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TESI DI LAUREA IN EARTH AND CLIMATE DYNAMICS

Carbon stocks in the wetlands of the Po river delta

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Dedica a mia madre e alla mia famiglia

Contents

Abstract

Deltaic wetlands are among the most varied and dynamic environments on Earth, occurring across all major continents. They provide a wide range of ecosystem services that benefit both wildlife and human communities. One of their primary services is carbon sequestration, wherein the waterlogged sediment conditions slow down organic matter decomposition and allow these ecosystems to store carbon long-term. This is particularly important in the context of ongoing climate change and the increasing anthropogenic pressures affecting coastal environments.

This thesis aims to investigate the factors controlling carbon storage in coastal wetlands of the Po river delta. Specifically, it examines the influence of wetland age, water content, sediment grain size, vegetation type, salinity, which also relates to the coastline and freshwater channel proximity, as well as previous land use before marsh formation. Organic matter content was estimated using the Loss on Ignition (LOI) method, and carbon content was estimated via elemental analysis. Additionally, a subset of samples was examined further via laser grain-size measurements.

Organic matter content and depth-integrated carbon stocks varied substantially among sites. Organic matter was strongly associated with gravimetric water content, whereas relationships with median grain size and mud content were weak. However, differences in recovered core length limited direct comparison of carbon stocks among wetlands.

The goal of this study is to provide a broad assessment of the carbon stocks of the Po river delta wetlands and to improve our understanding of the environmental factors controlling carbon accumulation, contributing to the evaluation of their role in climate change mitigation and coastal wetland management.

Riassunto

Le zone umide deltizie rappresentano alcuni degli ambienti più eterogenei e dinamici della Terra e sono presenti in tutti i principali continenti. Esse forniscono un'ampia gamma di servizi ecosistemici a beneficio sia della fauna selvatica sia delle comunità umane. Tra questi, uno dei più rilevanti è il sequestro del carbonio: le condizioni di saturazione idrica dei sedimenti rallentano i processi di decomposizione della materia organica, favorendo così l'accumulo e la conservazione del carbonio per lunghi periodi. Questo processo assume particolare rilevanza nel contesto degli attuali cambiamenti climatici e delle crescenti pressioni antropiche che interessano gli ambienti costieri.

La presente tesi si propone di analizzare i fattori che regolano lo stoccaggio del carbonio nelle zone umide costiere del Delta del Po. In particolare, vengono analizzati gli effetti dell'età della zona umida, del contenuto d'acqua, della granulometria dei sedimenti, della tipologia di vegetazione e della salinità. Quest'ultima variabile è inoltre strettamente correlata alla distanza dalla linea di costa e dalla rete dei canali di acqua dolce. Lo studio considera anche l'uso del suolo precedente alla formazione della zona umida, al fine di valutarne la possibile influenza sui processi di accumulo del carbonio. Il contenuto di materia organica è stato stimato mediante il metodo della perdita per ignizione (*Loss on Ignition*, LOI), mentre il contenuto di carbonio è stato determinato mediante analisi elementare. Inoltre, un sottoinsieme di campioni è stato sottoposto ad analisi granulometrica mediante diffrattometria laser.

Il contenuto di materia organica e gli stock di carbonio integrati sulla lunghezza delle carote hanno mostrato una notevole variabilità tra i siti. La materia organica è risultata fortemente associata al contenuto gravimetrico d'acqua, mentre le relazioni con la granulometria mediana e il contenuto di fango sono risultate deboli. Le diverse lunghezze delle carote recuperate limitano tuttavia il confronto diretto degli stock tra le zone umide.

L'obiettivo dello studio è fornire una valutazione complessiva degli stock di carbonio presenti nelle zone umide del Delta del Po e approfondire la comprensione dei principali fattori ambientali che regolano l'accumulo di carbonio. I risultati contribuiranno a una migliore valutazione del ruolo di questi ecosistemi nel processo di mitigazione dei cambiamenti climatici, nonché alla definizione di strategie più efficaci per la gestione e la conservazione delle zone umide costiere.

1. Introduction

Deltaic marshes are depositional landforms characterised by their worldwide presence and strong global importance as culturally and economically significant areas. They are located in intertidal zones, which are generally very flat, periodically flooded areas controlled by the interaction of tidal and riverine regimes. They are vegetated areas hosting a variety of halophytic and freshwater plants that stabilise deltas by promoting deposition, reducing erosion, and creating favourable conditions for further wetland expansion *(Zhang et al., 2024).*

Presently, coastal zones are among the most important areas for humans. They are highly productive and host extensive agricultural, livestock-farming, and aquaculture areas *(Simeoni & Corbau, 2009; Wright et al., 2019).* They support around 40% of the world's population, and their disruption negatively impact those communities, which already face instability from the dynamism of coastal environments and as such have less opportunity to adapt to further stresses. Lastly, and very importantly for today's climate, — coastal zones, and in particular the coastal wetlands, are areas with a very high carbon-storage capacity *(Duarte et al., 2005; Howard et al., 2014).* The combination of high rates of organic-matter deposition and slow decomposition due to the waterlogging of the soils makes them highly effective at sequestering and preserving carbon for extremely long periods, over timescales of hundreds to thousands of years. Unlike terrestrial carbon sink ecosystems, coastal wetlands are also less likely to reach these carbon storage limits due to their high rates of vertical accretion *(Howard et al., 2014; Maxwell et al., 2024).* This ecosystem service is vital for future global climate adaptability, as these areas have a strong potential for outpacing sea level rise and retaining carbon in the process.

Deltaic wetlands are particularly vulnerable to the effects of climate change. The vegetation of these ecosystems is very sensitive to salinity and tide level fluctuations, which results in a distinct gradation of various plant species, influenced by their ability to adapt to and survive these harsh conditions *(Sarika & Zikos, 2021).* As a result, minor environmental changes can lead to destabilisation of these delicate communities. A few centimetres of sea level rise can lead to extensive lateral flooding, submerging the marshes occupying those areas, some of them permanently. While some areas are able to outpace global sea level rise, if vertical accretion and marsh migration speeds aren't able to keep up with sea level rise rates, the deltaic wetland communities are lost, leading to losses of biodiversity and blue-carbon sinks.

There is a need to better understand what controls the carbon-sink potential of deltaic wetlands, in particular in areas where new wetlands are being naturally or artificially formed. The main purpose of this study is to examine a range of deltaic-wetland characteristics and assess how these differences affect carbon storage. To reach this goal, we analysed 8 deltaic wetlands in the Po river delta with a total of 10 cores, using the sediments, the vegetation, the history of the areas, as well as relevant studies to further our understanding of the key influencing factors on carbon contents in them.

