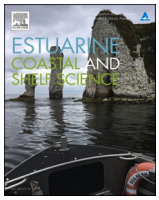
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Emerging trade-offs in saltmarsh ecosystem services under sea-level rise

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ABSTRACT

Coastal defence and carbon storage by coastal wetlands provide an increasingly recognised means of adaptation and mitigation in the face of climate change, yet these same services are threatened by the impacts against which they protect. Our understanding to date tends to consider impacts of rising sea levels on individual marsh services but fails to consider trade-offs and potential interactions between them. For instance, sea-level rise has the potential to enhance carbon storage but may decrease soil stability, erosion resistance and wave-attenuation capacity by creating sub-optimal growth conditions, causing plants to be weaker and smaller. As such, we aim to answer the question: will rising sea levels drive unidirectional impacts, or contrasting 'trade-offs', between saltmarsh carbon storage and coastal defence? We conducted a field experiment across increasing inundation durations beyond the usual seaward limit of *Spartina anglica* growth, mimicking SLR at established vegetation patches, and measured (1) carbon decomposition rates using the teabag index as proxy, (2) sediment stability, and (3) biomechanical traits of *S.anglica* as proxy for wave-attenuation capacity. With increasing inundation duration, rates of carbon decomposition slowed, supporting carbon storage, and therefore positively impacted climate change mitigation. In contrast, both sediment stability and vegetation stiffness decreased and hence negatively impacted climate change adaptation. Our findings point to a short-term trade-off in climate ecosystem services with SLR, where positive impacts on carbon storage may offset negative impacts on coastal defence services. However, since lower sediment stability increases the chance of marsh erosion under extreme events, this will increase over time the likelihood of sediment resuspension and the ultimate rerelease of previously stored carbon into the marine carbon cycle. Thus, the interaction between ecosystem services may lead to a net negative impact of SLR on climate mitigation services. Overall, we highlight the necessity of taking a multi-service approach to considering the impact of global change effects on ecosystem services.

1. Introduction

Current and projected rates of global climate change and sea-level rise (SLR) dictate an urgent need to combat rising atmospheric CO_2 levels. Even in the most positive scenarios where humanity succeeds in rapidly reducing CO_2 emissions, sea-levels are expected to continue to rise, imposing major challenges (IPCC, 2019). There are currently 680 million people globally living in low-lying coastal zones and therefore at a higher risk of flooding under accelerated SLR (IPCC, 2019). While 'hard engineering' structures such as dikes and seawalls have, up to now, been the dominant defence strategy against coastal flooding, changing global conditions call for strategies with greater capacity for adaptation (Temmerman et al., 2013; Bouma et al., 2014; Schoonees et al., 2019; Huynh et al., 2024). Nature-based solutions (NbS), such as incorporating

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wave-reducing saltmarshes into flood defences, may provide a means to protect coastal communities against rising sea-levels and extreme storm events (Möller et al., 2014; Zhu et al., 2020a).

While coastal defence may increasingly serve as a primary motivation for saltmarsh conservation and restoration in at-risk areas, marshes will provide a range of other co-benefits, or ecosystem services (Barbier et al., 2011). One such service, particularly relevant for climate change mitigation, is carbon storage (Macreadie et al., 2021a; Temmink et al., 2022; Mason et al., 2023). Recent estimates show an average saltmarsh standing carbon stock of 400 Mg ha^{-1}, making saltmarshes one of the most carbon-dense ecosystems in the world (Temmink et al., 2022). Via these regulating 'climate services', saltmarsh areas have the capacity to mitigate rising CO_2 levels by acting as a carbon sink, and to adapt to the impacts of climate change, e.g. via sediment accretion to keep pace with sea-level rise. While promising, a paradox-like situation may occur if those saltmarsh services that may help to mediate climate change effects are in turn also threatened by climate-change effects such as SLR, storms and droughts. These effects may impact marsh structure and functioning, particularly where vegetation die-back is possible, and therefore will influence the delivery of ecosystem services (Kirwan and Mudd, 2012; Watson et al., 2016; Strain et al., 2017). The role of marshes in NbS over the coming years will thus depend on the balance between their ability to mitigate climate change, and their ability to adapt to and resist it.

Where vertical accretion equals or exceeds the rate of SLR, it is likely that saltmarshes will be able to maintain their elevation relative to mean sea-level and thus keep pace with rising water levels (Kirwan et al., 2016; Saintilan et al., 2022). It is therefore probable that some marshes will remain present despite accelerating SLR (Campbell et al., 2022). Marsh resilience to SLR is, however, dependent on sufficient space for landward migration, as well as site-specific drivers. Particularly important are the local rate of relative SLR (depending on local scale processes such as subsidence) and the suspended sediment concentration in the water column (Kirwan et al., 2010; Kirwan and Megonigal, 2013). While the marsh might grow vertically, enabling it to keep up with SLR, its seaward boundary can retreat due to erosion at the seaward edge as a result of increased wave exposure (Fagherazzi et al., 2020a). If landward accommodation space is not available, e.g. due to hard coastal defence infrastructure, the marsh extent will decrease (Saintilan et al., 2022). Where suspended sediment supply is limited, saltmarsh vegetation will face higher sea-levels and consequently longer inundation times (Strain et al., 2017; Törnqvist et al., 2020). In order to understand, and potentially project, how saltmarsh coastal defence and carbon storage might be influenced by SLR, it is therefore necessary to have a mechanistic understanding of the processes by which these services are provided, and, consequently, how they might be impacted by increasing inundation times should local relative SLR rates be very high, or sediment supply be limited and landward accommodation space absent.

The coastal defence capacity of the saltmarsh predominantly requires two characteristics: an elevated, erosion resistant bed and tall, stiff vegetation. First, the accretion of sediment which later consolidates and is stabilised by plant roots builds up a stable, elevated platform over which wave height and energy will be reduced as they propagate across the surface (Gedan et al., 2011; Shepard et al., 2011; Möller et al., 2014; Marin-Diaz et al., 2022, Marin-Diaz et al., 2023). Second, waves are attenuated as they pass through vegetation, provided the canopy is of sufficient height and stiffness (Bouma et al., 2005; Ysebaert et al., 2011; Reents et al., 2022). Where flooding time increases with rising sea-levels, sediment moisture content may increase, leading to wetter, less stable sediments which are more vulnerable to erosion (Crooks and Pye, 2000; Cao et al., 2022). Increasing inundation times will also alter growing conditions for vegetation, potentially leading to species distribution shifts (Noto and Shurin, 2017; Strain et al., 2017), which will influence vegetation-wave interactions, or cause die-off (Watson et al., 2016), and may limit wave attenuation by vegetation.

Saltmarsh carbon storage, in turn, depends on the ability of the marsh to store carbon autochthonously (e.g. via vegetation) and allochthonously (via sediment trapping) (Kirwan and Mudd, 2012; Saintilan et al., 2013; Temmink et al., 2022), as well as the retention of the carbon which is stored in the soil (McTigue et al., 2021; Neubauer and Megonigal, 2021). In recent years, carbon uptake under SLR has been well-studied. Productivity may increase initially, increasing carbon sequestration (Kirwan and Mudd, 2012; Miller et al., 2022). Longer term SLR is likely to have more detrimental effects for carbon storage if marsh die-back occurs (Kirwan and Mudd, 2012), particularly where sediment accretion cannot keep pace with rising sea-levels (Kirwan and Megonigal, 2013; Saintilan et al., 2022). Carbon loss, on the other hand, remains largely unstudied, but represents a critical piece of the carbon storage 'puzzle'. Where inundation time increases and soils become more waterlogged and anoxic, decomposition by microbial communities may slow (Spivak et al., 2019), depending on the presence of vegetation (Mueller et al., 2016). Since this would decrease the release of sediment carbon stores, slower decomposition would represent a positive influence on the carbon storage capacity of the marsh.

