International Journal of Applied Earth Observation and Geoinformation 136 (2025) 104337

Contents lists available at ScienceDirect

International Journal of Applied Earth Observation and Geoinformation

journal homepage: www.elsevier.com/locate/jag

A spatiotemporal framework to assess the bio-geomorphic interplay of saltmarsh vegetation and tidal emergence (Western Scheldt estuary)

Jing Feng [a,b,*], Tim J. Grandjean [a], Johan van de Koppel [a,c], Daphne van der Wal [a,b]

[a] NIOZ Royal Netherlands Institute for Sea Research, Dept Estuarine and Delta Systems, P.O. Box 140, 4400 AC Yerseke, the Netherlands
[b] Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, P.O. Box 217, 7500 AE Enschede, the Netherlands
[c] Groningen Institute for Evolutionary Life Sciences, University of Groningen, P.O. Box 11103, 9700 CC Groningen, the Netherlands

ARTICLE INFO

Keywords:
Relative sea level change
Morphodynamics
Western Scheldt estuary
Saltmarsh vegetation
Emersion duration
Plant diversity

ABSTRACT

Sea level changes will significantly drive hydrodynamic, morphological, and ecological development of estuaries. However, the interplay of geomorphology and vegetation at estuary scales remains unclear. To better understand this process, we take the Western Scheldt estuary in the Netherlands as an example to reveal the link between changes in emersion duration and vegetation dynamics in the period 1993–2016. We found that tidal flats in the Western Scheldt become steeper—higher intertidal areas increased in elevation and emersion duration, whereas the low-lying edges of tidal flats experienced a decrease in elevation and emersion duration. We found that longer emersion duration was associated with increased plant diversity and cover. Furthermore, we detected the unique spatiotemporal response patterns of four abundant plant species to geomorphological variations. Our study suggests that on a large estuary scale, geomorphological changes are coupled to the richness and cover of plant communities, and that potential changes in relative sea level can induce structural modifications of the plant communities. It also emphasizes the importance of assessing the potential effects of localized relative sea level changes while considering all aspects of natural processes and direct and indirect human influences. Our study provides a framework to assess the bio-geomorphic processes in a spatially explicit way.

1. Introduction

Given intensified global warming, sea level rise (SLR) is expected to accelerate (Nicholls and Cazenave, 2010; Khojasteh et al., 2023). Due to the regional variability of SLR, its influences on coastal areas are difficult to predict. More importantly, absolute SLR is just one factor influencing tidal amplitude and coastal morphology. With reduced sediment supply, vertical land movements and frequent or intense human activities (Nicholls et al. 2021), the potential threats on coastal areas cannot be overlooked, encompassing elevated flood risk, and the submergence of coastal wetlands (Leuven et al., 2019). As one of the important components of estuaries, saltmarshes are featured by halophytic vegetation, and are regularly flooded by tidal waters (Allen, 2000; Van der Wal et al., 2008; Van Belzen et al., 2017). Saltmarshes contribute to many essential ecosystem services and maintenance of biodiversity (Dronova et al., 2022), such as flood defense (Temmerman et al., 2023), carbon storage (Temmink et al., 2022) and, with adjacent unvegetated tidal areas, they provide food and habitats for benthic invertebrates, fish and birds (Dissanayake et al., 2018). However, saltmarshes are vulnerable to localized relative sea level change resulting from absolute SLR (Kirwan and Megonigal, 2013; Lovelock et al., 2015; Roman, 2017), reduced sediment supply (Cox et al., 2022b; Grandjean et al., 2024) and anthropogenic disturbances (Van Dijk et al., 2021; Fivash et al., 2023). Relative sea level rise may threaten the saltmarsh ecosystem, including concerns about drowning (Balke et al., 2016), hydrodynamic changes (Khojasteh et al., 2021), erosion, shifts in eco-geomorphic feedbacks (Crotty et al., 2020), biodiversity loss and ecosystem resilience reduction (Schuerch et al., 2018; Khojasteh et al., 2021).

Emersion duration of intertidal areas is determined both by the tidal regime and elevation (Sandi et al., 2018), and may vary particularly due to changes in absolute sea level, as well as through erosion and accretion of sediment and vertical land movement (Laengner et al., 2019; Laengner and Van der Wal, 2022; Grandjean et al. 2024), effectively representing localized relative sea level changes. Changes in tidal emergence may reshape the structure of saltmarsh plant communities (Noto and Shurin, 2017) by altering salinity and related soil and hydrological factors (Bockelmann et al., 2002; Redelstein et al., 2018), which drive plant species distribution and abundance (Gallego-Tévar

* Corresponding author at: NIOZ Royal Netherlands Institute for Sea Research, Dept Estuarine and Delta Systems, P.O. Box 140, 4400 AC Yerseke, the Netherlands.
E-mail address: jing.feng@nioz.nl (J. Feng).

https://doi.org/10.1016/j.jag.2024.104337
Received 25 March 2024; Received in revised form 13 September 2024; Accepted 17 December 2024
Available online 22 December 2024