The Po delta is a vitally important area to the Italian economic and cultural landscape. However, like many other deltas worldwide, it is presently facing increasing environmental and anthropogenic stresses. Accordingly, this study provides information for regional policymakers and environmental authorities on the importance of coastal wetlands as crucial carbon sinks, as well as an overview of the present situation which could motivate future protection and restoration efforts in the delta of the Po river.

2. Study site

2.1 The structure of the Po delta

The Po river delta is a tidally influenced system, with the tidal range of circa 1 m *(van Yperen et al., 2026),* fed by the largest river catchment in Italy. The river flows over northern Italy, from west to east– where the river enters the Adriatic sea. The delta is supported by the main distributaries of the Po: Po di Maistra, Po della Pila, Po delle Tolle, Po di Gnocca (Po della Donzella), and Po di Goro. The Po di Levante branch, where once the main river passed through, is now deteriorated and is even considered inactive by some *(Simeoni & Corbau, 2009).* The delta has a broadly triangular, multi-lobe shape and progrades asymmetrically towards the southeast.

2.2 Historical context

The Po floodplain and its delta have been populated by human communities since antiquity due to its productive landscape and have been shaped significantly not only by the expected morphodynamic patterns in the area, but also by anthropogenic agricultural, industrial, and urbanising efforts. It is important to note that, the “natural” or expected morphodynamic patterns are difficult to define. Given that humans have shaped the environment of the Po and its delta significantly, these changes are not only reflected in the morphodynamics of the system but are also deeply incorporated into it at the present time. As such, a clear separation of the two may not be possible.

The modern Po delta, as it looks today, began to form around 400 years ago during the Porto Viro cutoff, which shifted the course of the eastern portion of the Po to its current direction from one further North. This development caused rapid delta progradation, which led to the development of a large number of wetlands, originally spanning almost 120,000 ha *(Simeoni & Corbau, 2009; Corbau et al., 2019b)*. The delta went through a number of changes after that, undergoing multiple phases of land reclamation that enabled the development of extensive agricultural areas *(Corbau et al., 2019a)*, which significantly reduced the total wetland area. By the end of the 20th century, the rapid development slowed due to progressive implementation of protective land policies as well as due to natural hazards *(Corbau et al., 2019a)*, but the delta still continued to lose wetlands, while agricultural areas increased in total area *(Corbau et al., 2019b)*.

In the present day, the Po delta continues to serve as an important economic area, both as an agricultural zone and as an aquaculture area *(Simeoni & Corbau, 2009)*. There is a prediction of the delta experiencing progressive farmland restoration and rural abandonment, which could have a certain positive impact on its natural areas *(Simeoni & Corbau, 2009)*. How significant this effect would be is unclear, as the delta also faces a number of threats due to modern climate change, such as decreased sediment delivery *(Syvitski et al., 2005)*, increasing sea level rise, soil degradation associated with freshwater exploitation, and high torrentiality, which specifically forces local governance into building a large amount of "artificial stabilisation", such as dykes and levees *(Simeoni & Corbau, 2009)*. As supported by Bijlsma et al. in the IPCC report of 1995, the high sensitivity of the delta combined with its low adaptability to climate change creates a high risk of disruption and loss for the Po delta, and in turn – the human and other communities living there.

2.3 The wetlands of the Po delta

The delta hosts a large number of wetlands of varying ages, including areas that show evidence of previous farmland use. These wetlands display a wide range of salinity, which can be examined by observing the vegetation gradient and the proximity of the wetlands to the distributary channels.

The areas of interest were selected across the Po delta, for a total of 8 wetlands, 2 north of Po della Pila and 6 south of it, for a spatially explicit assessment of carbon storage variability. In total, 10 cores were harvested from the wetlands, where most produced 1 core each, and some – 2 cores. The locations of P2/P3, as well as P11/P12 were drawn from the same wetlands, respectively.

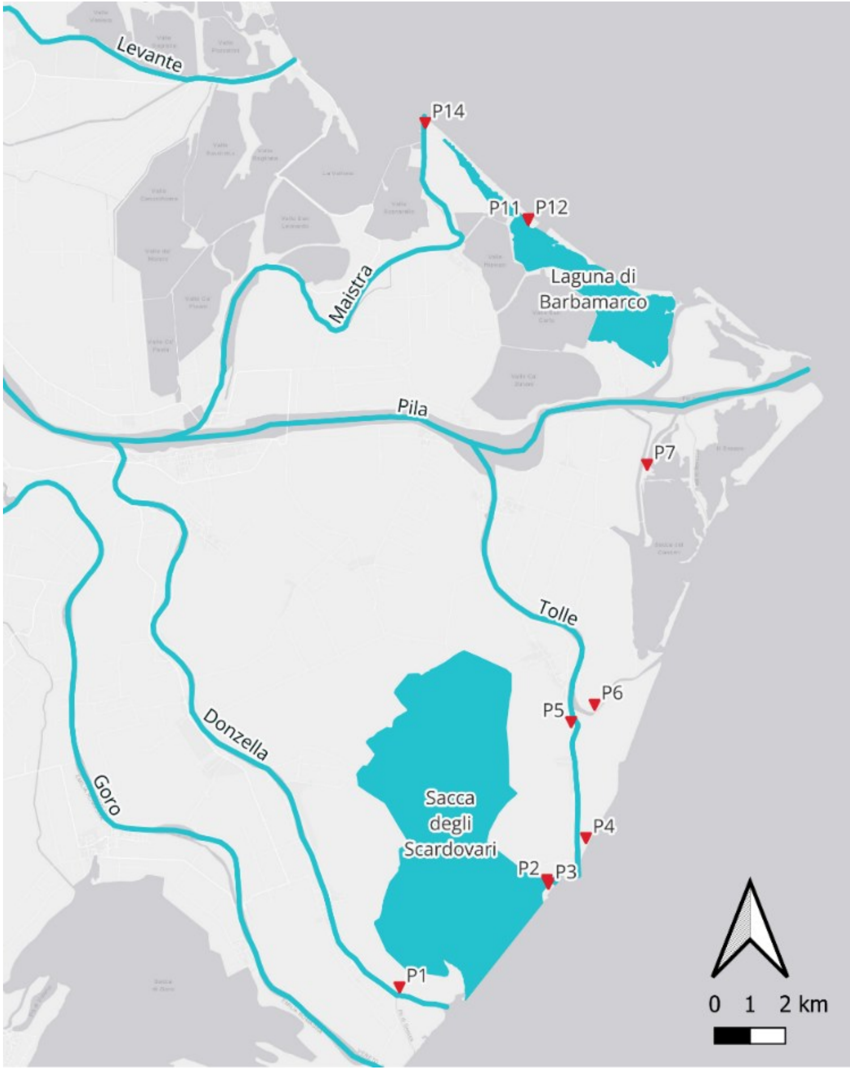


Figure 1. *Map of the Po river delta. Locations of the study sites are marked with red triangles.*

