LIMNOLOGY AND OCEANOGRAPHY
Letters

ASLO
Open Access

Limnology and Oceanography Letters 2024

doi: 10.1002/lol2.10436

LETTER

Dense vegetation hinders sediment transport toward saltmarsh interiors

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Scientific Significance Statement

Saltmarshes are highly valued coastal ecosystems developing near sea level, which are threatened by sea level rise, and whose survival depends on their capacity to gain elevation by sediment accretion. A generally persisting paradigm is that dense vegetation facilitates sediment accretion by locally trapping suspended sediments and producing organic matter. However, the long-term relevance of such local processes has never been studied at the landscape scale. Using a state-of-the-art numerical model compared with field observations, we reveal important, contrasting insights, indicating that dense saltmarsh vegetation inhibits sediment accretion at the landscape scale by hindering sediment transport from tidal channels to platform interiors. Our findings warn against overestimation of the capacity of densely vegetated coastal wetlands to survive future rates of accelerating sea level rise.

Abstract

To save saltmarshes and their valuable ecosystem services from sea level rise, it is crucial to understand their natural ability to gain elevation by sediment accretion. In that context, a widely accepted paradigm is that dense vegetation favors sediment accretion and hence saltmarsh resilience to sea level rise. Here, however, we reveal how dense vegetation can inhibit sediment accretion on saltmarsh platforms. Using a process-based modeling approach to simulate biogeomorphic development of typical saltmarsh landscapes, we identify two key mechanisms by which vegetation hinders sediment transport from tidal channels toward saltmarsh interiors. First, vegetation concentrates tidal flow and sediment transport inside channels, reducing sediment supply to platforms. Second, vegetation enhances sediment deposition near channels, limiting sediment availability for platform interiors. Our findings suggest that the resilience of saltmarshes to sea level rise may be more limited than previously thought.

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Associate editor: Stephen Monismith

Author Contribution Statement: OG, SF, and ST came up with the research question and designed the study approach. OG implemented the numerical model. OG designed the model setup, with substantial contributions of JPB and YX. OG conducted the model result analysis, with substantial contributions of MGK, SF, and ST. OG wrote the paper, with substantial contributions of all co-authors.

Data Availability Statement: Supporting data and source code are available in the Zenodo repositories https://doi.org/10.5281/zenodo.8262328, https://doi.org/10.5281/zenodo.8256561, https://doi.org/10.5281/zenodo.11395640, https://doi.org/10.5281/zenodo.11396904 and https://doi.org/10.5281/zenodo.11401186.

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

Saltmarshes develop within the tidal range in the presence of favorable conditions for plant growth (Fagherazzi et al. 2020). They are among the most productive ecosystems (Barbier et al. 2011), providing invaluable services such as natural shoreline protection against storms (Temmerman et al. 2022) and carbon sequestration (Rogers et al. 2019). However, accelerating sea level rise (Schuerch et al. 2018) and decreasing sediment supply (Tognin et al. 2021) threaten their survival, which mainly depends on their ability to gain elevation by sediment accretion at rates greater than sea level rise (Kirwan et al. 2016). Saltmarshes are dissected by complex tidal channel networks, which control the supply of sediments toward the vegetated platforms and therefore play an essential role in saltmarsh accretion. It is generally hypothesized that sediment distribution is affected by geometric characteristics of tidal channel networks, such as drainage density (i.e., total length of channel network per unit surface area; Marani et al. 2003) and drainage efficiency (which also accounts for channel branching and meandering; Kearney and Fagherazzi 2016). Indeed, high drainage density or efficiency means that the average distance between tidal channels and internal areas is low, which may potentially facilitate sediment distribution over saltmarsh platforms. However, the impact of channel network geometry on long-term saltmarsh accretion, and hence resilience to sea level rise, remains poorly quantified.

Saltmarsh vegetation influences the geometry of tidal channel networks. The establishment of vegetation on a bare intertidal landscape increases flow concentration and facilitates channel formation within topographic depressions (D'Alpaos et al. 2006) and between expanding pioneer patches (Temmerman et al. 2007). Vegetation stabilizes channel banks and contributes to meander formation (Finotello et al. 2018). Certain vegetation traits, such as slow patchy colonization pattern and high stem density, promote the self-organization of channel networks with relatively high drainage density and efficiency (Schwarz et al. 2018). Dense vegetation facilitates local sediment accretion by trapping mineral sediments and producing organic matter (Fagherazzi et al. 2012). However, the combined impact of saltmarsh vegetation on both channel network self-organization and long-term accretion patterns remains poorly understood.