et al., 2019). Variability in inundation or emersion has driven the development of saltmarsh vegetation communities (Deng et al., 2014; Strain et al., 2017), further influencing vegetation zonation and subsequently altering plant species diversity (Grenfell et al., 2016; Noto and Shurin, 2017; Lawrence et al., 2022). Specifically, emersion duration is related to the mechanisms involving vegetation succession, such as bottom-up control of sediment accretion (Elschot et al., 2017) and the process of seedling establishment (Willemsen et al., 2018). As very few plant species can endure the extreme environment with frequent inundation, plant community development can be significantly hampered or altered (De Leeuw et al., 1994; Casanova and Brock, 2000; Pétillon et al., 2010; Harezlak, 2023). Given the importance, inherent complexity and vulnerability of saltmarshes, it is urgent to understand the responding patterns of saltmarshes to relative sea level change, particularly under the impact of intensifying human activity (Barbier, 2012). Previous studies have also emphasized that human interference, similar to absolute SLR, alters tidal amplitudes and subsequently impacts morphodynamics (Leuven et al., 2019; Fivash et al., 2023). In the Western Scheldt, deepening and narrowing of the estuary have amplified tides (Van Maren et al., 2015; Wang et al., 2019). Increased tidal flows make lower intertidal areas more susceptible to erosion, leading to further lowering. With sufficient suspended sediment load, more sediment is transported onto the tidal flat, gradually raising the elevation of the higher tidal flats. This steepening of estuaries could facilitate the expansion of saltmarshes (Fivash et al., 2023). The shift from pioneer to low marsh, and from lower marsh to higher marshes can also be seen in the Seine estuary (Cundy et al., 2007). Building on this, our study further focuses on the response of vegetation dynamics, particularly given that the extent to which the structure and composition of saltmarsh plant communities are affected by relative sea level change remains unclear. Additionally, few studies addressed the bio-geomorphic interactions at relatively larger scales of time and space via direct measured data. This study therefore provides a reference framework, supporting the development of estuarine management strategies.

In our study, we aim to empirically demonstrate the connections between localized relative sea level changes and vegetation dynamics at an estuary scale. Here, we study the links between changed emergence and plant diversity/cover by using emersion duration maps and vegetation maps of the Dutch Western Scheldt estuary over a period of decades (1993–2016). Changes in emersion duration are expected to result in shifts in the habitats occupied by abundant saltmarsh plant species, and subsequently structural modifications in plant communities. We address the following three scientific questions: 1) What are the spatiotemporal variations of emersion duration in the Western Scheldt? 2) To what extent is plant diversity/cover associated with changes in emersion duration? 3) What are the responses of four abundant plant species to changes in emersion duration? We then discuss the coupling of emergence and plant diversity/cover in light of relative sea level change.

2. Material and methods

2.1. Research area

The Western Scheldt, a tide-dominated estuary, with numerous tidal flats, is located in the southwest Netherlands bordering the North Sea (Fig. 1), where the regional mean sea-level rise rate is 1.92 ± 0.40 mm/year (Vermeersen et al., 2018). It provides access to the seaports of Vlissingen, Terneuzen (the Netherlands), Antwerp and Gent (Belgium). The tidal range during spring tides is 4.45 m at the mouth in Vlissingen and 5.67 m at Bath in the upper estuary near Saeftinghe (Rijkswaterstaat, 2016). Both tidal amplitude and tidal amplification have been increasing in the upper reaches of the Scheldt estuary since the last century (Wang et al., 2019). To improve the accessibility of the port of Antwerp, three periods of channel deepening activities occurred in 1973–1976, 1997–1998, and 2010 (Van Dijk et al., 2021; Elias et al., 2023). Additionally, maintenance dredging ensures the main channel's navigability, with dredged sediments mainly deposited in secondary channels and occasionally in the main channel's deepest sections, and, since 2010, also at the shallow subtidal tips of shoals (Elias et al., 2023). Such a flexible strategy was introduced in 2010 to minimize negative impacts (Elias et al., 2023). The dredging activities amplified the tidal range in particularly the upper estuary (Wang et al., 2019), primarily by decreasing the low water level (Van der Wal et al., 2008). Dredging and deposition of sediment in the subtidal zone had both direct and indirect effects on morphology (e.g., Cox et al., 2003). This includes the increase in elevation of a number of tidal flats (De Vet, 2020; Fivash et al., 2023), even though there was no direct disposal of dredged material in the intertidal zone.

2.2. Methods

2.2.1. Changing patterns in the emersion duration and morphology

We quantified spatiotemporal patterns of inundation using 20 m × 20 m resolution emersion duration maps (1996, 2001, 2004, 2008, 2010, 2011, 2012, 2015, 2016) provided by Rijkswaterstaat (directorate-general of the ministry of infrastructure and water management of the Netherlands). These maps were created from the 20 m × 20 m elevation maps (airborne LIDAR topography complemented by shipborne multibeam and single beam bathymetry, both corrected to m NAP, the Dutch ordnance datum) and water level data relative to m NAP (recorded by Rijkswaterstaat every 10 min at five tide gauge stations along the Western Scheldt) during the three previous years, with emersion duration calculations based on the dominant M2 tidal component (Kers et al., 2013). This approach ensured that the emersion

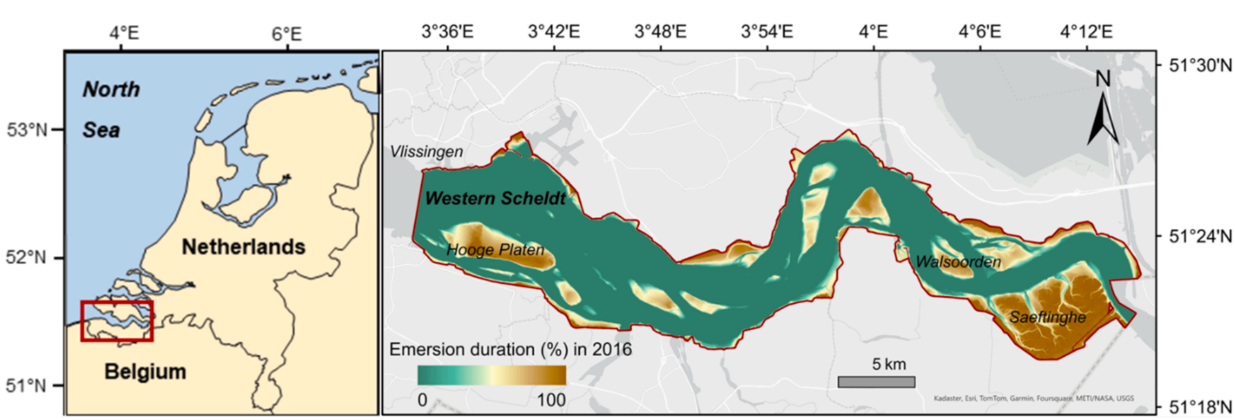

Fig. 1. The location of Dutch Western Scheldt (SW, Netherlands) in Western Europe and the boundary of the study area in this research. Note. The embanked area in 2016 was selected as the boundary.