The sampling locations displayed a variety of distinguishing characteristics. P2 and P3, as well as P11 and P12, were located in back-barrier marsh environments in the Sacca degli Scardovari and Barbamarco lagoons, respectively. Both marshes displayed salt- or brackish-marsh vegetation (*Salicornia* species), where the vegetation also clearly demonstrated distinct zonation *(Img. 1, 2)*. Conversely, the remaining sampling locations were freshwater environments. P1, P4, and P5 all show evidence of previous human activity, with satellite images showing vegetation following clear delineations from previous farmland. P6 is located near a distributary of Tolle. P7 is located near a distributary of Pila, in a marsh just past a dam which controls sediment supply to the channel. P14 is located right at the inlet of Maistra, and only shows up on satellite images between 2002 and 2008, as the Maistra inlet relocated further south.

Sample name	Wetland age estimate (years)	Salinity
P1	16-22	Freshwater
P2	<49	Saltwater
P3	<49	Saltwater
P4	>49	Freshwater
P5	<16	Freshwater
P6	>49	Freshwater
P7	~49	Freshwater
P11	17-24	Brackish
P12	17-24	Saltwater
P14	>24	Freshwater

Table 1. *Basic sample characteristics (age and salinity levels).*

3. Materials and methods

3.1 Fieldwork; core sampling and qualitative analysis

The sediments were sampled using a standard auger corer with 3 cm by 1 m dimensions, by driving the instrument into the substrate until the resistance from the underlying sediment was too severe to continue. Given this, the core length ranged from around 30 centimetres to the full length of the corer. The cores were then split into individual samples, with the top 10 centimetres being cut into 2.5-centimetre-long sections and the subsequent length into 5-centimetre ones, for a total of 85 samples. Finally, each sample was bagged and brought to the laboratory at the University of Padova, where it was refrigerated and processed over the following weeks. During sampling, some sections of the sediment cores were lost because of differences in sample water content — sections with especially high water content slipped out of the corer and were unrecoverable.

The sampling locations were selected via satellite imagery, with the wetland age used as the qualifier. The goal was to select wetlands of different ages, both old and young, to assess the effect of wetland age on marsh carbon content. For the wetlands of P2/P3 and P11/P12, respectively, the sampling was performed twice due to the presence of distinct transition zones within them. This decision was made to better understand how carbon storage may vary with relatively small environmental changes, such as salinity and, therefore, vegetation. As can be seen from appendices 1 and 2, these transition zones can be very sharply delineated.

To analyse the vegetation, we performed qualitative analysis of the species present in the sampling locations. Additionally, we took detailed photographs of the vegetation and the locations themselves to support our in-field observations using visual analysis of the photographs and correlating them with the vegetation database of Parco Naturale Regionale Veneto del Delta del Po. Due to the seasonality of the days during which we collected our samples (Late April, June), not all of the plants presented blooms or fruits. As such, information for plant identification was limited.

3.2 Sediment processing and analysis

To determine organic matter and carbon contents, Loss on Ignition (LOI) and combustion elemental analysis (EA) were performed. Before analysis, the samples were dried in an oven at 45-60 degrees Celsius for 24 hours, or until constant mass was reached. The samples were weighed before and after drying to determine gravimetric water content. They were then divided into three subsamples for LOI, elemental analysis, and grain-size analysis. For LOI, samples were heated to 375 degrees Celsius in a muffle furnace for 16 hours, causing the combustion of organic matter and the loss of structurally bound water from some minerals.

Elemental analysis was performed using a Vario MICRO CHNS analyser (Elementar Analysensysteme GmbH). This method quantifies total carbon directly but is more time-consuming and expensive than LOI. Therefore, all samples were analysed by LOI, whereas a representative subset spanning the observed LOI range was selected for EA. Because untreated samples contain both organic and inorganic carbon, corresponding post-LOI samples were analysed alongside untreated material, and organic carbon was estimated from the difference. The resulting relationship between EA-derived OC and LOI-derived OM was described using a polynomial regression, which was then used to estimate OC in the remaining samples *(Fig. 3)*.

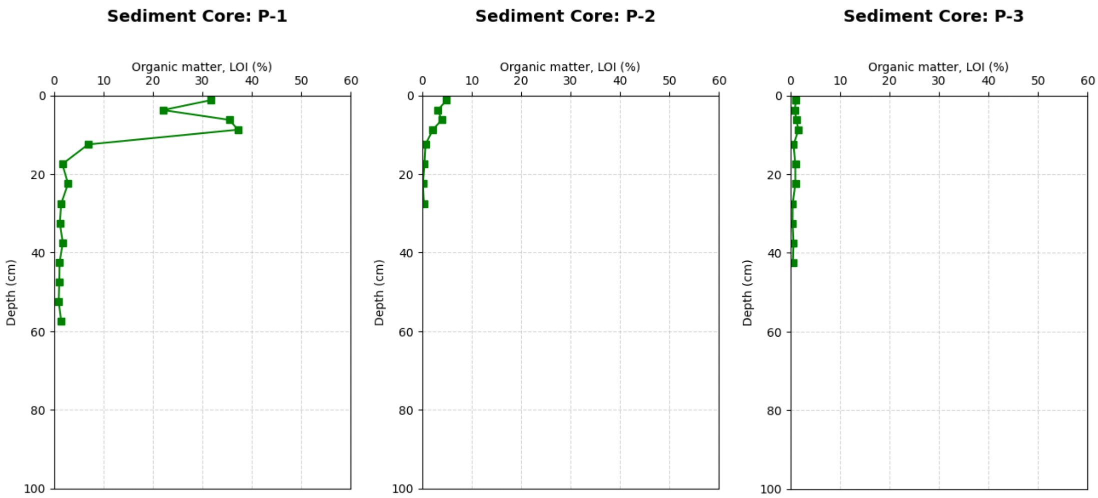
Using a laser mastersizer, we processed a number of samples for grain size, selected using the same distribution method as for the EA so the samples were representative of the varying organic contents. It is worth noting that the mastersizer measurements were somewhat compromised by the presence of OM within the samples. To account for this, the sample measurements which presented a peak correlating with OM size (above 1 mm) were cut off *(App. 3)*.