Carbon loss may also occur via mechanical losses if more sediment is eroded and resuspended (McTigue et al., 2021; Campbell et al., 2022). Carbon loss under SLR is therefore inextricably linked to changes in sediment stability and coastal defence, since a less stable sediment is more likely to erode. While impacts of SLR on ecosystem services have been explored individually (Kirwan and Mudd, 2012; Macreadie et al., 2013; Mueller et al., 2016; Zhu et al., 2020b), a multi-service approach is generally lacking. Identifying potential 'trade-offs' and interactions between services will be critical to understanding future ecosystem service provision of saltmarshes.

We conducted a multi-ecosystem service field experiment in an area of extremely low-lying restored saltmarsh vegetation in the Western Scheldt (up to half a meter below the usual local lower elevation limits of marsh vegetation), as a 'real-time' proxy for marsh exposure to higher inundation times with SLR. In doing so, we aimed to identify the impacts of SLR on saltmarshes with insufficient sediment supply to maintain their elevation relative to SLR, and therefore where sublethal impacts under gradual increases in inundation may be long-lasting. Using a gradient of inundation durations, we aimed to assess how rising sea-levels in such scenarios would influence a) carbon decomposition, b) sediment stability and c) biomechanical vegetation characteristics. We hypothesised that carbon decomposition would slow with increasing inundation duration (a positive impact), while sediment stability and vegetation strength would decrease (a negative impact). As such, we aimed to provide comprehensive evidence of a potential 'trade-off' in saltmarsh climate services with sea-level rise.

2. Materials and methods

2.1. Site description

The study site, Perkpolder (51°23′57" N, 4°1′25" E), lies on the southern bank of the Western Scheldt estuary in the SW Netherlands (Fig. 1A). Perkpolder is a unique location in that it is 75ha of former agricultural area surrounded by dikes (Fig. 1B), in which tidal flooding was reintroduced in June 2015 through managed realignment (van de Lageweg et al., 2019). The Western Scheldt has a semi-diurnal cycle and a tidal range of 4.4–5.5 m (Baeyens et al., 1997). At Perkpolder, *Spartina anglica* seedlings were planted at 15 locations in July 2015 following tidal reintroduction (van de Lageweg et al., 2019). Seedlings survived at 6 locations and formed expanding *S.anglica* tussocks, with additional small tussocks now also appearing (Fig. 1C).

Being surrounded on three sides by a seawall, Perkpolder has negligible wave action (van de Lageweg et al., 2019). These calm conditions, decreasing physical stress on the vegetation, have allowed *S. anglica* survival at much lower elevations (0.45–1.25 m + NAP, Normaal Amsterdams Peil) than otherwise seen in the estuary (i.e. approx. 1 m + NAP and higher, (Van der Wal et al., 2008a). Since such substantially

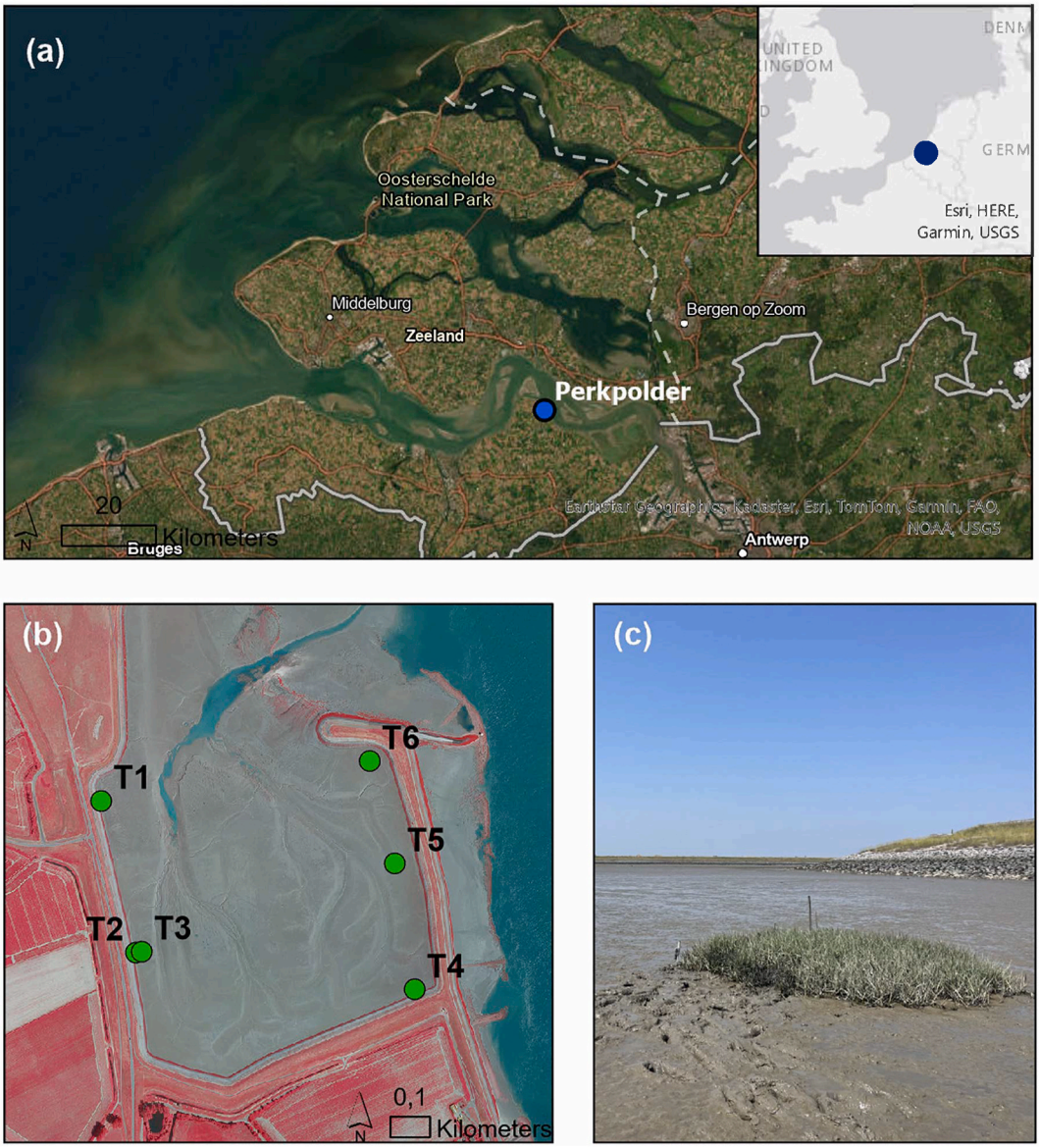


Fig. 1. (a) Position of the study location, Perkpolder, in the Western Scheldt estuary, NL. (b) False colour aerial image of Perkpolder, showing the positions of the vegetated tussocks sampled (green circles). (c) Example of a tussock vegetated with Spartina anglica where measurements were taken within and outside of vegetation. For interpretation.

lower elevations result in longer tidal inundation time, we selected this site to investigate the conditions which would be experienced if a current, low marsh community (at a higher elevation than Perkpolder) was exposed to higher sea-levels and thus longer inundations. This translated to an inundation duration at vegetated areas ranging from 25 to 33 %, or an average of 6–8 h daily with no tides skipped (including at neap tide) compared to naturally established marshes in the same estuary, which would typically have a maximum inundation similar to the highest tussocks (generally <30 % but increasing to 46.2 % at the lowest edges) (Van der Wal et al., 2008b). While marshes with a consistent supply of sediment are likely to accrete quickly enough to maintain their elevation relative to SLR, this is an inundation range to which low marsh edges with insufficient sediment accumulation could realistically be exposed in coming years, particularly with the added potential of storm surges. As such, Perkpolder represented a 'proxy' site for SLR conditions at marshes which fail to accrete sufficiently to keep pace with sea-level rise. Measurements were taken at the naturally established tussock adjacent to tussock 1 (to avoid interference with other measurements), as well as planted tussocks 2, 3, 4, 5 and 6, which are the largest naturally expanding tussocks at this location with comparable vegetation density.