maps accurately represented the specific hydrodynamic conditions. The accuracy of LIDAR elevation data is approximately 10 cm, while water level data accuracy is 1.5 cm, leading to a reported mean accuracy for the emersion-duration data of just over 10 cm (Dijkstra and Holzhauer, 2015). However, in areas with dense vegetation, LIDAR tends to overestimate the ground elevation. Due to limited data, we combined the emersion duration data from 1996 with the vegetation map from 1993 and the emersion duration data from 2001 with the vegetation map from 1998 to represent the years 1993 and 1998 respectively. This gives a mismatch of three years between the vegetation and the emergence map for these two cases. This was considered acceptable since major dredging operations occurred between 1997 and 1998. The 1996 emersion duration data was used as the baseline for further analysis. To fully understand the underlying relationship between changes in emersion duration and elevation, we also used the initial 20 m × 20 m resolution elevation data issued by Rijkswaterstaat for further analysis. Sen's slope estimator (Sen, 1968), a non-parametric method, was used to define the yearly average changes in emersion duration and elevation for each individual pixel respectively (i.e. using the median of the slopes calculated by pairwise points as the yearly average change rate). In addition, Rijkswaterstaat regularly classifies the Western Scheldt into ecotopes (ecomorphological mappable units) according to the criteria of height, depth, flow velocity, duration of inundation, salinity and sediment composition. These ecotope maps (1996, 2001, 2004, 2008, 2010, 2011, 2012, 2015, 2016, 2018, 2020) were applied to analyze the development of area of saltmarsh, intertidal flat and water in the Western Scheldt, respectively. To test the significance of areal changes over time, we employed the non-parametric Sen's estimator (Sen, 1968) and a Mann-Kendall trend test (Mann, 1945) using the R package "wql" (Jassby and Cloern, 2024) in R v.4.3.2 (R Core Team, 2023).

2.2.2. Changing patterns in the structure of the vegetation community

We quantified the changes in vegetation communities' structure on the basis of changing patterns of species richness (as a metric of taxonomic diversity) and total species cover (Zanzottera et al., 2020). Vegetation maps from 1993 (Asmuth et al., 1996), 1998 (Koppejan, 2000), 2004 (Reitsma, 2006), 2010 (Pranger and Tolman, 2012), and 2016 (Reitsma and de Jong, 2018), all available from Rijkswaterstaat, were utilized in this study. These maps had been classified through manual delineation of homogeneous areas as vector polygons using 1:5000 or 1:10000 aerial photographs, aided by field surveys at plots. Each polygon included information on present vegetation communities and plant cover. Some uncertainties were reported for particularly the field surveys. For example, for the vegetation map of 2010, this included the difficulty of identifying certain plant species due to grazing (e.g., hampering the distinction between *Festuca rubra* and *Juncus gerardii* in parts of Saeftinghe) and due to the late timing in the season (August/September) of the field work (e.g., limiting determination of *Salicornia spec.* at species level) (Pranger and Tolman, 2012). Rules were followed to ensure the quality when drawing the vegetation maps, including a point interval between 1.5 m and 50 m to accurately define the polygons, and for recent maps, a maximum deviation of 1 m between drawn lines and aerial photo boundaries (Pranger and Tolman, 2012). The minimum mapping unit of a polygon was 10 m × 10 m or 5 m × 20 m (Pranger and Tolman, 2012). Using these readily available vegetation maps, we extracted the minimum and maximum coverage of plant species, calculated the mean cover for abundant plant species (as the average of the minimum and maximum cover percentage) and counted the total number of plant species (taken as species richness) for each polygon of each map. Then we transformed and resampled these polygons into a 20 m-resolution raster data set corresponding to the emersion duration rasters for further analysis. Sen's estimator (Sen, 1968) was also used to define the yearly average change in total species cover and species richness respectively for each pixel based on the total time period. Pixel-based analysis enabled establishing the connection between emersion-duration changes and vegetation dynamics. In addition, reduced major axis regression (Harper, 2016) was used in correlation analysis between change rates of total plant species cover and species richness.

2.2.3. Changing patterns in abundant plant species

To test if the emersion duration changes also affect plants at single species' scale, we selected four abundant plant species in the Western Scheldt for further analysis. The four most abundant plant species were identified based on their total cover across the five stages of the vegetation maps. These include the annual (1) *Salicornia spec.* (*Salicornia europaea* and *Salicornia procumbens*); and the perennials (2) *Spartina spec.* (*Spartina anglica* and *Spartina townsendii*); (3) *Bolboschoenus maritimus*; and (4) *Phragmites australis*. We used the average distribution cover to represent the cover of each species in each polygon. Then we linked these cover maps to emergence maps. Vegetation information from vector polygons was assigned to the central point of each emersion duration raster cell intersecting with the polygons in the corresponding period, facilitating further analysis. All the above procedures were run in ArcGIS 10.8.2 (ESRI, 2021). The assessment of yearly average change in species cover is identical as above (i.e. Sen's slope). All raster data related to yearly average change in different metrics were all created in Google Earth Engine (GEE) (Gorelick et al., 2017) using code for calculating Sen's slope from Laengner and Van der Wal (2022). Finally, to reveal the responding patterns of these four abundant species to emersion-duration changes, we compared with their habitats by using the proportions of distribution area along the emersion gradient. All statistical analyses were conducted with the software R v.4.3.2 (R Core Team, 2023).