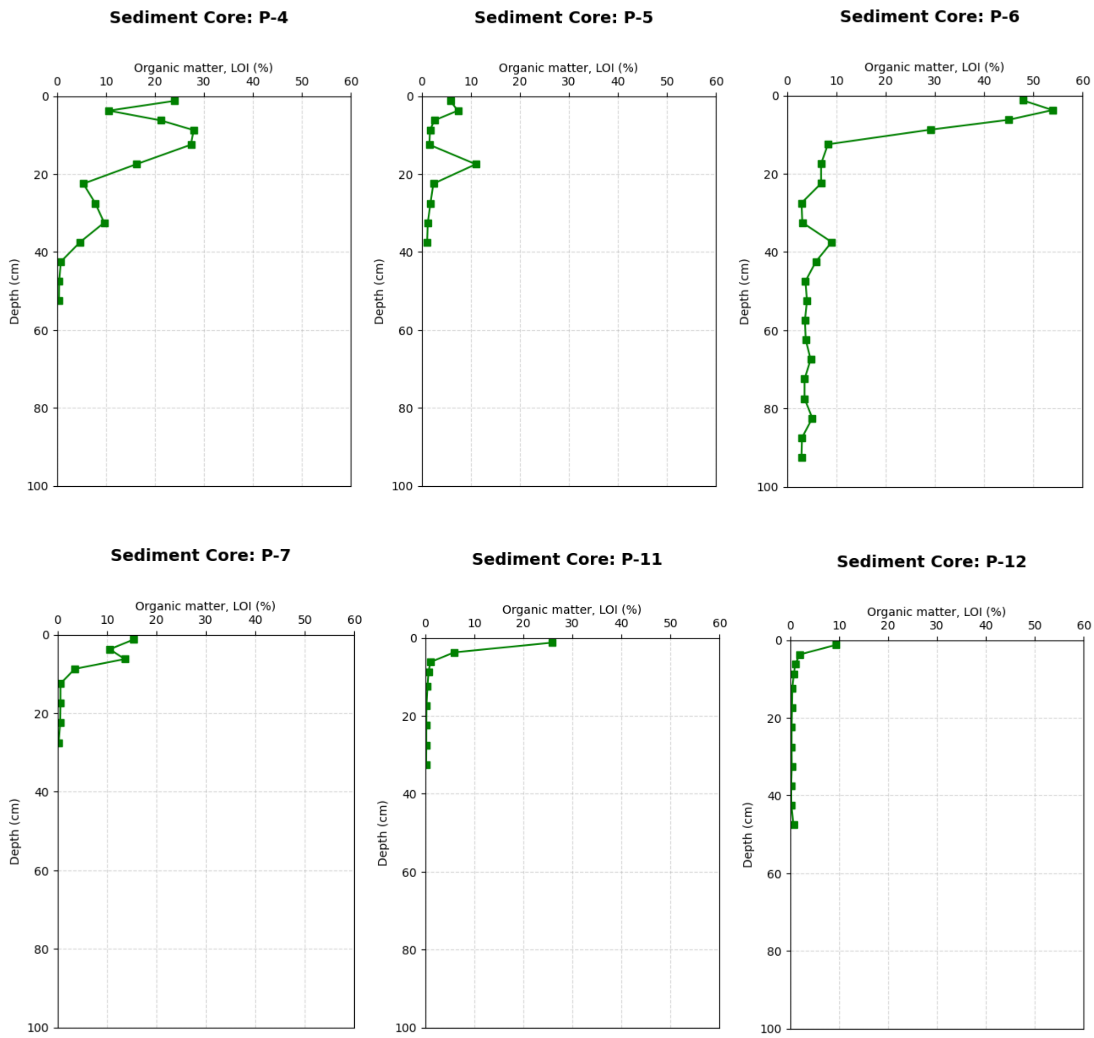
Lastly, following Kolker et al. *(2009)*, dry bulk density (DBD) was estimated from LOI-derived OM. Estimated DBD and OC content *(Fig. 3)* were then used to calculate soil carbon density and depth-integrated carbon stocks for the recovered cores. Because DBD was estimated from LOI-derived OM, uncertainty in OM propagates into the resulting carbon-stock estimates.

4. Results

4.1 Organic matter content in the Po river delta

LOI-derived OM content in the Po Delta wetlands ranged from slightly negative values to over 50%. The slightly negative estimates are not physically meaningful and were interpreted as analytical uncertainty around zero. The lowest OM content occurred in core P3 *(Fig. 2c),* which remained close to zero throughout its depth, whereas the highest values occurred in P6 *(Fig. 2f)*, followed by P4 *(Fig. 2d)*. Cores P2, P7, P11, and P12 showed a rapid decrease in OM with depth *(Fig. 2b, g, h, i)*. By contrast, P1, P4-P6, and P14 displayed irregular depth distributions with several OM-rich layers *(Fig. 2a, d-f, j)*. P14 also showed increasing OM below 70 cm depth.





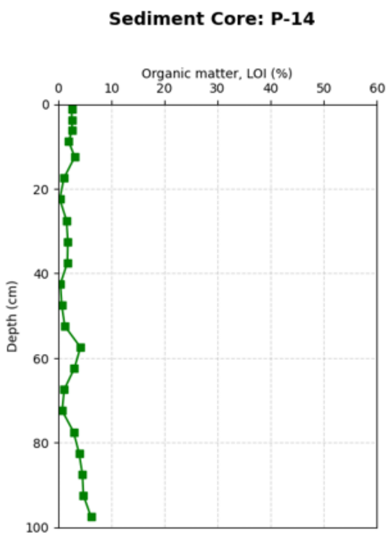


Figure 2 (a-j). *LOI-derived organic matter content against core depth.*

4.2 Relationship between organic carbon and LOI

To estimate soil OC from the LOI data, 20 samples spanning the observed OM range were selected for EA, and the relationship between OM and OC was determined (Fig. 3).