In addition to the influence of vegetation, the geometry of tidal channel networks is controlled by abiotic factors, such as platform elevation and tidal range (Liu et al. 2022), which both govern channel-forming flood and ebb discharges. Disentangling vegetation impacts on channel network self-organization from observations of different systems is therefore very challenging, but numerical modeling is a widely used alternative approach, in which environmental conditions can be fully controlled (Kirwan et al. 2016). Saltmarsh models able to explicitly simulate the impact of vegetation on tidal channel self-organization necessitate large computational resources, as they require grid resolutions of a few meters to represent the formation of small channels. As a result, their application is often limited to relatively small domains of less than 1 km^2 and relatively short periods of a few decades (Belliard et al. 2015; Wang et al. 2021), or they resort to very simplified hydro-morphodynamics equations (Rodríguez et al. 2017; Mariotti 2020). Here we use high-performance supercomputing and the multiscale biogeomorphic model Demeter (Gourgue et al. 2022) to explicitly simulate the interactions between tidal flow, sediment transport and saltmarsh vegetation dynamics over a domain of 4 km^2 and a period of 200 yr. More precisely, we perform a virtual controlled experiment, in which we enable or disable plant establishment in a saltmarsh environment, to isolate and understand the direct impact of saltmarsh vegetation on its ecosystem. Such controlled experiment is hardly possible in the field, as vegetated saltmarshes and unvegetated mudflats do not occur in the same environmental conditions.

Our results confirm prior observations that tidal channel networks are denser and more complex with vegetation than without. However, they also reveal that the drainage density and the drainage efficiency are not suitable indicators for sediment supply toward saltmarsh platforms, as they do not account for the impact of vegetation on the hydrodynamics and the sediment transport at the landscape scale. Our study identifies two key mechanisms by which saltmarsh vegetation hinders sediment transport from tidal channels to platform interiors: platform vegetation concentrates flow and sediment transport within channels and enhances sedimentation near channels. These vegetation-induced processes combined reduce sediment accretion in saltmarsh interiors.

Methods

Numerical model

We use the biogeomorphic model Demeter (Gourgue 2022) to simulate explicitly the feedbacks between intertidal hydrodynamics, sediment transport and vegetation dynamics (Supporting Information Fig. S1a; Gourgue et al. 2022). Demeter uses the finite-element model Telemac (Hervouet 2007) to simulate the hydro-morphodynamics in a two-dimensional horizontal framework (Supporting Information Section S1.1). The vegetation resistance force on the hydrodynamics is modeled as the drag force on a random array of rigid cylinders (Baptist et al. 2007), with parameters calibrated against flume measurements of flow deceleration within, and flow acceleration around, real vegetation patches of the considered species (Gourgue et al. 2021).

Demeter also includes a cellular automaton that simulates the vegetation dynamics through stochastic evaluation of establishment, lateral expansion, and die-off processes (Supporting Information Section S1.2), which are modulated by hydrodynamics conditions provided by Telemac (i.e., hydroperiod and exposure to excessive bed shear stress; Supporting Information Section S1.3). We use a morphological acceleration factor (Lesser et al. 2004; Roelvink 2006) to upscale one semi-diurnal tidal cycle of hydrodynamics to 1 yr of morphodynamics, after which the vegetation module is updated (Supporting Information Fig. S1b; Section S1.4).

Model setup

We simulate the development of an initially bare intertidal landscape (Supporting Information Fig. S2) colonized by saltmarsh pioneer species occurring globally but presenting contrasting colonization and morphological traits. *Spartina* marshes encroach intertidal mudflats in small, isolated patches of dense, tall stems, which slowly grow laterally (Fig. 1a–l). *Salicornia* marshes encroach intertidal mudflats quickly and homogeneously over large areas with sparse, short stems (Fig. 1m–x). We also consider a control case without vegetation (Fig. 1y–ad). See Supporting Information Section S2 for more details on the model setup. The environmental conditions and the different model parameter values are representative of the macrotidal, moderately turbid Western Scheldt Estuary, the Netherlands (Supporting Information Tables S1–S3), allowing for a fair comparison with available field observations (Supporting Information Section-S3). We also perform a model sensitivity analysis to assess whether our conclusions still hold for configurations representing a larger variety of systems (Supporting Information Section S4).