3. Results

3.1. Changing patterns in the emersion duration and morphology

On average, particularly the higher intertidal areas have undergone an increase in emergence, while lower, less frequently emerged areas are net drowning or eroding, as evidenced by the process of gradient change in emersion duration (Fig. 2a). For most intertidal flats in the Western Scheldt, the yearly average change in emersion duration decreased around the lower edges, while the centre of the tidal flats experienced less flooding (Fig. 2b). Based on a significant positive correlation between changes in emersion duration and elevation (Fig. S1), an increase in elevation is confirmed for the higher intertidal areas and a downward trend at the low-lying edges of the intertidal flats (Fig. 2b, inset). Thus, confirming De Vet et al. (2017), there is a trend towards steeper transitions between high-lying intertidal areas (intertidal flats or marshes) and subtidal channels. In addition, a significant expansion of saltmarsh was detected during 1996–2020 (Fig. 3a).

3.2. Changing patterns in the structure of the vegetation community

Over time, we found an increase in plant species richness in the high-lying intertidal areas and a downward trend in the low-lying areas when comparing the emergence changing map (Fig. 2) with the map of changes in plant species richness (Fig. 4a). When selecting a fixed maximum vegetated boundary (i.e. including the pixels vegetated at least in one time step), an increase in average species richness over time was detected (Fig. S2b). Similarly, denser vegetation communities mainly appeared on the emerging high-lying tidal flats (intertidal flats Hooge Platen and Walsoorden) and landward high marsh (the south-eastern side of Saeftinghe) (Fig. 4b). Additionally, we observed a positive response between emergence and plant species richness as well as total cover (Fig. 4c,d). Furthermore, the response patterns of plant species richness and cover to morphological development are coupled, demonstrating a significant positive correlation ($r = 0.57$, $p < 0.001$, Fig. S4a). We also confirmed this consistency in two other scenarios: one only covering the large saltmarsh area Saeftinghe and the other

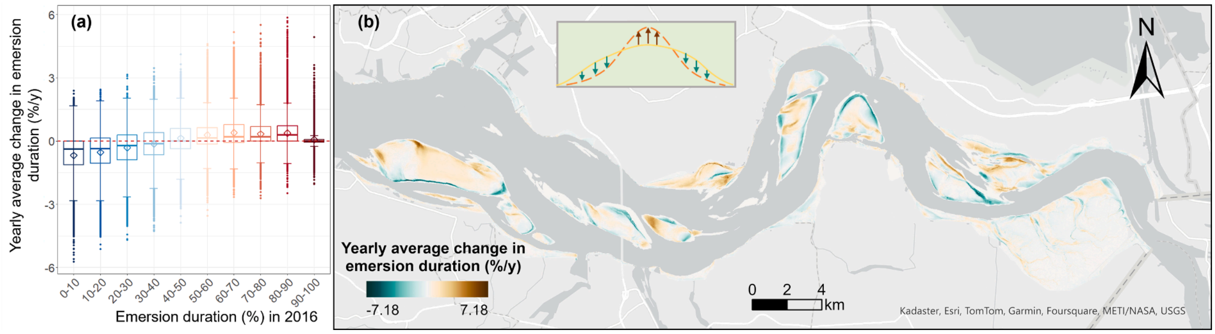

Fig. 2. (a) The relationship between yearly average change in emersion duration (%/y, 1993–2016) and the emersion duration (%) of 2016. (b) Yearly average change in emersion duration (%/y) between 1993–2016 in the Western Scheldt. Brown areas show places with an increase in emersion duration, while green areas show a reduction in emersion duration. The inset shows how the higher parts of the tidal flats (highest emersion duration) become higher, while the lower parts become lower (See also Fig. S1).

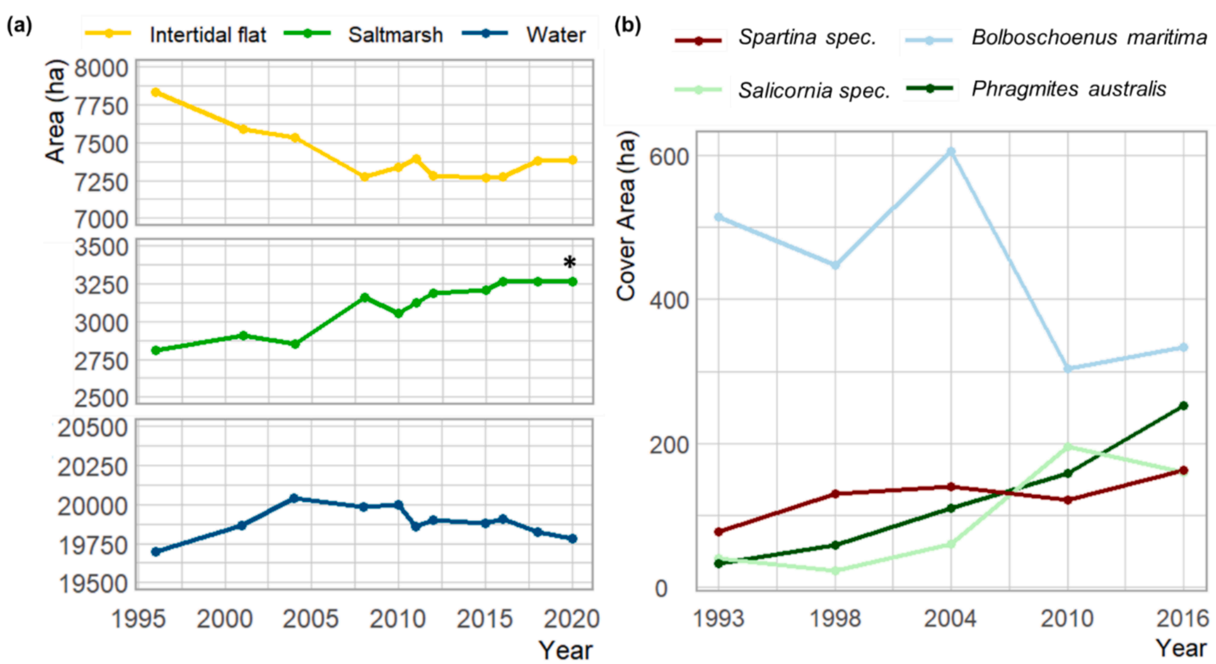

Fig. 3. (a) The development of different components based on ecotope maps during 1996–2020; (b) the development of four abundant plant species during 1993–2016, Western Scheldt. Note:* the area showed significant changes over time, as detected by the Mann-Kendall test with a 95 % confidence interval ($p < 0.05$) (Table S1).

excluding Saeftinghe (Fig. S3 and S4b,c). Increased emergence was associated with an increase in plant species richness and total cover, while more frequent inundation limited vegetation development. Specifically, the optimum plant diversity/cover for each time step consistently occurred at a point below 100 % emersion duration (Fig. S5).