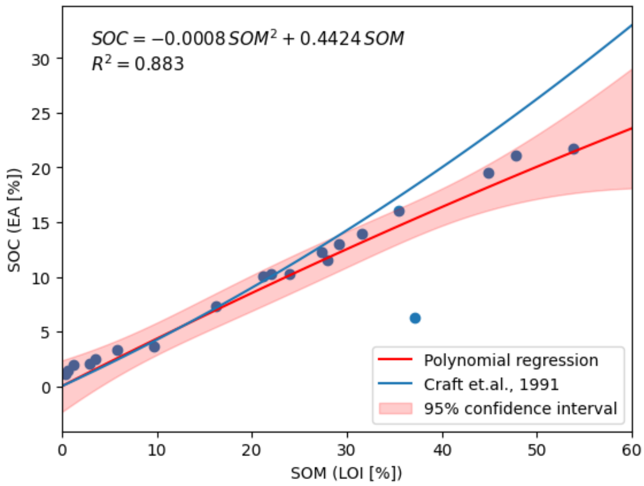


Figure 3. *LOI-derived soil organic matter content [%] versus EA-derived soil organic carbon content [%].*

Following Craft et al. (1991), we performed a polynomial fit between OC and OM in the samples. The following regression equation was obtained, where the coefficient uncertainties represent 95% confidence intervals:

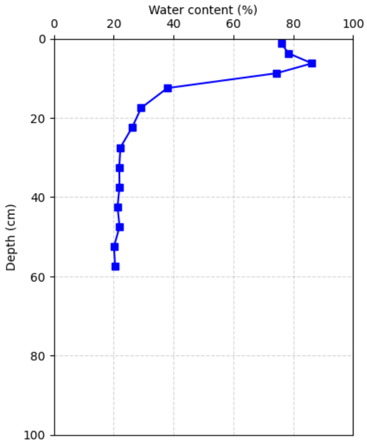
$$SOC = (0.4424 \pm 0.2255)SOM + (-0.0008 \pm 0.0045)SOM^2$$

The regression fit was found to be strong ($R^2 = 0.883$).

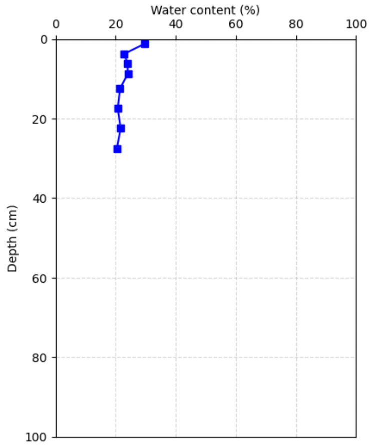
4.3 Soil organic matter and water content

Our samples showed a variation of water content between 20 and 90%. Given our data, OM showed a strong positive association with gravimetric water content accross all samples. The trends displayed by the water content curves closely follow those observed in OM content plots *(Fig. 2, a-j)*. Additionally, a simple exponential regression was fitted for OM and water content *(Fig. 4k)*. This further supports the strong correlation between these values ($R^2 = 0.891$).