Tidal inundation was measured at Perkpolder using HOBO U20L-04 pressure sensors. These pressure sensors were placed at the lowest measurement location (outside Tussock 6) from 10th May to 7th August 2023 and recorded pressure at a 10-min sampling interval.

2.2. Sediment characteristics

Surface sediment characteristics were investigated using sediment samples of 3 cm ∅ and 3 cm depth, collected using a modified syringe with the top removed. Sediment samples were weighed and freeze-dried. Moisture content (%) was calculated as the wet weight – dry weight/wet weight of the sample. Dry bulk density (g cm^{-3}, hereafter referred to as bulk density) was calculated as the sediment dry weight/sample volume (Dadey et al., 1992). Sediment organic carbon content was measured by high temperature oxidation with a Thermo EA1112 element analyser. To determine grain size distribution, samples were analysed with a Malvern® Mastersizer2000 laser diffraction analyser.

2.3. Carbon decomposition

Organic matter decomposition was measured using the globally standard Tea Bag Index (TBI), following the protocol developed by Keuskamp et al. (2013). The use of this method allows for comparison of decomposition rates of known teabag material in different conditions, here allowing the comparison of decomposition at different inundation durations, but more broadly allowing comparison with published decomposition rates in different soil conditions and ecosystems worldwide. Using known organic matter contents in green (Lipton, Unilever, EAN: 8714100770542) and rooibos (Lipton, Unilever, EAN: 8722700188438) teabags, we measured the initial decomposition rate of the hydrolysable fraction of plant material and the stabilisation factor, or proportion of the hydrolysable fraction which stabilised and was not decomposed during teabag burial.

To adapt the TBI for use in frequently inundated, saline soil, we first calculated a leaching correction factor for the hydrolysable fraction of the teabags in a laboratory experiment. This accounted for the rapid leaching of some organic material when inundated, leaving a smaller fraction to be decomposed by microbial activity. Eight replicates of each teabag (green, rooibos) were placed into 80 ml of either saline (25 ppt) or fresh water in a glass beaker. Following 3 h of submergence, teabags were dried in an oven at 70 ° C for 48 h, after which the dry loose tea was weighed. From these values, a leaching factor was calculated to account for mass loss from both leaching into saline water and oven drying, as follows:

$$Leaching\ factor\ (LF) = \frac{TB_{DW} - TB_{ww}}{TB_{DW}} \quad 1$$

Where TB_{DW} (g) is the dry weight of the loose tea and TB_{WW} (g) is the wet weight of the loose tea.

A correct hydrolysable fraction (H_g) was then calculated as:

$$H_g = \frac{H_{g\ (Standard)} - LF}{1 - LF} \quad 2$$

Where $H_{g\ (Standard)}$ was the hydrolysable fraction as provided by Keuskamp et al. (2013).

Between 8th – 10th May 2023, 192 teabags were buried at Perkpolder. We buried teabags at 6 tussocks (Fig. 1), within (vegetated) and outside (unvegetated) of the tussocks, with 8 replicates of both green and rooibos teabags per location. Teabags were buried by digging a small hole at a depth of 4 – 8 cm, placing one green and one rooibos teabag inside, filling the remaining hole with the excavated sediment and marking the location with a small bamboo stick. This depth was selected to be deep enough to prevent dislodgement, but shallow enough to be in the active layer of the sediment and where the largest changes with SLR might be expected, in line with previous TBI studies (Keuskamp et al., 2013; Tang et al., 2023).

After 90 days, as recommended by Keuskamp et al. (2013), the teabags were retrieved from the field. Loose mud on the bags was removed by gently brushing the outside, after which the teabags were dried in an oven at 70 ° C for 48 h. The dried, loose tea was then weighed, and the decomposition values (decomposition rate, k and stabilisation factor, S) calculated, according to Keuskamp et al. (2013) and Tang et al. (2023) as follows:

$$W_r(t) = a_r e^{-kt} + (1 - a_r) \quad 3$$

Where $W_r(t)$ is the dry weight of the rooibos loose tea following burial (t = time, days), a_r is the hydrolysable fraction of the rooibos tea and k is the initial decomposition rate.

$$S = 1 - \frac{a_g}{H_g} \quad 4$$

Where S is the stabilisation factor and a_g is the hydrolysable fraction of the green tea.

$$a_r = H_r(1 - S) \quad 5$$

Values used for hydrolysable fraction (H_r and H_g) were those calculated in the earlier leaching experiment.

2.4. Sediment erodibility

Sediment erodibility was quantified using two indicative measurements which have previously also been used as a proxy for erodibility (Watts et al., 2003; Amer et al., 2017). Sediment shear strength was measured at 0 cm (surface), 10 cm and 20 cm, to be within and below the root layer, using an Eijkelkamp field inspection vane tester, with values converted into kPa. For each measurement, the vane was inserted vertically into the sediment to the relevant depth (0 cm, 10 cm, 20 cm) and slowly twisted until the sediment material failed, at which point the torque at failure was recorded (see e.g. Brooks et al. (2023)). Penetration resistance of the sediment was measured to a maximum depth of 40 cm using an Eijkelkamp Penetrologger, consisting of a rod with a cone end (with a surface area of 5 cm^2) which was inserted vertically into the sediment at a constant rate to measure the resistance of the sediment at 1 cm depth intervals.

2.5. Vegetation properties

On Wednesday 1st November 2023, stem samples of *Spartina anglica* were collected from Perkpolder. Eight shoots were selected at each tussock, incorporating a range of lengths and diameters to ensure a representative sample of stems present in the field, and clipped close to the base, before transportation back to the Royal Netherlands Institute for Sea Research (NIOZ), Yerseke, Netherlands. Here, the length of each stem and outer diameter 5 cm above the base were measured using a calliper. Afterwards, the bottom 10 cm of each stem was cut for breakage tests, since this is the area where stem breakage is most likely to occur (Vuik et al., 2018a). For each stem, 3-point bending tests were conducted using an Instron EMSYSL7049 flexure test machine and following the methodology of Reents et al. (2022) and Zhu et al. (2020b). These tests involve placing the bottom 10 cm of the stems between two supporting pins and loading the stems with a 5 kN loading cell moving at a constant rate of 10 mm min^{-1}. The vertical deflection of the stem and the force applied were recorded. From these values, breaking point was defined as the maximum force withstood by the stem (N), and the following other properties were calculated according to the methodology described in (Zhu et al., 2020c):

Flexural stiffness, the resistance of the stem to bending, (EI, Nm^2), was defined as:

$$EI = \frac{s^3 F}{48D} \quad 6$$

Where s is the distance between the supporting pins of the Instron (m), F is the force applied (N) and D is the vertical deflection of the stem (m).

Second moment of area, incorporating stem morphology, i.e. diameter, (I, m^4), was defined for circular stems as:

$$I = \frac{\pi d^4}{64} \quad 7$$

Where d is the stem diameter (m).

Youngs Modulus (MPa), which excludes the morphology of the stem to describe only the stiffness of the plant material, was defined as:

$$E = \frac{EI}{I} \quad 8$$

2.6. Data analysis

Water pressure measurements (Pa) from the HOBO Pressure sensors

were converted into water level (cm). Average duration of high tide was calculated as the average daily duration for which water level was higher than the elevation of any given point. Inundation duration (%) was used for the remaining analysis, defined as the average proportion of a tidal cycle spent submerged.

Data were separated into those from vegetated and unvegetated positions. Means, standard deviations and standard errors were calculated for each measurement point using the dplyr package in RStudio Version 4.2.2 (Wickham et al., 2023).