3.3. Changing patterns in abundant plant species

In terms of the most abundant species, except *B. maritimus*, the areas with *P. australis*, *Salicornia spec.* and *Spartina spec.* were overall increasing (Fig. 3b). Despite experiencing a sharp decline (Fig. S6c), *B. maritimus* still remained in high-lying areas (Fig. 5c) and dominated the marsh coverage in 2016 (Fig. 3b). In addition, *B. maritimus* and *P. australis* mainly emerge in the upper estuary including the large marsh of Saeftinghe, while *Salicornia spec.* and *Spartina spec.* occupy the saltmarshes across the Western Scheldt (Fig. S7). Specifically, pioneer species *Salicornia spec.* and *Spartina spec.* have been facilitated by the rising elevation or emergence (Fig. S6a,b), thereby expanding on elevated tidal shoals (such as Hooge Platen and Walsoorden) and some saltmarsh edges (Fig. S7a,b). *Spartina spec.* demonstrates a relatively high inundation tolerance, corresponding to a broad range of emersion frequencies in which it was found (approximately from 60-100 % emersion duration) (Fig. 5a), followed by *Salicornia spec.* (Fig. 5b). Initially, the four most abundant plant species predominantly congregated on high-lying marsh areas; however, over time, they gradually shifted toward more inundated areas (Fig. S8 and S9).

4. Discussion

Globally, there is a common concern about estuaries facing the risk of land loss and submersion due to SLR (Cox et al., 2022b; Chen and Kirwan, 2023). However, using the Western Scheldt as a study system, we observed an overall increase in emersion duration and elevation in its intertidal areas. This finding aligns with De Vet (2020), who reported that human activities have induced elevation changes. The Western Scheldt, a geologically young estuary constrained by dikes and historical land reclamations, has been governed by dredging and disposal activities over the past few decades (Van Dijk et al., 2021; Elias et al., 2023;