Channel network analysis

We use TidalGeoPro (Gourgue and Pelckmans 2022) to identify channel and platform grid nodes using a multi-window median neighborhood analysis (Liu et al. 2015) and extract channel network skeletons (i.e., channel centerlines; Fagherazzi et al. 1999). On the platforms, TidalGeoPro computes the unchanneled path length (i.e., the shortest distance to a channel; Tucker et al. 2001). Along the skeleton, it computes the upstream tidal watershed area (based on distances to channels; Vandenbruwaene et al. 2013, 2015), the maximum upstream length (i.e., the length of the longest channel stretch within the upstream watershed), the total upstream length (i.e., the combined length of all channel stretches within the upstream watershed), the drainage density (i.e., the total upstream length divided by the upstream watershed area; Marani et al. 2003), the drainage efficiency (i.e., the inverse of the channel density divided by the mean unchanneled path length within the upstream watershed; Kearney and Fagherazzi 2016), the channel width, the channel depth and the channel cross-section area.

All model input and output files, as well as supporting data and source code to generate them and the figures of this manuscript are openly available (Gourgue et al. 2023a,b, 2024a,b,c).

Results

Our results show that vegetation facilitates faster development of secondary channels (i.e., smaller tributaries), but has little impact on large primary channels (Fig. 1, 2nd row). In the setup used here (Supporting Information Fig. S2), primary channels develop before any vegetation can establish in the seaward half of the domain (Fig. 1, 1st two rows), so that subsequent vegetation encroachment can only stabilize them. As a result, primary channels remain very similar over time and across scenarios (Fig. 1) and variations in tidal channel network characteristics (Fig. 2a,b) are mostly attributed to the development of secondary channels.

In general, the drainage density is higher with vegetation than without, and higher in *Spartina* marshes than in *Salicornia* marshes (Fig. 2a). While differences in drainage density across scenarios decrease over time, the drainage efficiency remains higher with vegetation than without on the long term (Fig. 2b). However, dense, branching channel networks do not necessarily promote high platform accretion rates: unvegetated mudflats accrete faster than sparse *Salicornia* marshes, which themselves accrete faster than dense *Spartina* marshes (Fig. 2c). These differences in accretion rates can be unequivocally attributed to differences in vegetation density, here and below defined in a broad sense that encompasses all parameters affecting the vegetation drag (i.e., stem density, diameter and height, bulk drag coefficient). Indeed, our model sensitivity analysis demonstrates that, all other things being equal, platforms accrete faster with decreasing vegetation density (Supporting Information Fig. S3) and confirms that unvegetated mudflats accrete faster than sparse *Salicornia* marshes, and even faster than dense *Spartina* marshes, regardless of sediment characteristics (Supporting Information Section S4).

Below we identify two overlooked mechanisms that contribute to this vegetation-induced reduction of platform accretion rates.

Vegetation decreases sediment supply from channels to platforms

The drag created by vegetation concentrates water flow into the channels and, at the same time, decreases flow velocities from the channels to the surrounding platforms (Fig. 3). This has crucial implications for the transport of sediments. While vegetated saltmarshes import more sediments than unvegetated mudflats during the flood phase (Fig. 4a), vegetated saltmarshes also endure more in-channel deposition (Fig. 4b). Indeed, because of the vegetation-induced drag on the platforms, less suspended sediments can leave the channels and flow onto the vegetated platforms. Hence, with vegetation, more sediments are trapped inside the channels, where they temporarily deposit at high-water slack, and hence more sediments are remobilized and exported from the system during the ebb phase (Fig. 4a). In total, unvegetated mudflats have a higher net sediment import balance than vegetated