The data were tested for normality using visual inspection of distribution and Shapiro-Wilke tests for normal distribution. Where p-values were <0.05, data were found to be not normally distributed. Since this was the case for most variables, generalised linear models (GLMS) were used for further analysis to test for relationships between inundation duration and variables of sediment characteristics as well as biomechanical traits of vegetation. From GLMs, p-values and McFadden's R^2 values were calculated to determine significance and strength of relationship, respectively. GLMs were also used to test for the influence of vegetation presence and inundation duration on carbon decomposition and carbon stabilisation, and of sediment depth, vegetation presence and inundation duration on sediment shear strength and penetration resistance in the top 10 cm sediment (to ensure both vegetated and unvegetated values were included at each depth). P-values <0.05 were used throughout to indicate a statistically significant result. All analyses were carried out in RStudio Version 4.2.2 (RStudio Team, 2022).

3. Results

3.1. Inundation duration and its effect on sediment characteristics

To test how marsh sediment is likely to react to conditions of prolonged inundation under future SLR scenarios, we measured a suite of sediment properties across an inundation gradient of the extremely low-lying marsh area at Perkpolder. Average inundation duration ranged from 25.4 ± 0.15 % (tussock 1) to 32.8 ± 0.37 % (tussock 6), which equated to an average daily inundation of 6.32 ± 0.03 h (tussock 1) to 8.14 ± 0.09 h (tussock 6). Inundation duration (%) was significantly correlated with all sediment characteristics that were measured (Fig. 2), indicating the potential for inundation duration to influence sediment dependent ecosystem services. Moisture content increased both with increasing inundation duration and with decreasing grain size (Fig. 2). Median grain size (D50) was low (29.5 ± 11.3 μm), indicating a relatively high silt content and low bulk density.

3.2. Inundation duration effect on carbon decomposition

Organic carbon (OC) content in the surface sediment layer was higher where inundation duration was higher ($R^2 = 0.41$, $p = 0.004$; Fig. 3). In addition, where inundation duration was highest (32.8 ± 0.37 %), there were two particularly high values of sediment organic carbon, 3.97 % and 3.71 % (Fig. 3).

Where carbon decomposition rate (k) and stabilisation factor (S) were tested versus inundation duration and vegetation status (vegetated or unvegetated) in one combined GLM, k was consistently higher (model estimate = 0.0009 ± 0.0003, t-value = 2.95, p = 0.005) and S lower (model estimate = −0.025 ± 0.012, t-value = −2.20, p = 0.032), in

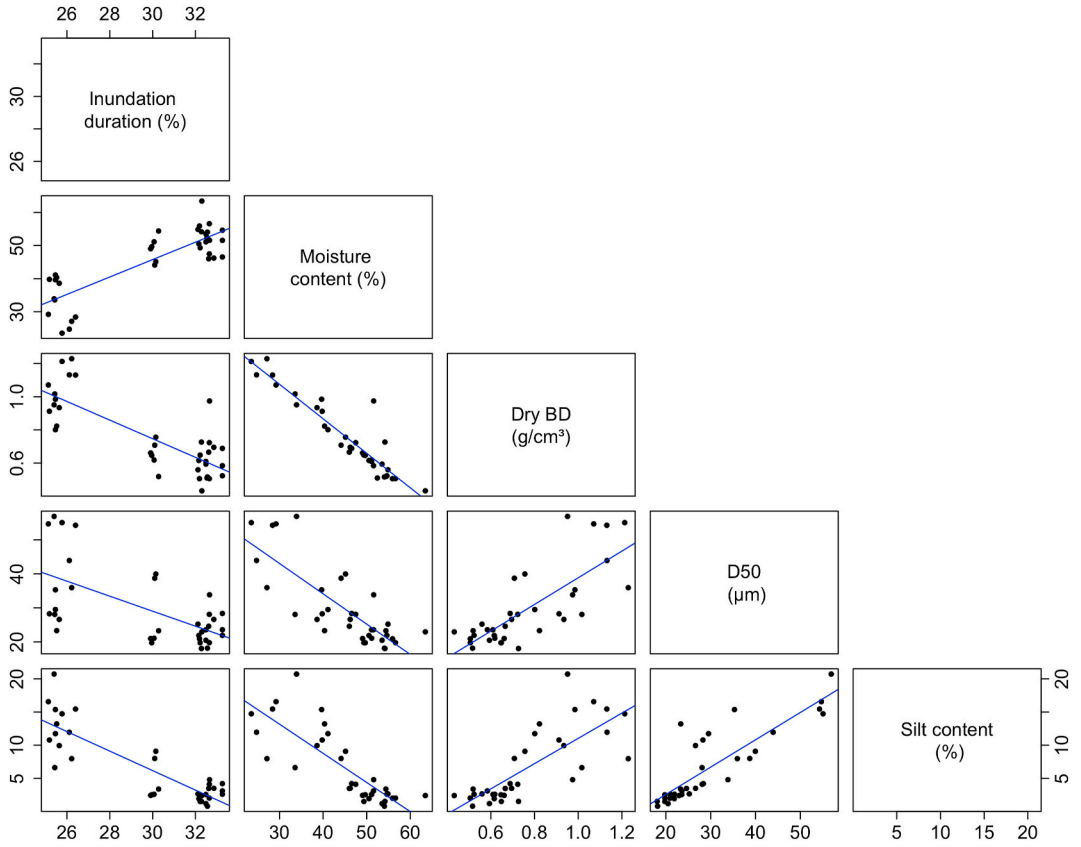


Fig. 2. Correlation matrix showing relationships between inundation duration and various sediment properties as an indication of the potential for inundation duration to influence sediment dependent ecosystem services. The sediment properties studied are surface sediment properties (moisture content (%), dry bulk density (g/cm^3), median grain size, D50 (μm) and silt content (%)). All measurements were collected at both vegetated Spartina tussocks and unvegetated mudflat at Perkpolder, Western Scheldt. Blue lines show significant relationships, where p-value < 0.05. For interpretation.

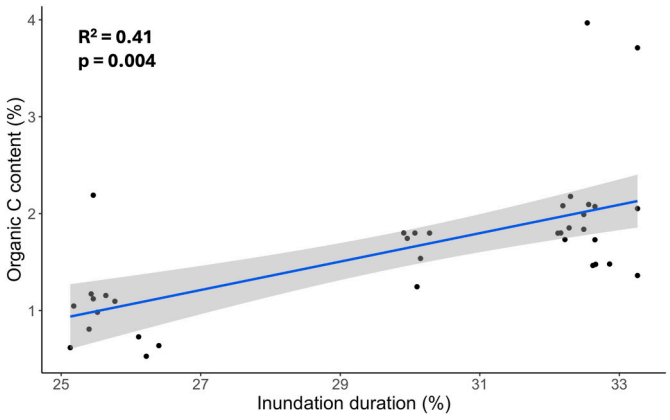


Fig. 3. Sediment organic C content (%) versus inundation duration (%) in the top 3 cm sediment including vegetated tussocks and unvegetated mudflat at Perkpolder, Western Scheldt. The grey band shows the 95 % confidence interval of the GLM. For interpretation.

vegetated compared to unvegetated locations, highlighting the contribution of vegetation (Fig. 4B and C). There was an inverse relationship between k (decomposition rate) and S (stabilisation factor) (Fig. 4A), indicating that where initial decomposition of labile organic matter was high, the conversion of organic material into more recalcitrant material was slower. As expected, decomposition rate (k) decreased with rising inundation duration (model estimate = −0.0002 ± 0.0000, t-value = −4.35, $p < 0.001$, Fig. 4B), while stabilisation rate increased with rising inundation duration (model estimate = 0.005 ± 0.002, t-value = 29.4, p = 0.005, Fig. 4C), indicating slower breakdown of carbon at longer inundation durations.