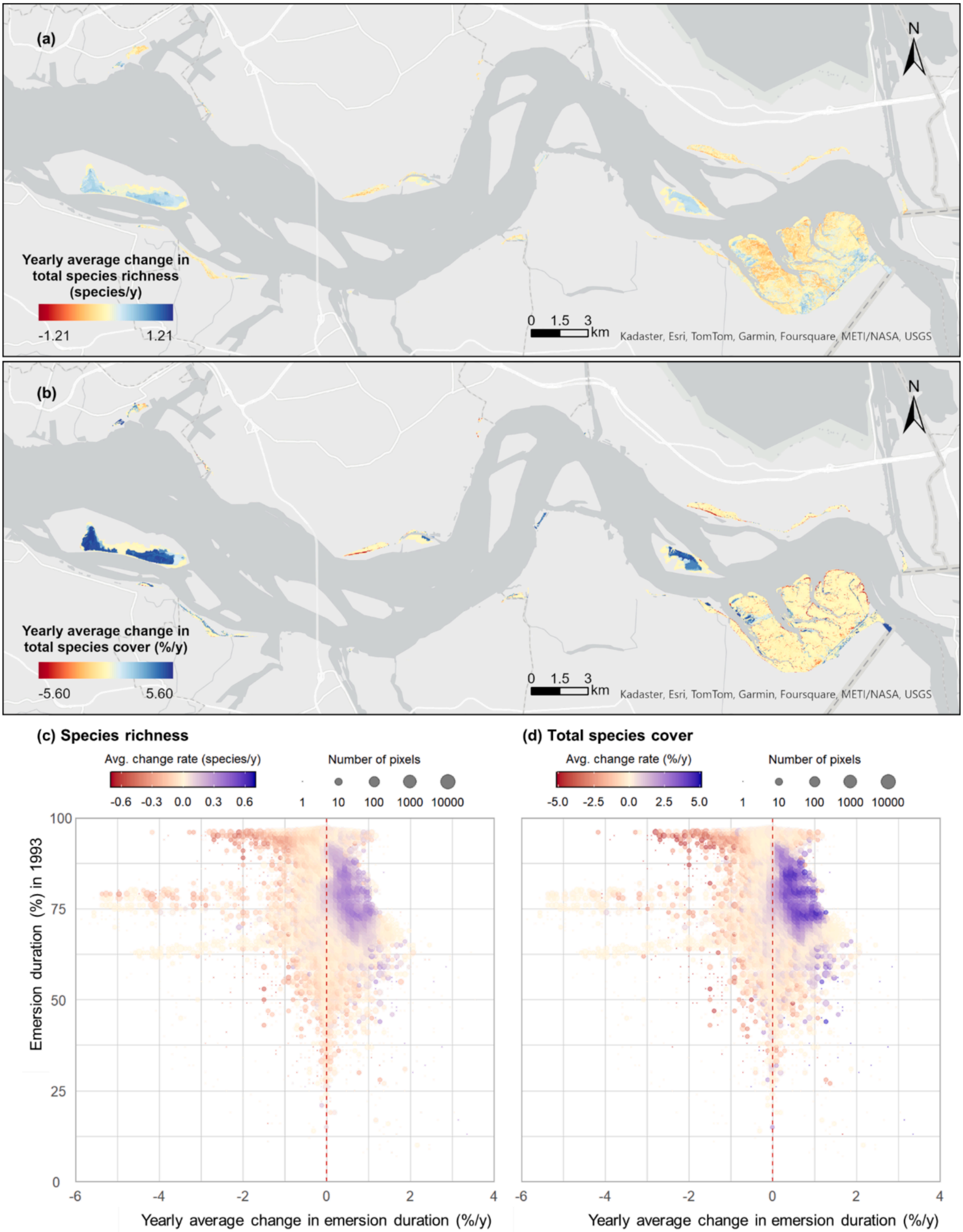

Fig. 4. (a) Yearly average changes in plant species richness (species/y) and (b) total cover (%/y), and their responses (c-d) to emersion-duration variations during 1993–2016 in the whole Western Scheldt. Emersion duration in 1993 was selected as a baseline condition. Regions colored in blue signify positive rates of changes in plant diversity response, whereas red regions denote negative rates, and light yellow dots denote no changes. The observed data include only pixels where plants once existed in history based on the series of vegetation maps.

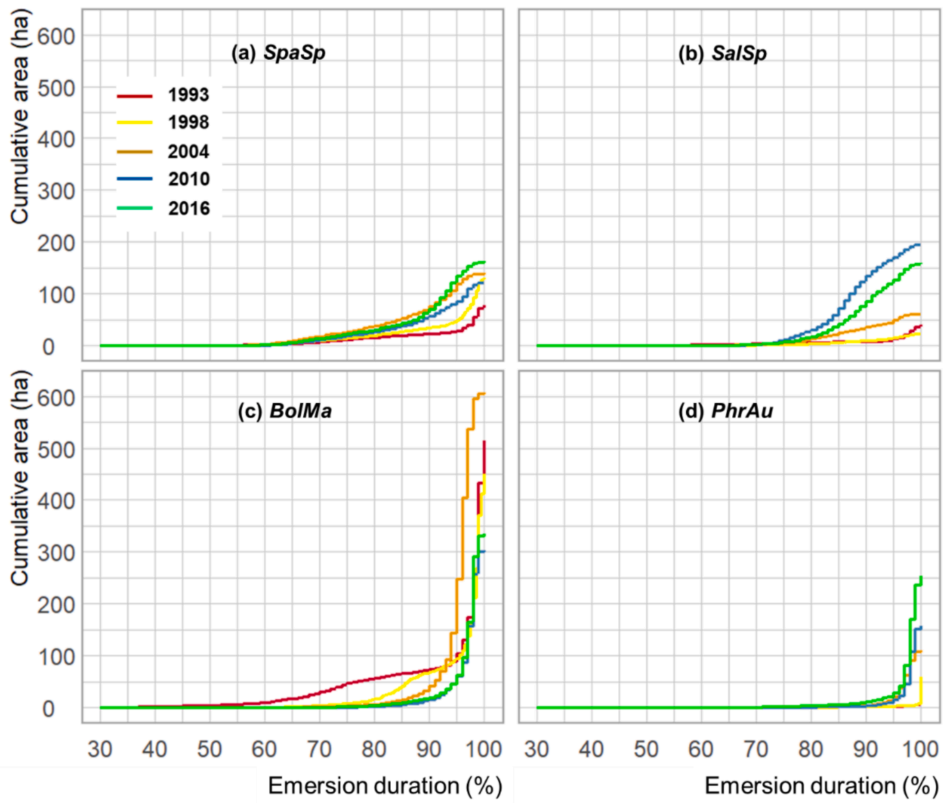

Fig. 5. Cumulative area of four abundant plant species along the emersion-duration gradient at five-time stages (1993, 1998, 2004, 2010 and 2016) in the Western Scheldt estuary, for the species (a) *Spartina spec.* (SpaSp), (b) *Salicornia spec.* (SalSp), (c) *B. maritimus* (BolMa) and (d) *P. australis* (PhrAu).

Fivash et al., 2023). Thereby the Western Scheldt can serve as a reference for understanding vegetation responses to human-induced geomorphological changes. We observed an increase in saltmarsh plant diversity/cover, benefiting from the rise in elevation, consequently potentially enhancing the resilience of the saltmarsh. Our findings suggest that changes in elevation influence the structure of the vegetation community, changing the distribution of habitats and plant species. We also provide empirical evidence of a positive relationship between plant diversity/cover and large-scale increased emergence or elevation of the tidal flats, until reaching an optimum. Conversely, low vegetation cover is anticipated in species confined to low-lying areas with increased inundation, where their performance weakens beyond critical thresholds (Grenfell et al., 2016).