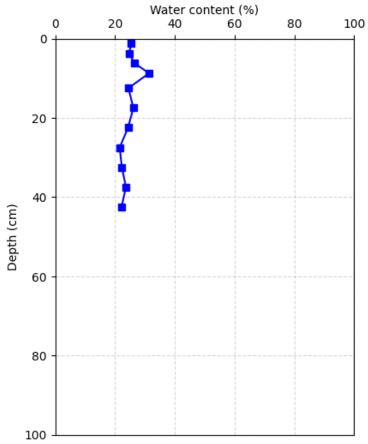
Sediment Core: P-1



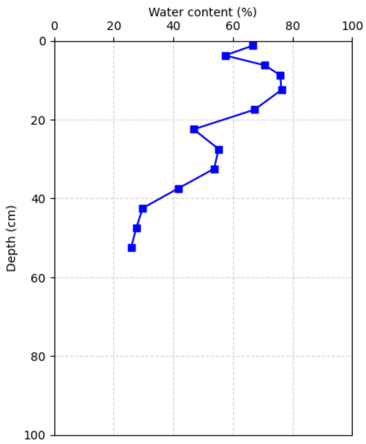
Sediment Core: P-2



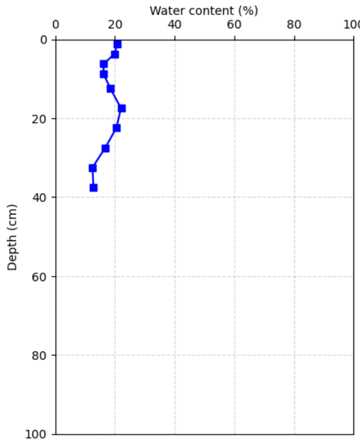
Sediment Core: P-3



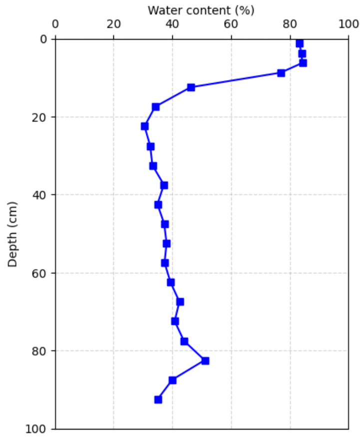
Sediment Core: P-4



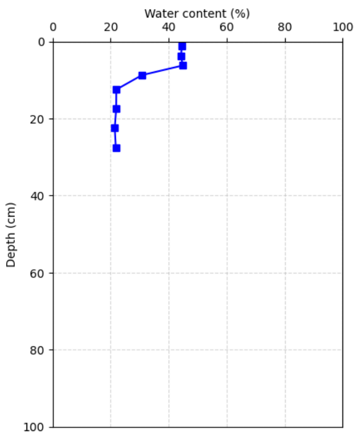
Sediment Core: P-5



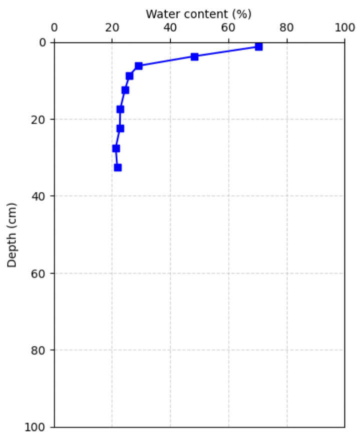
Sediment Core: P-6



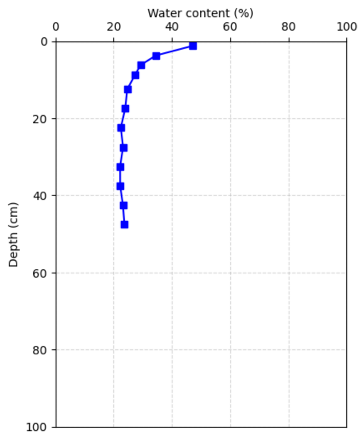
Sediment Core: P-7



Sediment Core: P-11



Sediment Core: P-12



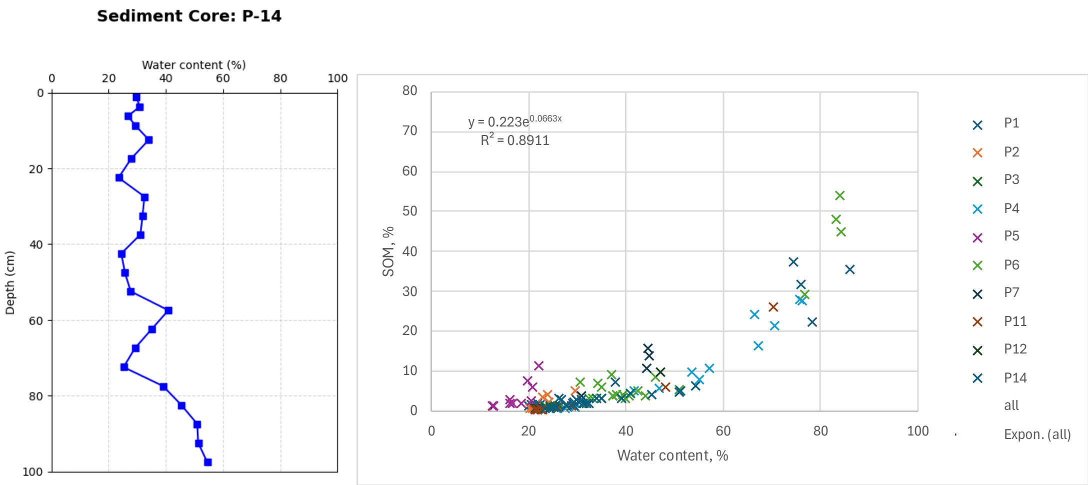


Figure 4 (a-k). *(a-j) Gravimetric water content against core depth. (k) Gravimetric water content against LOI-derived soil organic matter content, with colours identifying the source cores. The exponential curve describes the fitted relationship.*

4.4 Sediment grain size and organic matter content

The samples selected for mastersizer analysis show highly variable sediment grain sizes (lowest = 3.715 μm, highest = 813.708 μm), ranging from mud to coarse sand. The median grain size of these samples (D50) ranges between 17 and 234 μm.

Given our data, OM content showed weak to no correlation with sediment grain size *(Fig. 5b)*, and a weak correlation with mud contents within the samples *(Fig. 6)*, as well as a moderate correlation with sediment grain size when confined to the lowest size fraction, D10 ($R^2 = 0.404$) *(Fig. 5a)*.

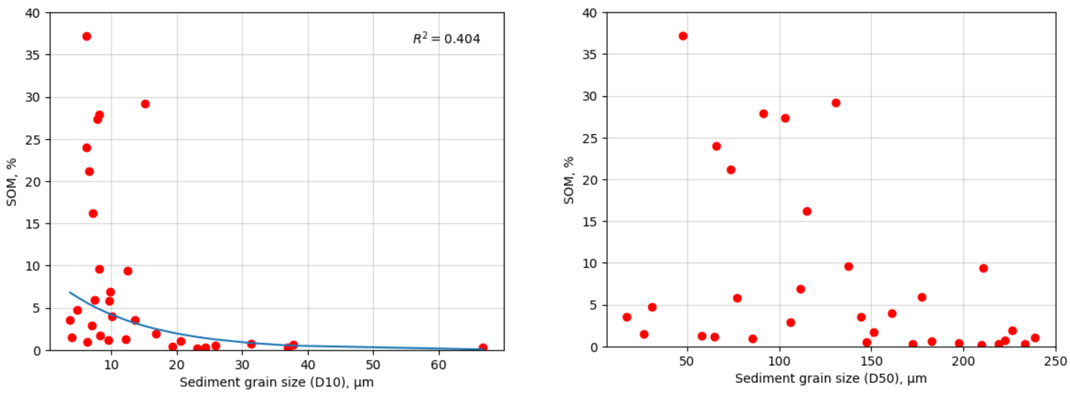


Figure 5 (a-b). *(a) D10 grain-size percentile against soil organic matter content for samples with D10 < 0.063 mm; the exponential curve describes the fitted relationship. (b) Median sediment grain size (D50) against soil organic matter content.*

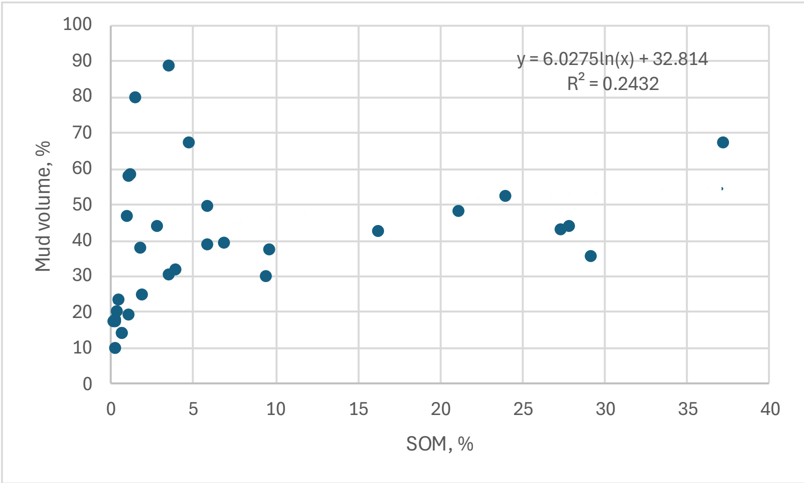


Figure 6. *Sediment mud volume against LOI-derived soil organic matter contents. A logarithmic curve describes the relationship.*

4.5 Vegetation of the Po delta wetlands

Using qualitative observations, we were able to construct a rough distribution of the Po delta wetland vegetation. In the freshwater wetland environments, *Phragmites australis* dominates the landscape. Additionally, nearly all of the freshwater wetlands (particularly P4-P6) contained several individuals highly likely to be *Amorpha fruticosa*, a shrub invasive to the Po delta. Generally, these shrubs were not located with *Phragmites* in the main body of the wetlands but instead surrounded the perimeter.

Wetlands with higher salinity were dominated by halophytic vegetation, where *Phragmites* and other freshwater plants would not be able to survive. A mix of *Salicornia* species, likely *S. veneta* or *S. fruticosa*, occupied areas which, due to the presence of the aforementioned plants, were understood to be salt marshes. All the salt marsh sites also contained *Limonium* species in smaller quantities, which were not flowering at the time but were identified by their characteristic leaf shape.