3.3. Inundation duration effect on sediment stability

Shear strength – a proxy for sediment stability - decreased with increasing inundation duration at all depths (Fig. 5, Table 1). Shear strength appeared to be higher in vegetated compared to unvegetated areas at the surface and 10 cm depth, however GLM testing including both vegetation status and depth indicated that vegetation did not have a significant effect (Table 1). Depth was also a significant explanatory variable of sediment shear strength (Table 1), showing higher shear strength deeper in the sediment, below the vegetation root layer. Peak penetration resistance – also a proxy for sediment strength - was lower at higher inundation durations (Fig. 6). Moreover, penetration resistance (tested to 10 cm depth in the GLM) was significantly increased by the presence of *S.anglica* and increased with depth (Table 1). There generally appeared to be a peak in penetration resistance around 10–20 cm (Fig. 6; average peak penetration resistance was at 15.91 ± 3.92 cm beneath the sediment surface.

3.4. Inundation duration effect on biomechanical properties of vegetation

Spartina anglica shoots growing at tussocks with higher inundation durations were shorter and weaker ($R^2 = 0.18$, $p < 0.001$), although variability of shoot characteristics was high (Fig. 7A). In terms of biomechanical properties, flexural stiffness and breaking point of stems both decreased with rising inundation duration ($R^2 = 0.07$, $p = 0.001$ and $R^2 = 0.04$, $p = 0.017$, respectively), with less stiff plants and lower breaking points where flooding time was higher, although R^2 values indicated weak relationships (Fig. 7B and C). Young's modulus showed no relationship with inundation duration, indicating that the property of the plant material itself did not vary when the influence of stem morphology (i.e., larger diameter for taller stems) was removed ($R^2 = 0.01$, $p = 0.295$, Fig. 6D).

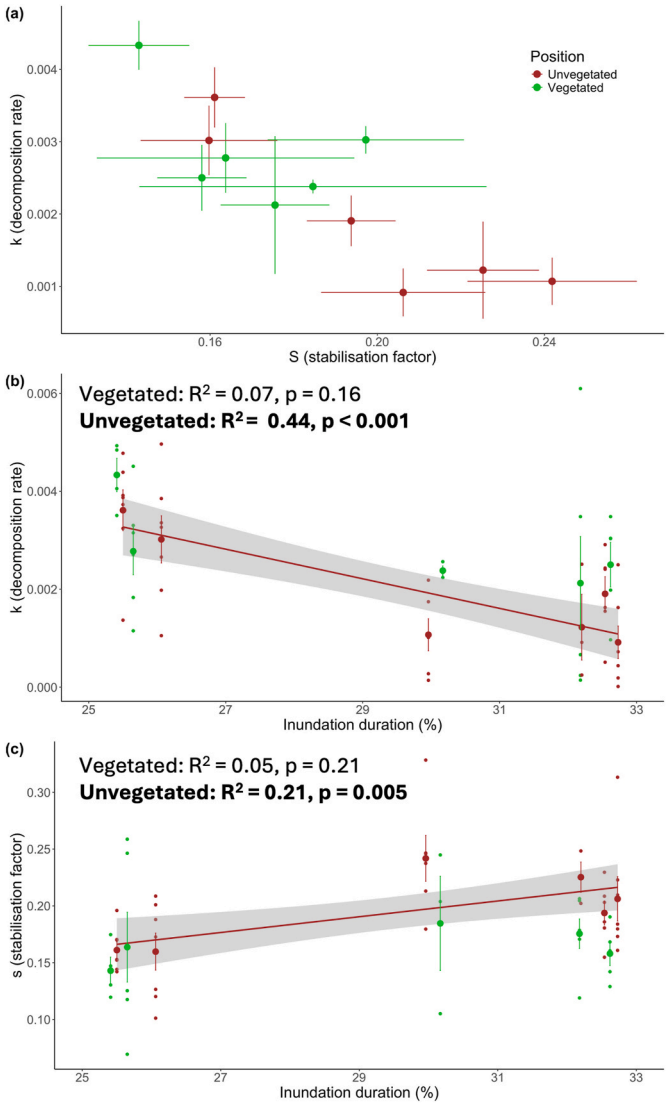


Fig. 4. (a) Carbon decomposition rate (k) versus Carbon stabilisation factor (S). (b) Carbon decomposition rate (k) versus inundation duration (%). (c) Carbon stabilisation factor (S) versus inundation duration (%). Colour refers to vegetation status, with green points and lines for vegetated areas (Spartina anglica) and brown points and lines for unvegetated areas. Large points show mean values, with error bars representing standard error. Lines show significant relationships, surrounded by grey bands showing the 95 % confidence interval. Note that statistical results shown here represent separate GLMs for vegetated and unvegetated positions, with statistical results shown in bold indicating a significant result ($p < 0.05$). For interpretation.

4. Discussion

4.1. Overall findings

Our results point towards the possibility that increasing inundation duration resulting from sea-level rise will have contrasting effects, or 'trade-offs', on multiple climate related ecosystem services provided by saltmarshes. Using a field study site with *Spartina anglica* continuing to grow at uniquely low elevations in the Western Scheldt estuary, we found that carbon decomposition was slower, and stabilisation of carbon higher, at higher inundation durations. This suggests a possible slowing of carbon losses under SLR conditions: in short, a positive effect (Fig. 8). Contrastingly, sediment shear strength, a proxy for erosion resistance, and vegetation stiffness, relevant for wave attenuation, were both negatively impacted by higher inundation durations (Fig. 8). Where

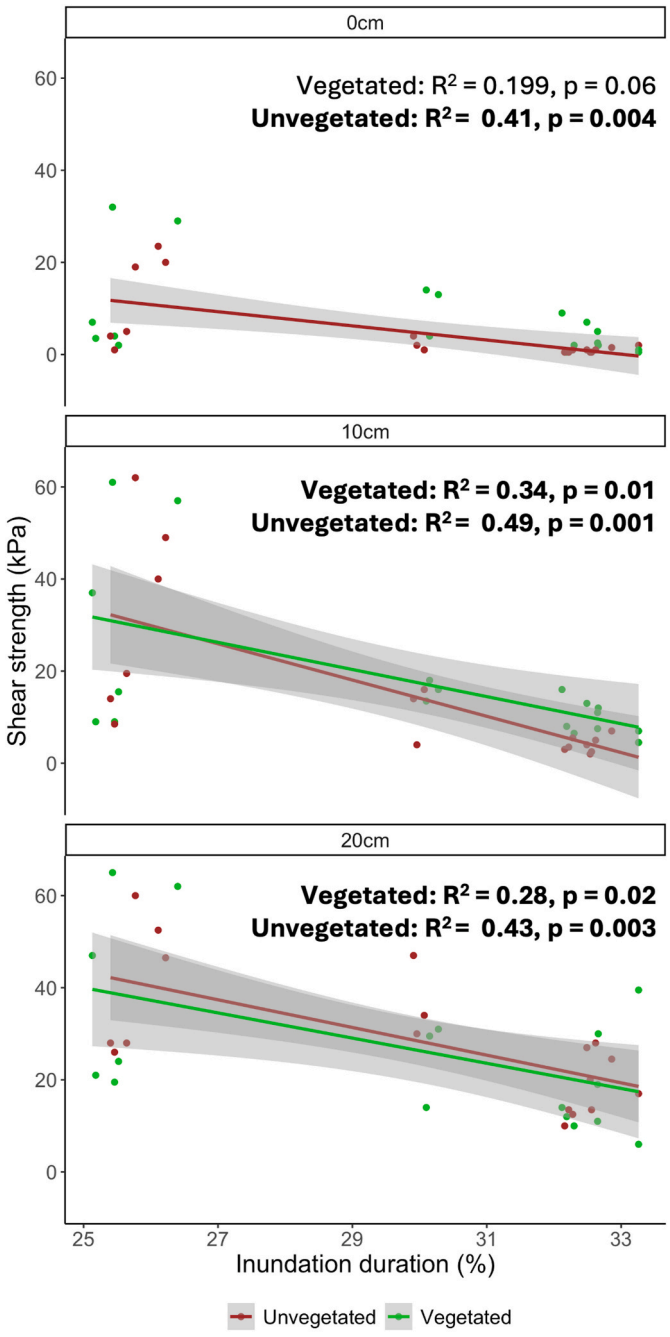


Fig. 5. Sediment shear strength (kPa) at 0, 10 and 20 cm depth at Perkpolder versus inundation duration (%). Green points and lines were vegetated with Spartina anglica, brown points and lines were unvegetated sediment. Lines show significant relationships, surrounded by grey bands showing the 95 % confidence intervals. Note that statistical results shown here represent separate GLMs for vegetated and unvegetated positions, with statistical results in bold indicating a significant result ($p < 0.05$). For interpretation.