In our case, morphological changes, including those due to dredging and dredge disposal, may have outweighed absolute SLR over the past decades in the Western Scheldt (Van Dijk et al., 2021; Elias et al., 2023; Fivash et al., 2023). We demonstrated how both emersion duration and elevation of the intertidal zone changed, and how this related to vegetation development in the past decades. Our study emphasizes the net effect on emersion duration, overlooking the interaction between absolute SLR and morphological changes, and without addressing or separating the causes of morphological change. Further studies could disentangle the contributions of each of these influences (and their interactions) on tidal emergence especially at long time scales. This serves as a reminder that the combined effects of processes such as vertical land motion, accretion/erosion and absolute sea level change are crucial in determining tidal emergence (Cahoon, 2015), and consequently, plant diversity/cover (Fig. 6). If the marsh elevation gain exceeds SLR, this results in higher emersion duration and greater plant diversity/cover until reaching the optimal conditions. The non-linear responses along the gradient of emersion duration also involve various environmental stressors and critical thresholds, such as transitions from land to submerged areas and changes from aerated to anoxic conditions (Lou et al., 2018). In optimal zones, diverse plant species may overlap, balancing these stressors and interspecific interactions (Kim and Ohr, 2020). Previous studies also indicate that optima for vegetation growth occur at intermediate elevations (Morris et al., 2002; Fagherazzi et al., 2012; Liu and Fagherazzi, 2021). In estuaries like the Western Scheldt, dredging significantly outweighs SLR in altering sediment budgets (Cox et al., 2022a), leading to consequential variations in geomorphic and submersion patterns and thereby influencing the development of saltmarsh. Pioneer species found potential habitats on emergent intertidal shoals and marsh edges, possibly influenced by major dredging activities (1973–1976, 1997–1998, Elias et al., 2023). As elevation increased, high marsh areas expanded. In recent years, limited change occurred in overall areas of saltmarshes and tidal flats. On the contrary, in the scenarios where elevation gain lags behind actual SLR or sediment supply is inadequate, the intertidal zone is expected to experience reduced emergence (Van der Wegen, 2013; Cox, et al., 2022b; Elmilady et al., 2022; Grandjean et al., 2024), potentially leading to less diverse or even monospecific vegetation communities (Grenfell et al., 2016). We found that frequent inundation led to lower plant diversity and cover. This could even result in a transition into unvegetated intertidal flat or open water if the elevation falls below a threshold unsuitable for plant growth due to prolonged inundation (Cahoon et al., 2011, 2019). Saltmarsh plant species composition and extents could persist when the marsh vertical development at least matches the rate of SLR (Rayner et al., 2021). This framework underscores the significance of intrinsic eco-geomorphic response mechanisms in tidal flat-marsh development and sustainability, emphasizing the necessity to consider the unique hydro-geomorphological settings, elevation capital, surface elevation change, and the interplay between anthropogenic forces and SLR within the marsh (Kirwan et al., 2016; Cahoon et al., 2019).

Despite of the vulnerability to climate change, saltmarshes may exhibit considerable adaptability to changes in relative sea level, thereby ensuring their continued functioning. Specially, as a critical

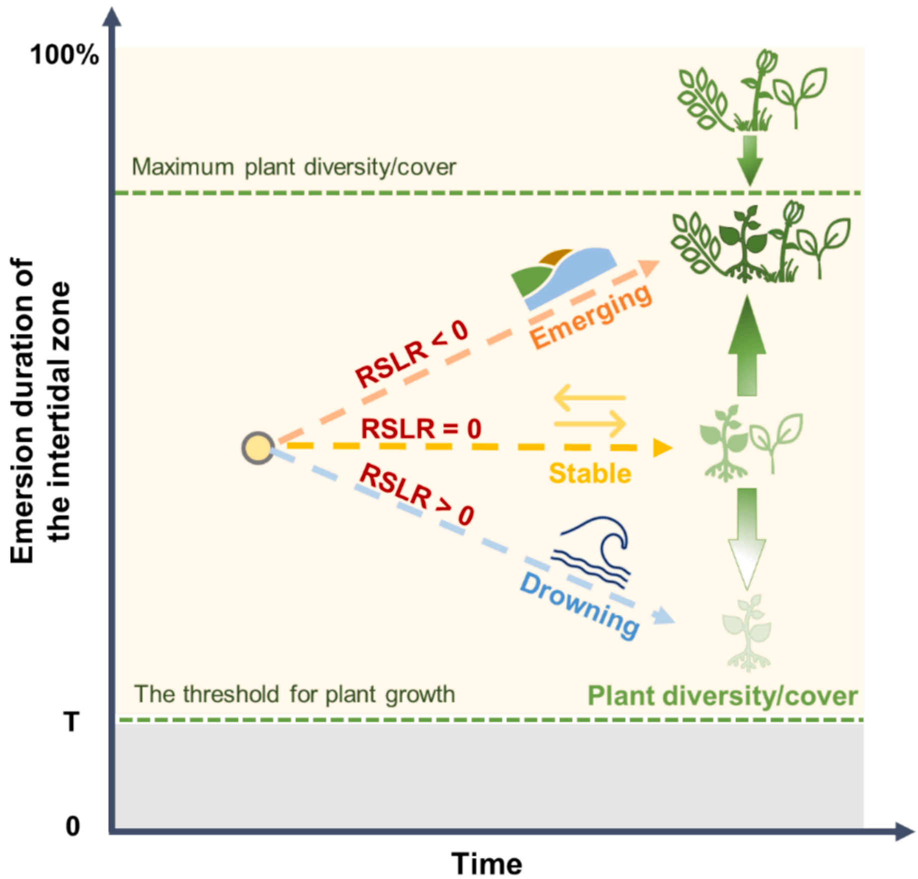

Fig. 6. Conceptual diagram of main drivers to change the emergence of the local area of the intertidal zone and its ecological consequences. RSLR denotes relative sea level rise. Non-linear change of plant diversity/cover along with emersion-duration gradient (Supported by Fig. S5).

aspect of resilient and healthy saltmarshes, sediment budget or availability should not be overlooked (Ganju et al., 2017; Liu and Fagherazzi, 2021). As highly dynamic entities, the ultimate fate of saltmarshes hinges on the pace of SLR and sediment supply (Fagherazzi et al., 2020). The long-term persistence of saltmarshes is favored by lower rates of SLR, ample sediment supply, and larger tidal ranges (FitzGerald and Hughes, 2019). Implementing restoration and management actions, such as enhancing sediment supply or elevation capital, can bring about positive changes in marsh vertical development, serving to prevent or reverse marsh degradation and loss (Cahoon et al., 2019). Specifically, these processes are intricately connected to changes in inundation patterns, influencing both vegetation growth and its spatial distribution. However, the distribution of plant species is influenced by many environmental stressors, such as sediment properties (Schwarz et al., 2015), with inundation representing a particularly complex gradient that correlates with numerous edaphic factors (Lou et al., 2018). For example, the growth of *B. maritimus,* predominantly found in Saeftinghe, may be subject to soil salinity (Mathiventhan et al., 2022) and the grazing activity of geese (Elschot et al., 2017). Additionally, local factors such as wave exposure and sediment properties may also link to vegetation establishment in intertidal areas (Hu et al., 2015; Wang et al., 2017). Further research is needed to determine how plants adapt to relative sea level change, considering the full range of interactive environmental factors.