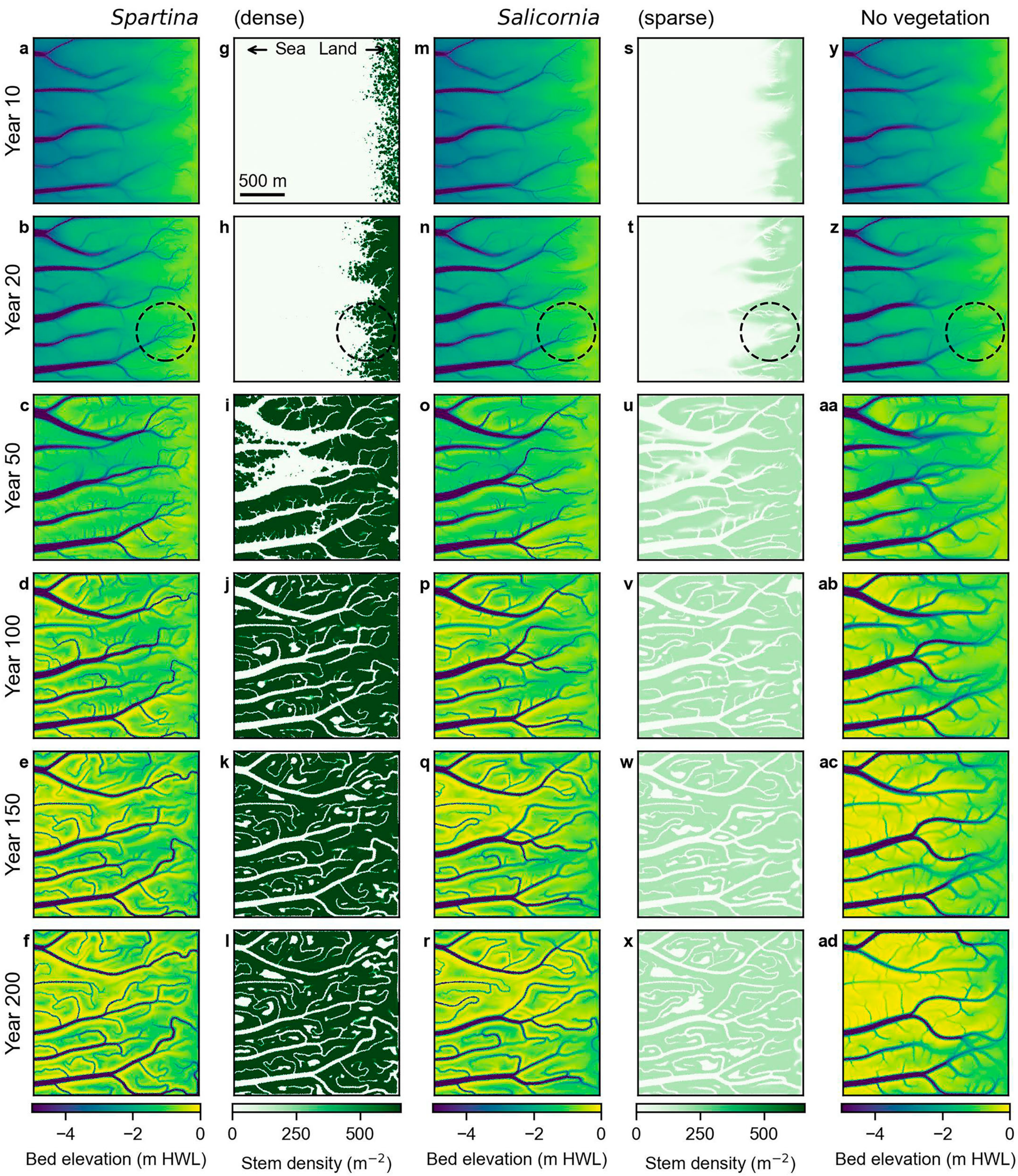

Fig. 1. Evolution of bed elevation and stem density for dense *Spartina* marshes (**a–l**), sparse *Salicornia* marshes (**m–x**), and unvegetated mudflats (**y–ad**). Each panel shows the full area of interest defined in Supporting Information Fig. S2. The bed elevation is expressed with respect to the high-water level (HWL). Black dashed circles indicate an active zone of vegetation-induced secondary channel development.

