G. (2021). Accelerated sea-level rise limits vegetation capacity to sequester soil carbon in coastal wetlands: A study case in southeastern Australia. *Earth's Future*, *9*(9). https://doi.org/10.1029/2020EF001901
Scarton, F., Day, J. W., & Rismondo, A. (2002). Primary production and decomposition of Sarcocornia fruticosa (L.) scott and Phragmites australis Trin. Ex Steudel in the Po delta, Italy. *Estuaries*, *25*(3), 325–336. https://doi.org/10.1007/BF02695977
Serrano, O., Lovelock, C. E., B. Atwood, T., Macreadie, P. I., Canto, R., Phinn, S., et al. (2019). Australian vegetated coastal ecosystems as global hotspots for climate change mitigation. *Nature Communications*, *10*(1), 4313. https://doi.org/10.1038/s41467-019-12176-8
Sifleet, S., Pendleton, L., & Murray, B. C. (2011). *State of the science on coastal blue carbon A summary for policy makers*. Nicholas Institute for Environmental Policy Solutions. Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:State+of+the+Science+on+Coastal+Blue+Carbon+A+Summary+for+Policy+Makers#0
Silvestri, S., D'Alpaos, A., Nordio, G., & Carniello, L. (2018). Anthropogenic modifications can significantly influence the local mean sea level and affect the survival of salt marshes in shallow tidal systems. *Journal of Geophysical Research: Earth Surface*, *123*(5), 996–1012. https://doi.org/10.1029/2017JF004503
Temmerman, S., Meire, P., Bouma, T. J., Herman, P. M. J., Ysebaert, T., & De Vriend, H. J. (2013). Ecosystem-based coastal defence in the face of global change. *Nature*, *504*(7478), 79–83. https://doi.org/10.1038/nature12859
Tognin, D., D'Alpaos, A., Marani, M., & Carniello, L. (2021). Marsh resilience to sea-level rise reduced by storm-surge barriers in the Venice Lagoon. *Nature Geoscience*, *14*(12), 906–911. https://doi.org/10.1038/s41561-021-00853-7
Tognin, D., Finotello, A., D'Alpaos, A., Viero, D. P., Pivato, M., Mel, R. A., et al. (2022). Loss of geomorphic diversity in shallow tidal embayments promoted by storm-surge barriers. *Science Advances*, *8*(13), eabm8446. https://doi.org/10.1126/sciadv.abm8446
Tommasini, L., Carniello, L., Ghinassi, M., Roner, M., & D'Alpaos, A. (2019). Changes in the wind-wave field and related salt-marsh lateral erosion: Inferences from the evolution of the Venice lagoon in the last four centuries. *Earth Surface Processes and Landforms*, *44*(8), 1633–1646. https://doi.org/10.1002/esp.4599
Treasury, H. (Ed.). (2022). *The green book: Appraisal and evaluation in central government*. OGL Press. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1063330/Green_Book_2022.pdf
van Ardenne, L. B., Jolicouer, S., Bérubé, D., Burdick, D., & Chmura, G. L. (2018). The importance of geomorphic context for estimating the carbon stock of salt marshes. *Geoderma*, *330*, 264–275. https://doi.org/10.1016/j.geoderma.2018.06.003
Van de Broek, M., Temmerman, S., Merckx, R., & Govers, G. (2016). Controls on soil organic carbon stocks in tidal marshes along an estuarine salinity gradient. *Biogeosciences*, *13*(24), 6611–6624. https://doi.org/10.5194/bg-13-6611-2016
Watson, R., Noble, I., Bolin, B., Ravindranath, N., Verardo, D., & Dokken, D. (2000). Land use, land-use change, and forestry. Intergovernmental Panel on Climate Change Special Report. 978-0521800839.
Xie, D., Schwarz, C., Brückner, M. Z. M., Kleinhans, M. G., Urrego, D. H., Zhou, Z., & van Maanen, B. (2020). Mangrove diversity loss under sea-level rise triggered by bio-morphodynamic feedbacks and anthropogenic pressures. *Environmental Research Letters*, *15*(11), 114033. https://doi.org/10.1088/1748-9326/abc122
Yang, Z., Tognin, D., Finotello, A., Belluco, E., Puppin, A., Silvestri, S., et al. (2023). Long-term monitoring of coupled vegetation and elevation changes in response to sea level rise in a microtidal salt marsh. *Journal of Geophysical Research: Biogeosciences*, *128*(6). https://doi.org/10.1029/2023jg007405
Zhou, J., Wu, Y., Zhang, J., Kang, Q., & Liu, Z. (2006). Carbon and nitrogen composition and stable isotope as potential indicators of source and fate of organic matter in the salt marsh of the Changjiang Estuary, China. *Chemosphere*, *65*(2), 310–317. https://doi.org/10.1016/j.chemosphere.2006.02.026