Our study provides implications and insights for future research on bio-geomorphic interactions under the influence of relative sea level change. In the short term, it benefits flood control security at first sight due to the positive bio-geomorphic feedback between enlarging seaward establishment of vegetation at the fringe and raising height of colonized flats in Western Scheldt (Fivash et al., 2023). Additionally, we observed a nonlinear rise in plant diversity/cover correlated with increased emergence. The continuous formation of new marsh and rising elevation are expected to enhance both plant diversity and cover. However, over the long term, the effects on saltmarsh may be contradictory. When inundation infrequently occurs, plant species richness and cover may decline from their optimal levels. Furthermore, the distinct spatial distribution pattern in the Western Scheldt from seawards to landward comprises channels, intertidal flats, saltmarsh, and dikes. This signifies that the development of intertidal flat and saltmarsh is confined to a limited space, with dikes for flood protection at the rear and navigation channels alongside. In essence, the expansion of saltmarsh vegetation is typically accompanied by a reduction in intertidal flats, resulting in the loss of crucial ecological habitats for benthic communities and birds (Fivash et al., 2023). Besides, a steeper transition between water and high marsh has the potential to alter the tidal amplitude of the estuary, thereby increasing the risk of flooding upstream (Leuven et al., 2019; Fivash et al., 2023). The reminder emphasizes that understanding the marsh evolution and sustainability necessitates consideration of both vertical and horizontal dynamics (Fagherazzi et al., 2020; Grandjean et al., 2024). In addition, this apparent contradiction also fuels the diversity-stability relationship debate (Gross et al., 2014), indicating that changes in diversity could be an intermediate attribute rather than the ultimate cause of ecosystem stability in response to climate change and human interventions (Craven et al., 2018).

In future studies, enhanced monitoring of saltmarsh vegetation and relative sea level change is imperative across multiple spatiotemporal scales and various ecological levels. This is crucial for evaluating the morphological development of tidal flats and saltmarshes (erosion/accretion of sediment and lateral expansion/loss of tidal flat and saltmarsh area) and informing adaptation or mitigation strategies against relative sea level change (Pétillon et al., 2023; Grandjean et al., 2024). A spatially explicit framework based on time-series was proposed to examine the outcomes of the bio-geomorphic interplay driven by relative sea level change within saltmarshes on an estuary scale, offering valuable insights for managing other deltas and estuaries. Given the generalization of this spatiotemporal framework, especially in areas with limited data, remote sensing can be directly employed to construct the dataset, including time-series of inundation frequency maps (Laengner and Van der Wal, 2022), and classification maps of saltmarsh extent (e.g., Laengner et al., 2019) and their plant species and communities.

This study reveals how vegetation growth is related to emersion duration. Hereby, did not separate or quantify the causes of changes in emersion duration or localized relative sea level changes, nor the interactions of drivers. Understanding the interaction between absolute SLR and various human interventions, such as dredging and disposal of dredged material, land claim and sand extraction (De Vriend et al., 2011) is crucial for future coastal management. For example, predicting whether SLR-induced lag effects will impact dredging activities remains uncertain, depending on the effect of tidal asymmetry on sediment transport (Van der Wegen, 2013; Guo et al., 2021) and mud dynamics, which could extend timescales of morphodynamic adaptation (Elmilady et al., 2022). In addition, to better predict and evaluate the interplay between vegetation dynamics and changes in emergence or local relative sea level, it is essential to understand time-lag effects of geomorphological development and vegetation (Wang and Temmerman, 2013), including the diverse morphological and life-history traits of plants (Schwarz et al., 2018), such as plant height and dispersal strategies.

5. Conclusion

In this study, we provided empirical evidence linking changes in tidal emergence to vegetation dynamics in the Western Scheldt estuary from 1993 to 2016. The research demonstrated that the increase in elevation and emersion duration played a pivotal role in driving the extent and structure of saltmarsh vegetation at the estuary scale. Specifically, increased emersion duration had a positive effect on the plant diversity/cover until reaching an optimum. Additionally, we have found that the responses of species richness and cover appear to be interlinked, influenced by the changes in tidal emergence duration. A continuous habitat differentiation was observed among the four abundant plant species along the emergence gradient over time. Our analysis revealed that *Spartina spec*. and *Salicornia spec.* dominate the foreshore intertidal areas, while *B. maritimus* was reduced to high-lying areas. The rapid expansion of *P. australis* have been facilitated by the increasing elevation of the high marsh. Our study provides a unique spatiotemporal framework for exploring saltmarsh bio-geomorphic interactions across different vegetation levels.

CRediT authorship contribution statement

Jing Feng: Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tim J. Grandjean:** Writing – review & editing, Visualization, Formal analysis, Conceptualization. **Johan van de Koppel:** Writing – review & editing, Supervision, Conceptualization. **Daphne van der Wal:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Data curation, Conceptualization.

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.

Acknowledgements

We gratefully thank the following colleagues: Annette Wielemaker for assistance with GIS data preprocessing; Tjeerd J. Bouma, Jim van Belzen, Gregory S. Fivash, Jesse Bootsma and Xuerong Wu for suggestions on data analysis, visualization and manuscript writing. The first author (J. Feng) was supported by the China Scholarship Council (CSC, grant number: 202004910421).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jag.2024.104337.

Data availability

The derived data and code can be found in the 4TU. Research Data repository with the doi: 10.4121/fe23a0c6-b13a-49c5-accf-a09dc211983d. The raw data including open source maps of emersion duration, elevation, vegetation and ecotope are available from Rijkswaterstaat (https://rijkswaterstaatdata.nl/).

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Further reading

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