valuation of coastal wetlands for ecosystem services is receiving increasing attention (Gedan et al., 2011; Shepard et al., 2011; Macreadie et al., 2021b; Mason et al., 2023), potential trade-offs in services should be a key consideration for both the management and restoration of intertidal areas for Nature-based Solutions.

4.2. Carbon loss under SLR

The finding that carbon loss may be slower under SLR agrees with our hypothesis. While the teabag index (TBI) cannot provide absolute rates of decomposition for the local vegetation species, it allows both i) across-systems comparisons by being a generic, globally-applicable approach and ii) within-ecosystem comparison of treatment effects, such as revealing that decomposition rates are likely to become slower as flooding duration gradually increases. Obtaining exact numbers for locally produced organic-materials requires additional experiments with such materials. The TBI itself is known to be sensitive to differences in soil moisture content (Keuskamp et al., 2013). While tidal flushing lower in the tidal frame may enhance conditions for microbial breakdown of organic matter (Middleton and McKee, 2001), the influence of water-logging on soil biogeochemistry appears to be dominant in driving carbon decomposition. Where increasing tidal duration leads to more waterlogged sediment, a lower oxygen content creates a strongly reducing environment, in which the breakdown of organic matter by microbial activity is slower (Tang et al., 2023). This is an effect not limited to saltmarsh systems, it has also been shown in peatlands (Wilson et al., 2016) and across coastal wetlands (Chapman et al., 2019). As such, where SLR results in a shift towards more frequently inundated conditions, carbon previously stored by sequestration of marsh vegetation may be better preserved. Hence, SLR may strengthen the preservation of carbon in saltmarsh ecosystems. Alongside faster carbon accumulation under SLR (Kirwan and Mudd, 2012; Saintilan et al., 2022), this may contribute towards the security of saltmarshes as a net carbon sink.

There are, however, some caveats which should be considered alongside the potential positive impact of SLR on carbon losses and accumulation. Climate effects are not isolated; rising sea-levels are likely to occur alongside a multitude of effects, including increased rainfall and rising air and water temperatures, which are known to increase the turnover of belowground litter in marsh systems (Tang et al., 2023). Tang et al. (2023) did find that the influence of soil warming is strongly

Table 1
Model estimates from generalised linear models testing the influence of inundation duration (%), vegetation presence and depth (cm) on sediment shear strength (kPa) and penetration resistance (kPa).

Shear strength (kPa)				
Observations = 108 $\chi^2(4) = 15300$, p = 0.000 Pseudo-R^2 (Cragg-Uhler) = 0.520 Pseudo-R^2 (McFadden) = 0.087				
	Estimate	**Standard Error**	**t-value**	**p-value**
Intercept (unvegetated, 0 cm)	81.91	11.00	7.45	0.000***
Inundation duration (%)	−2.56	0.36	−7.09	0.000***
Depth (10 cm)	9.99	2.76	3.62	0.000***
Depth (20 cm)	21.49	2.76	7.79	0.000***
Vegetation (vegetated)	1.27	2.25	0.57	0.574
Penetration resistance in top 10 cm sediment (kPa)				
Observations = 1080 $\chi^2(3) = 2722607$, p = 0.000 Pseudo-R^2 (Cragg-Uhler) = 0.35 Pseudo-R^2 (McFadden) = 0.04				
	Estimate	**Standard Error**	**t-value**	**p-value**
Intercept (unvegetated, 0 cm)	293.30	20.79	14.10	0.000***
Inundation duration (%)	−10.34	0.68	−15.28	0.000***
Depth	12.64	0.73	17.22	0.000***
Vegetation (vegetated)	26.23	4.22	6.22	0.000***

*** indicates significant p-value <0.001. Number of observations = 108 (shear strength) and 1080 (penetration resistance).

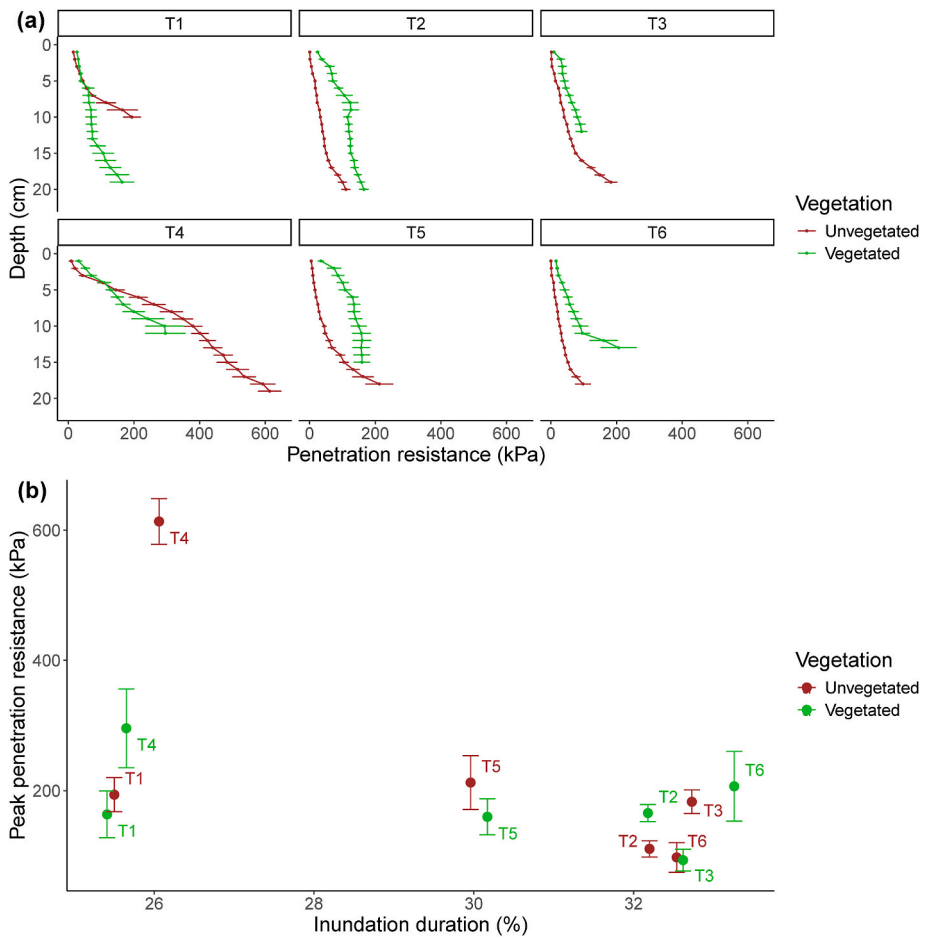


Fig. 6. (a) Depth profiles of sediment penetration resistance (kPa) at Perkpolder (T1, T2, T3, T4, T5, T6). (b) Peak penetration resistance (kPa) versus inundation duration (%). Green points and lines show measurements taken from vegetated locations, brown points and lines from unvegetated locations. Error bars in all panels show standard error. In panel (b), labels T1-6 indicate tussock number. For interpretation.