Many of the marshes also presented a variety of grasses, both halophytic and freshwater kinds. *Juncus maritimus*, found in brackish transition zones, akin to the one in P11, were primarily found in elevated areas, while freshwater species occupied areas around *Phragmites*, further away from the water.

4.6 Carbon stocks of the Po delta wetlands

Depth-integrated carbon stocks calculated over the recovered core lengths ranged from 1,191 to 13,164 t C km-2. The highest cumulative values occurred in P6 and P4, whereas the lowest occurred in P3, P2, P12, and P11. However, because recovered core lengths varied from 28 to 100 cm, these values are not directly comparable among sites and should not be interpreted as carbon stocks standardised to a common soil depth.

The calculated stocks were generally lower than values reported for Venice Lagoon salt marshes by Puppin et al. *(2024)*, although the value for P6 fell within the published range. Direct comparison remains limited because the present estimates were integrated over unequal recovered core lengths.

Sample name	Total core length (cm)	Total carbon stock (10^3 ton/km²)
P1	60	5.705
P2	28	1.430
P3	43	1.191
P2 & P3 (averaged)		1.310
P4	51	8.009
P5	40	4.613
P6	90	13.164
P7	28	2.783
P11	35	1.453
P12	50	1.276
P11 & P12 (averaged)		1.365
P14	100 (Full)	6.311

Table 2. *Depth-integrated carbon stocks calculated over the recovered core lengths.*

5. Discussion

5.1 Organic matter content in the Po river delta

The samples we collected from the Po river delta presented highly variable OM content from site to site. These inconsistencies between the different wetlands of the delta demonstrate historic records of past depositional events as well as how the environmental conditions of the areas affected total retained OC. By observing the different spatial and temporal snapshots of the delta, we see its dynamic range of hydrological, vegetational, and sedimentary factors, all of which affect OM content distribution as well as one another.

In the first case, we observe rapidly decreasing OM content with depth (sites P2, P7, etc.). This relationship is suggested to be influenced by organic matter decomposition *(Craft et al., 1991; Puppin et al., 2024)*. In the second case, OM presented an irregular distribution with depth (P1, P4, etc.). These correlate with freshwater marsh locations dominated by

Phragmites australis reeds. The various spikes of OM throughout the depth profile likely indicate high organic deposition events of the past.

At the site of P14, which showed an OM spike at high depths while simultaneously having low readings of OM above it, a past marsh location can be inferred. P14 is located right at the Po di Maistra inlet which relocated to its present position after 2002. It is therefore plausible that the wetland at this location is very young, which would explain the low OM readings throughout the length of the core. This can also be explained by the proximity of the wetland to the inlet, as the other young wetland cores did not present low topsoil OM scores. Therefore, we can infer that at P14, the water flow is stronger than at other locations and is too strong for OM to stabilise in the soil profile. It also contained an organic increase at the bottom of the core, unlike other wetlands under our observation. This could then correspond to previous wetland activity, prior to the relocation of the Maistra.

5.2 Relationship between organic carbon and LOI-derived organic matter

Following Craft et al., the increase in OC with increasing soil OM could be related to OM decomposition. This would imply a correlation between OC and the age of the organic deposits, as older deposits undergoing anaerobic decomposition may become relatively enriched in carbon compared with recently deposited OM *(Craft et al., 1991)*.

Although Craft et al. developed a general model, past research suggests that case-specific equations provide higher accuracy *(Puppin et al., 2024)*. Indeed, our data show a closer correlation with our regression equation rather than with Craft et al.'s *(Fig. 2)*, however, the overall fits are rather close. This is likely the result of site-specific environmental influences which alter the distribution, such as lower overall OM concentrations in our cores.

5.3 Soil organic matter and water content

From figures 2 and 4, a clear positive relationship between OM and water content can be seen, which is to be expected based on past research. Generally, soil OC correlates with soil water holding capacity *(Manns et al., 2016)*, which is a majority component of OM. High values of both OM/OC and water content also tend to align with high amounts of soil aggregates, which are made up of soil organic and mineral particles. The increasing size and complexity of soil OM molecules result in a greater number of ionic bonding sites and surface area in soil aggregates, which affects water transmitting and holding capacity of the soils *(Manns et al., 2016).*

By contrast, Minasny and McBratney argue that the studies supporting soil OM as a strong factor in soil water capacity and retention lack sufficient quantitative analysis and vary in estimations of just how strong the effect of OM presence is. They arrived at the conclusion that it does indeed have a positive effect on water retention; however, it is only relevant to conditions at saturation. Using a neural network they developed, they also found that water retention with increasing OC was higher for subsoil rather than topsoil, contrary to what might be expected, as topsoil generally has higher contents of OM.

Our data show a strong association between gravimetric water content at sampling and LOI-derived OM. However, measured water content is not equivalent to water-retention capacity or degree of saturation. Because porosity, volumetric water content, and water-retention curves were not measured, we cannot test whether OM enhanced water retention through the mechanisms discussed by Manns et al. *(2016)* and Minasny and McBratney *(2018).* Conversely, wetter and more reducing conditions may favour OM preservation by slowing decomposition *(Howard et al., 2014; Maxwell et al., 2024)*, and such are the conditions typical of deltaic wetlands and correspond to the ones we observed in the field. The established relationship therefore only demonstrates covariation between water content and OM and does not allow the causality to be fully determined.

5.4 Sediment grain size and organic matter content

Our idea that sediment grain size would inversely correlate with OM contents in the samples was only partially correct, as it only provided a moderate correlation when confined to the lowest sediment fraction *(*$R^2 = 0.404$, Fig. *5a).* This is in line with previous research *(De Falco et al., 2004)*, which shows that sediments larger than mud typically show little to no relationship with OM. Following up on this, sediment mud contents can be used as an alternative predictor of OM contents *(De Falco et al., 2004, Puppin et al., 2025)*, with a positive correlation. This relationship arises due to mud sediments having larger amounts of complexing sites because of the high total sediment surface area and therefore being able to bind with higher amounts of organic compounds *(De Falco et al., 2004).*

However, our analysis showed a weak correlation between mud contents and OM. This difference could potentially be explained by OM deposition differences between the wetland sites. Research suggests that the capacity of the soil to hold organics, determined by mud volume, is not the only determinant of how much OM will be found there, and that the deposition of vegetation debris can override that dependency if it is high enough, in which case the visible relationship between OM and mud volume will be disrupted *(Serrano et al., 2016).*

5.5 Vegetation of the Po delta wetlands

The salt marsh areas contained a variety of halophytic vegetation species. Additionally, these areas were below the water table, with water above the ground surface, and the cores showed significant wetting during the sampling. The areas of salt marsh areas contained small topographic depressions and elevations, where lower areas are flooded for longer periods and experience higher salinity. This creates distinct vegetation zones – lower areas with better-adapted plants and higher ones with those of worse adaptation, respectively.