mediated by soil redox status governed partially by flooding duration, indicating that the positive effect of SLR on carbon losses may be dominant. Nitrogen limitation may also influence breakdown of organic matter via competition of microbial communities for nutrients (Noyce et al., 2019), and the presence of vegetation, as seen in the present study, can increase the breakdown of organic matter via root aeration (Mueller et al., 2016). The breakdown rate of organic matter will also depend on the vegetation species present at the site, and its current state of fractionation and partial decomposition, which was not quantified using the TBI. Perhaps most fundamentally, the ability of global saltmarshes to continue storing carbon will depend on their capability to keep up with SLR via vertical accretion, which often depends on sufficient sediment supply (Kirwan and Megonigal, 2013; Kirwan et al., 2016; Saintilan et al., 2022). As such, we emphasise the need to consider multiple climate, site, and regional drivers when projecting saltmarsh carbon budgets. Since historically high rates of relative SLR, e.g. during the late Holocene on the eastern coast of the US, have led to high saltmarsh carbon stocks (Rogers et al., 2019) and recent modelling studies have predicted a net increase in global saltmarsh carbon storage with SLR up to 2100 (Wang et al., 2021), a net positive influence on carbon storage is likely, provided that marsh drowning does not occur and sufficient landward accommodation space is available.

4.3. Coastal defence under SLR

Coastal defence, in contrast to carbon storage, will be deleteriously affected via multiple mechanisms. Here, our results indicated a universally negative impact of SLR driven by i) a reduction of sediment stability and ii) a reduction in vegetation height and stiffness. Erosion resistance is important for flood safety for the following two reasons: *i)* to preserve a sufficient marsh width to attenuate waves reaching a dike (Ysebaert et al., 2011; Zhu et al., 2020a; Marin-Diaz et al., 2023), with marsh edge dynamics and retreat depending on sediment strength (Wang et al., 2017) and bed level change (Willemsen et al., 2018) and *ii)* to reduce the breach-depth if a dike fails, thereby limiting inundation depth and extending the evacuation time (Zhu et al., 2020a; van den Hoven et al., 2023). Lower sediment stability, alongside higher sediment moisture content, was found at higher inundation durations. Even where a more consolidated top-layer of sediment may be present in a longer established marsh, sediment moisture content is likely to increase with SLR, which is well understood to lead to a lower sediment stability (Crooks and Pye, 2000; Cao et al., 2022). Shear strength has been used in the past as a proxy for erosion resistance of intertidal sediment (Watts et al., 2003; Amer et al., 2017). Consequently, wetter sediment under SLR may reduce the capacity of the saltmarsh to act as an erosion resistant coastal defence.

Vegetation also plays a major role in coastal defence, since plant stems can attenuate wave energy as they propagate across the marsh (Möller et al., 2014; Vuik et al., 2016; Marin-Diaz et al., 2023). Despite high variability typical of wild vegetation, we found that under higher inundation conditions, *Spartina anglica* shoots were shorter, less stiff and had lower breaking points. Effects of SLR on vegetation may even be more pronounced than seen here, given that the seawall at Perkpolder limits wave activity and physical stress on the plants (van de Lageweg

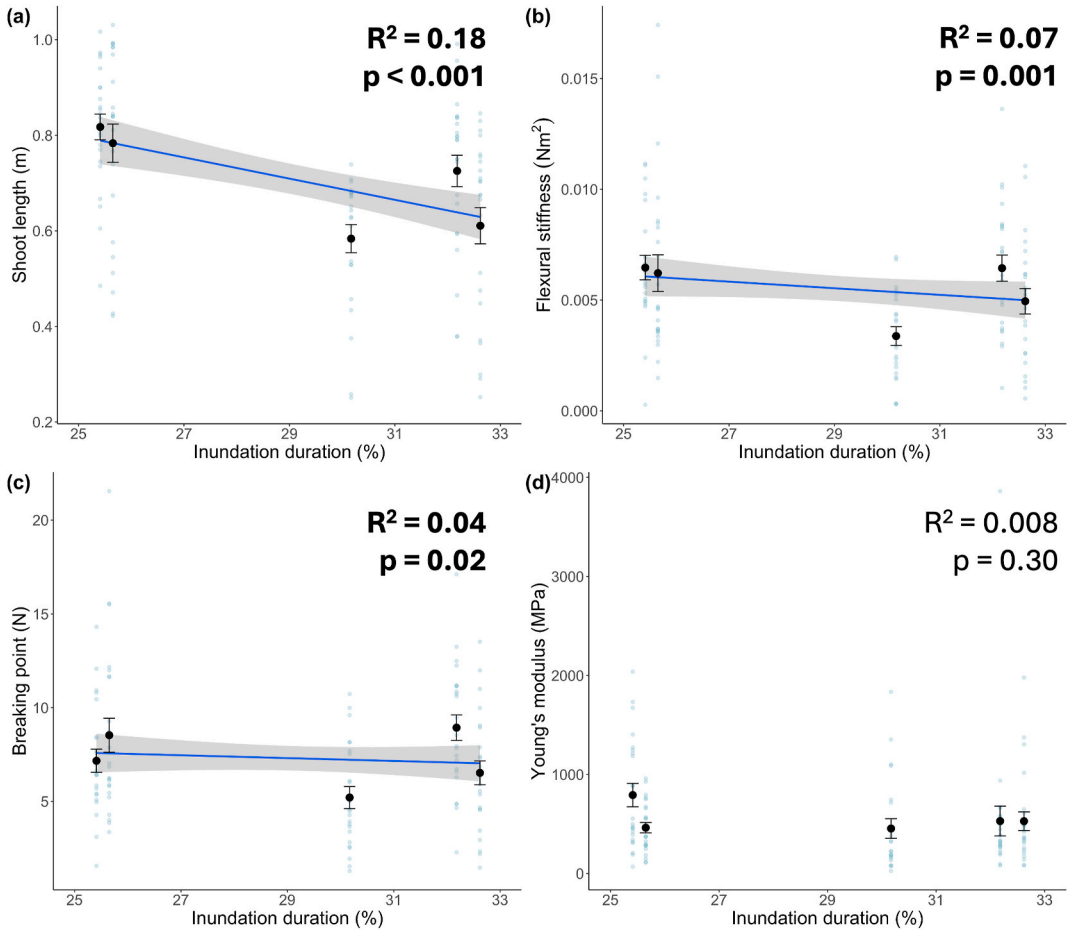


Fig. 7. Biomechanical properties of Spartina anglica versus inundation duration (%). (a) Shows shoot length (m), (b) shows flexural stiffness (Nm^2), (c) shows breaking point (N) and (d) shows Young's modulus (MPa). Black points show mean values and error bars show standard error. Lines show significant GLM results, while grey bands show the 95 % confidence interval, with statistical results in bold indicating a significant result ($p < 0.05$). For interpretation.

et al., 2019), while at most sites, without a seaward wave breaker, hydrodynamic forcing would increase with SLR (Fagherazzi et al., 2020b). This indicates that SLR could not only lead to a lower overall canopy height, but also to less stiff plants which have been shown to have a lower ability to attenuate wave energy, particularly under lower water levels (Bouma et al., 2005; Mullarney and Henderson, 2010; Rupprecht et al., 2017; Schoutens et al., 2020), although impacts on stiffness may vary by species. Wave attenuation capacity is even further reduced by the lower elevated bed relative to sea level, additionally hampering attenuation (Marin-Diaz et al., 2023), and lower wave attenuation due to reduced plant stiffness may result in a lower ecosystem engineering ability because of reduced sediment trapping (Bouma et al., 2005). Hence, coastal protection services may diminish with rising inundation times, amplifying SLR effects on coasts.