However, even relatively higher ground in these wetlands is presently showing signs consistent with sea-level rise, and, therefore, salinisation. Indeed, P2 and P3 specifically contained numerous areas with dying plants, particularly trees and grasses, consistent with indicators of progressive salt marsh encroachment onto previously brackish or even freshwater areas.

Generally speaking, the cores taken from freshwater marshes showed more variability in the carbon distribution compared to saltwater or brackish marshes, which had the expected exponential decay of OM with depth, save for P3, which had little to no OM at all. Comparatively, the sampled saltwater marshes showed the lowest overall OM values among all of the cores. These observations potentially indicate lower organic deposition in salt marshes due to smaller plants able to adapt to the saline conditions, and higher organic deposition in freshwater marshes, where vegetation is able to grow much larger and denser.

5.6 Carbon stocks in the Po delta wetlands

The raw depth-integrated stocks broadly followed the OM patterns, with P6 and P4 yielding the highest total values and the salt-marsh cores (P2/P3, and P11/P12) yielding the lowest values. However, these differences cannot be attributed solely to environmental conditions because recovered core lengths were strongly variable, from 28 to 100 cm. Our estimates were generally lower than the global values reported by Duarte et al. *(2013)* and the values estimated by Puppin et al. *(2024)* for the Venice lagoon, although some fell within the published ranges. A new, detailed comparison among sites and with published datasets would require stocks standardised to a common sampling depth.

Although the estimated values indicate substantial carbon storage, stock measurements alone do not quantify sequestration rates or demonstrate that these wetlands currently function as net carbon sinks. The results should therefore be interpreted as estimates of stored carbon rather than direct measures of sink strength.

6. Conclusions

In this study, we estimated organic carbon stocks across several wetlands of the Po delta and examined their relationships with local environmental conditions. Organic matter content and depth-integrated carbon stocks varied substantially among sites. Organic matter was strongly associated with gravimetric water content, whereas relationships with sediment grain size were generally weak, although a moderate relationship was observed for values within the D10 size range. Because recovered core lengths differed among sites and several environmental variables covaried, comparisons among wetlands should be interpreted with caution.

These results provide a first examination of carbon storage in the Po delta wetlands and identify priorities for further investigation. Because our study quantifies stocks rather than accumulation rates, it does not directly determine present-day carbon sequestration but instead aims to provide a springboard for subsequent research. Future assessments would benefit from sampling to a standardised depth and from direct measurements of dry bulk density, porosity, and soil-water retention properties, on top of the environmental characteristics already highlighted in our study. By examining all of them together, further research should provide a more holistic view of not only the carbon storage, but also the carbon accumulation rates of the Po delta wetlands and help in our understanding of their function in the contemporary carbon cycling.

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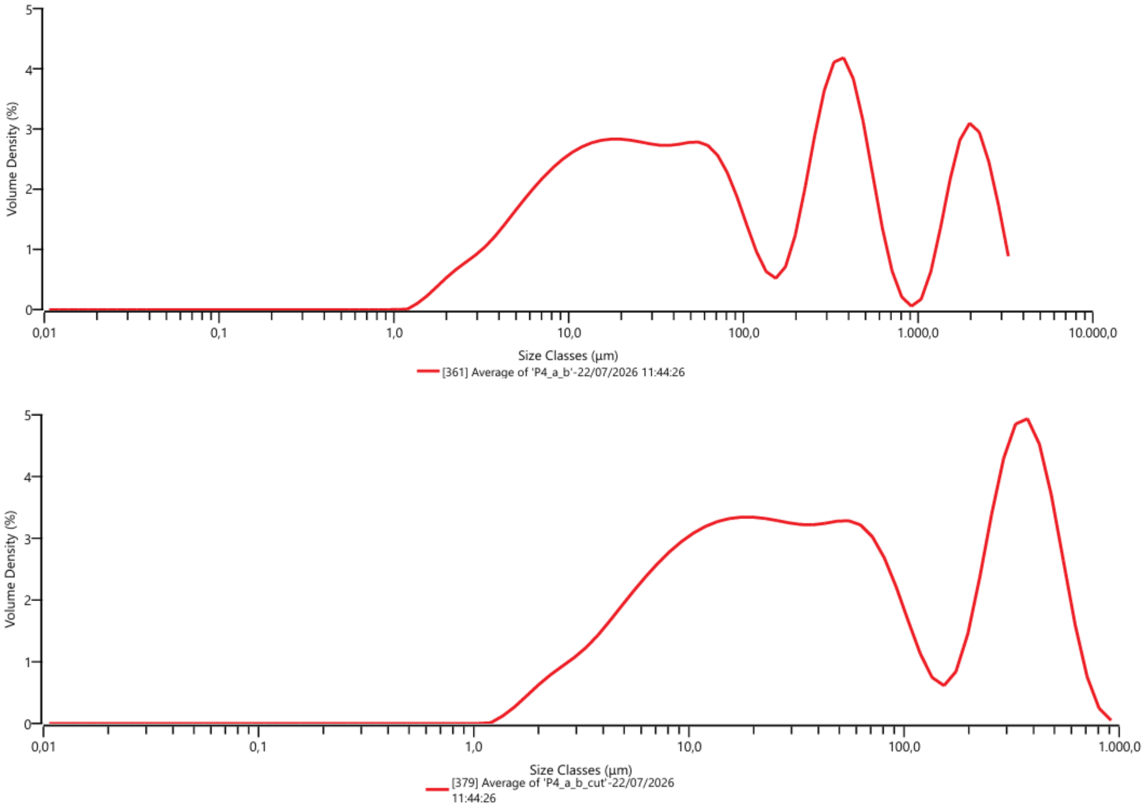
Appendices

Appendix 1. *Photograph of site P11 showing the sharp transition between brackish and saltwater wetlands. Juncus vegetation occurs on the left and Salicornia vegetation on the right.*

Appendix 2. *Close-up photograph of site P11 showing a mixture of Limonium, Salicornia, and grass vegetation, probably Juncus. Some vegetation appears dead, potentially because of increasing soil salinity associated with seawater intrusion.*



Appendix 3 (a-b). *Mastersizer grain size frequency measurement of sample P4-a, measurement b. (a) Sample contains an organic peak (900 µm ≈ 1250 µm). (b) The same sample, with the range of its measurements cut at 1000 µm.*

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