4.4. Trade-offs in ecosystem services under SLR are likely to be complex via cascading effects

The impact of higher sediment moisture content resulting from SLR may have a primary effect on sediment stability but will not, however, be limited to one ecosystem service. For example, wetter sediment with a lower stability will have a higher likelihood of erosion under both daily and storm conditions (Crooks and Pye, 2000; Cao et al., 2022). Eroded sediment may be redistributed onto the marsh or exported from the system entirely via the water column (Fagherazzi et al., 2020a). It is known that where coastal systems are degraded and carbon stores destabilised, higher microbial activity can release large quantities of greenhouse gases from breakdown of organic matter (Pendleton et al., 2012). This 'mechanical' loss of carbon represents another important factor in the overall marsh carbon budget (Fagherazzi et al., 2020a; Campbell et al., 2022) and if its pace exceeds that of carbon sequestration, it could contribute towards saltmarshes becoming a net carbon source. Consequently, the initial positive effect of SLR on carbon losses may be shifted to a negative effect in the longer term (Fig. 8).

It is therefore clear that the interaction between SLR impacts on sediment stability and organic carbon losses (and storage) may alter the provision of ecosystem services and the 'trade-offs' that may be expected in the shorter-term (Fig. 8). It is reasonable to expect that these interactions are not limited to just carbon losses and coastal protection. There have only been a handful of studies to date which have identified trade-offs in ecosystem services. For example, Van Loon-Steensma and Vellinga (2013) considered the potential trade-offs between flood defence and biodiversity from different marsh restoration techniques, where sediment supplementation may boost flood protection and expedite the timescale until the marsh platform is high enough to attenuate waves, but equally may impact ecosystem function for microfauna, meiofauna and foraging birds (Van Loon-Steensma and Vellinga, 2013). Xiao et al. (2018) highlight the influence of ecosystem structure in driving trade-offs between biodiversity and ecosystem service provision generally, while a meta-analysis conducted by Howe et al. (2014) demonstrates the importance of considering trade-offs in ecosystem management decisions to increase synergy and the likelihood of 'win-win' scenarios. Manipulative and field-based studies focused on trade-offs, however, remain generally lacking. The vast majority of studies focus on impacts on one service e.g. biodiversity or flood coastal defence (Tordoni et al., 2019; Paul et al., 2022; Tang et al., 2023) and

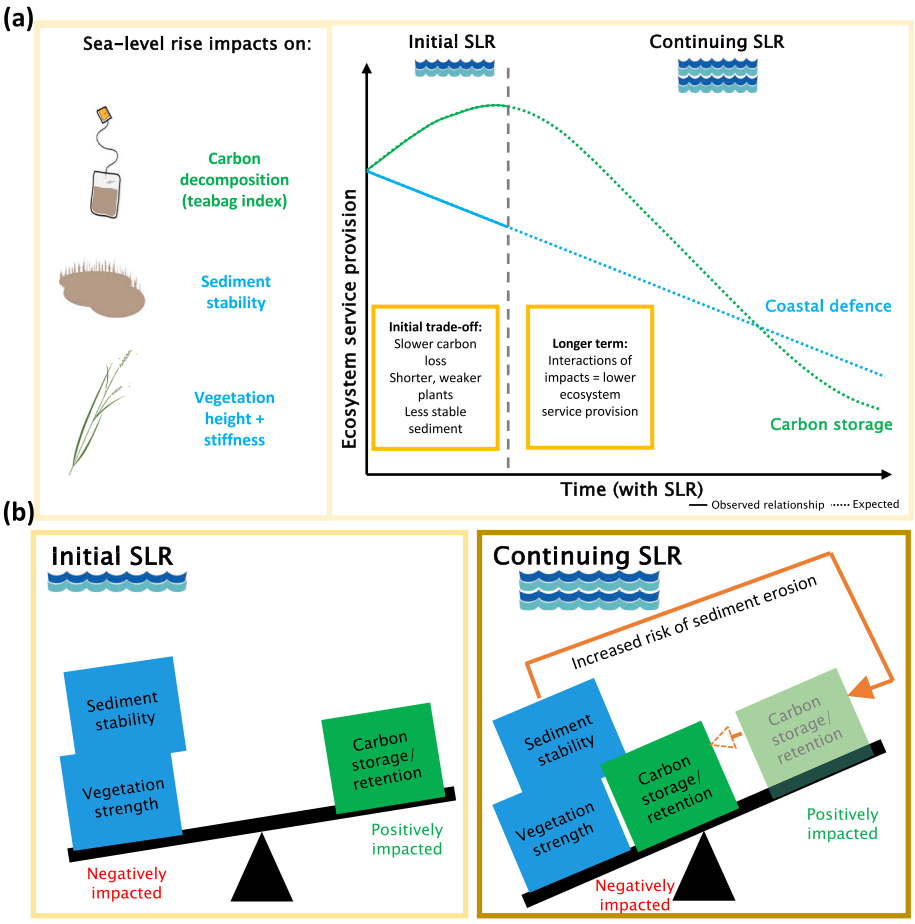


Fig. 8. Conceptual figure of interactions between saltmarsh climate services (carbon storage, sediment stability and vegetation strength) with initial and continuing sea-level rise (panel a). Initially, there is a trade-off in ecosystem services, where carbon decomposition is slowed and thus carbon storage positively impacted, and coastal defence negatively impacted via shorter, weaker vegetation and less stable sediment. Where SLR continues over time, erosion of less stable sediment may cause the release of sediment carbon stores, resulting in a shift towards negative impacts on both carbon storage and coastal defence. A lower position on the scales represents a negative impact from sea-level rise, higher represents a more positive impact (panel b). For interpretation.

indeed the present study addresses ecosystem service provision in only one type of saltmarsh with *Spartina anglica* vegetation. While process-based knowledge of each ecosystem service is integral to understanding the mechanisms by which they will be affected, this lack of 'multiple service' approach in a variety of marsh typologies represents a major current knowledge gap in the field of ecosystem services.

5. Conclusions

While saltmarshes with sufficient sediment supply may experience a limited increase in inundation duration in the coming years, the results taken from this unique site in the Western Scheldt indicate that where sediment accretion is limited, or where SLR is slow enough that vegetation experiences sub-lethal impacts, sedimentary processes governing coastal defence and carbon losses are likely to be substantially impacted. Our results indicate that SLR will, in the short term, drive contrasting impacts on saltmarsh coastal defence properties compared to carbon loss, but it is evident that longer term interactions between impacts will generate a negative overall effect. Without a holistic approach to considering global change effects and ecosystem services, we will remain unable to reduce uncertainty surrounding ecosystem service provision over the coming years. This uncertainty has been widely identified as a roadblock for improving the impetus to apply NbS (Bouma et al., 2014; Vuik et al., 2018b; Seddon et al., 2020). A multi-service approach, considering both interactions and trade-offs between services under different conditions, is therefore a critical next step to enabling the rollout of ecosystem service motivated restoration and conservation of coastal ecosystems in the coming years.

Open research statement

The data from this study are openly available in the research repository 4TU: https://doi.org/10.4121/22a67949-4c53-4fb9-a01c-ceede142aa19.

CRediT authorship contribution statement

Victoria G. Mason: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Pim W.J.M. Willemsen:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Rosemary O. Adams:** Writing – review & editing, Methodology. **Bas W. Borsje:** Writing – review & editing, Funding acquisition, Conceptualization. **Gregory S. Fivash:** Writing – review & editing, Formal analysis. **Johan van de Koppel:** Writing – review & editing, Supervision, Funding acquisition. **Marte M. Stoorvogel:** Writing – review & editing, Methodology, Conceptualization. **Tjeerd J. Bouma:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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