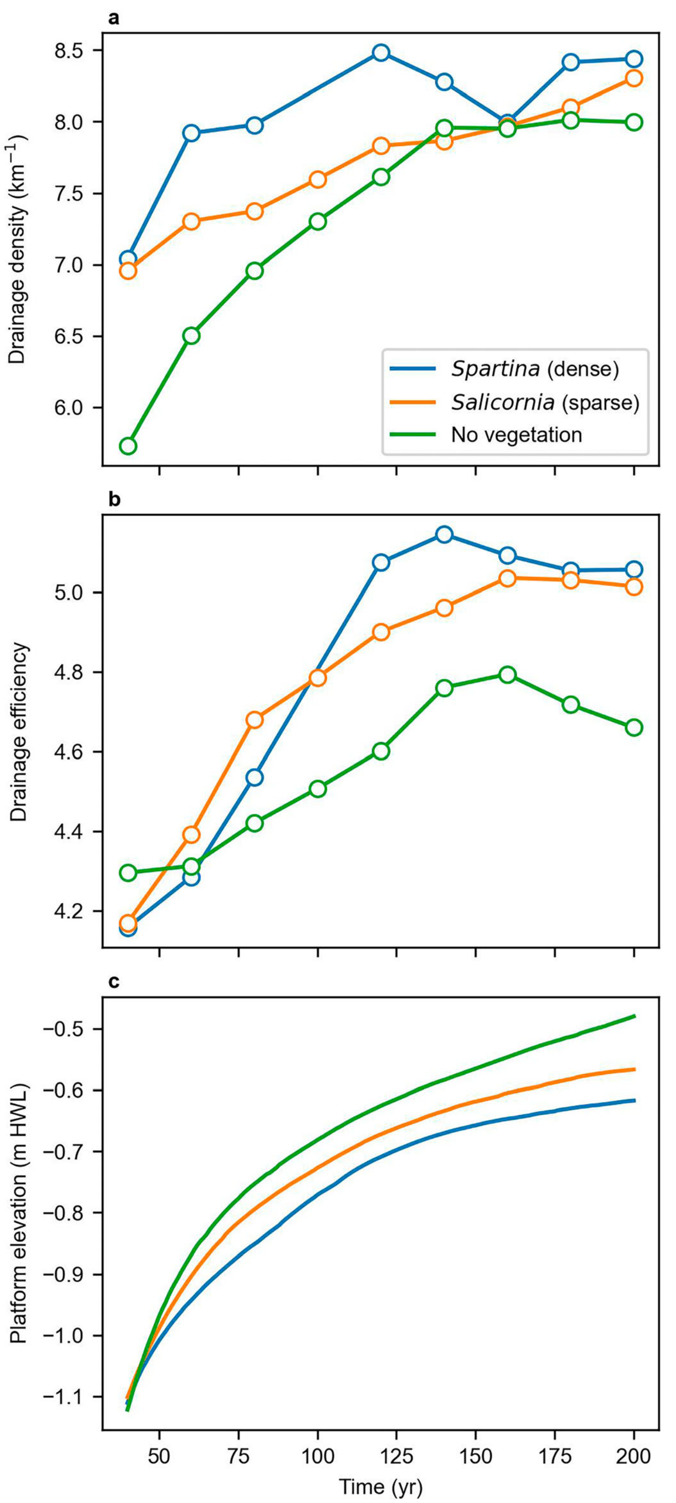

Fig. 2. Evolution of drainage density (**a**), drainage efficiency (**b**), and platform elevation (**c**) for *Spartina* marshes, *Salicornia* marshes, and unvegetated mudflats. The drainage density and the drainage efficiency are computed for each primary tidal channel at the seaward boundary ($x = 0$; Supporting Information Fig. S2) and are weight-averaged using watershed areas. The mean platform elevation is computed excluding tidal channels and is expressed with respect to the high-water level (HWL).

saltmarshes (Fig. 4a). The same reasoning holds when comparing *Spartina* and *Salicornia* marshes. The higher drag created by vegetation in dense *Spartina* marshes systematically leads to more temporary in-channel deposition than in sparse *Salicornia* marshes, and lower net sediment import on average.

This feedback between platform vegetation drag and temporary in-channel sedimentation explains why unvegetated platforms experience higher sediment supply and accretion rates than sparse *Salicornia* marshes, and even more so than dense *Spartina* marshes (Fig. 2c).

Vegetation increases near-channel sedimentation

The drag created by vegetation also enhances sedimentation on the platforms close to the channel edges, which has two important implications: it deprives saltmarsh interiors of suspended sediments, and it creates levee-depression patterns (Fig. 5a,b), ultimately leading to pond formation (Fig. 5d,e). Because of the differences in flow resistance between vegetated platforms and unvegetated channels, flooding occurs first through the channel network, then from the channels into the platforms once the water level inside the channels exceeds the elevation of the channel banks. From the channels to the platforms, the flow velocities quickly drop (Fig. 3a, b) and the sediments rapidly settle, which over time leads to levee formation close to the channels and depressions away from them. After 200 yr, the elevation difference between levees and ponds is on average about 60 cm in dense *Spartina* marshes and 50 cm in sparse *Salicornia* marshes (Fig. 5a,b), suggesting that this mechanism is amplified with increasing vegetation density.

Without vegetation, suspended sediments can be transported more easily toward platform interiors, and there is no levee-depression pattern (Fig. 5c). Without vegetation, the differences in flow resistance between platforms and channels are much lower and flooding occurs as sheet flow from the open-water body, with flow velocities more homogeneously distributed (Fig. 3c). The fact that the platforms of the unvegetated system (Fig. 5c) are on average higher than the levees of the vegetated saltmarshes (Fig. 5a,b) is another illustration that, with vegetation, there is more temporary in-channel deposition (Fig. 4b), and therefore less sediment transport from the channels to the platforms (previous section).

Discussion

The increasing threat of accelerating sea level rise makes saltmarsh vulnerability a crucial issue of the present century (Ganju et al. 2017; Jankowski et al. 2017; Schuerch et al. 2018; Murray et al. 2019; Saintilan et al. 2020). As coastal wetlands are expected to face sea level rise rates that are globally unprecedented in recent history (Oppenheimer et al. 2022), numerical models are essential to predict their fate. Here we use a multiscale process-based modeling

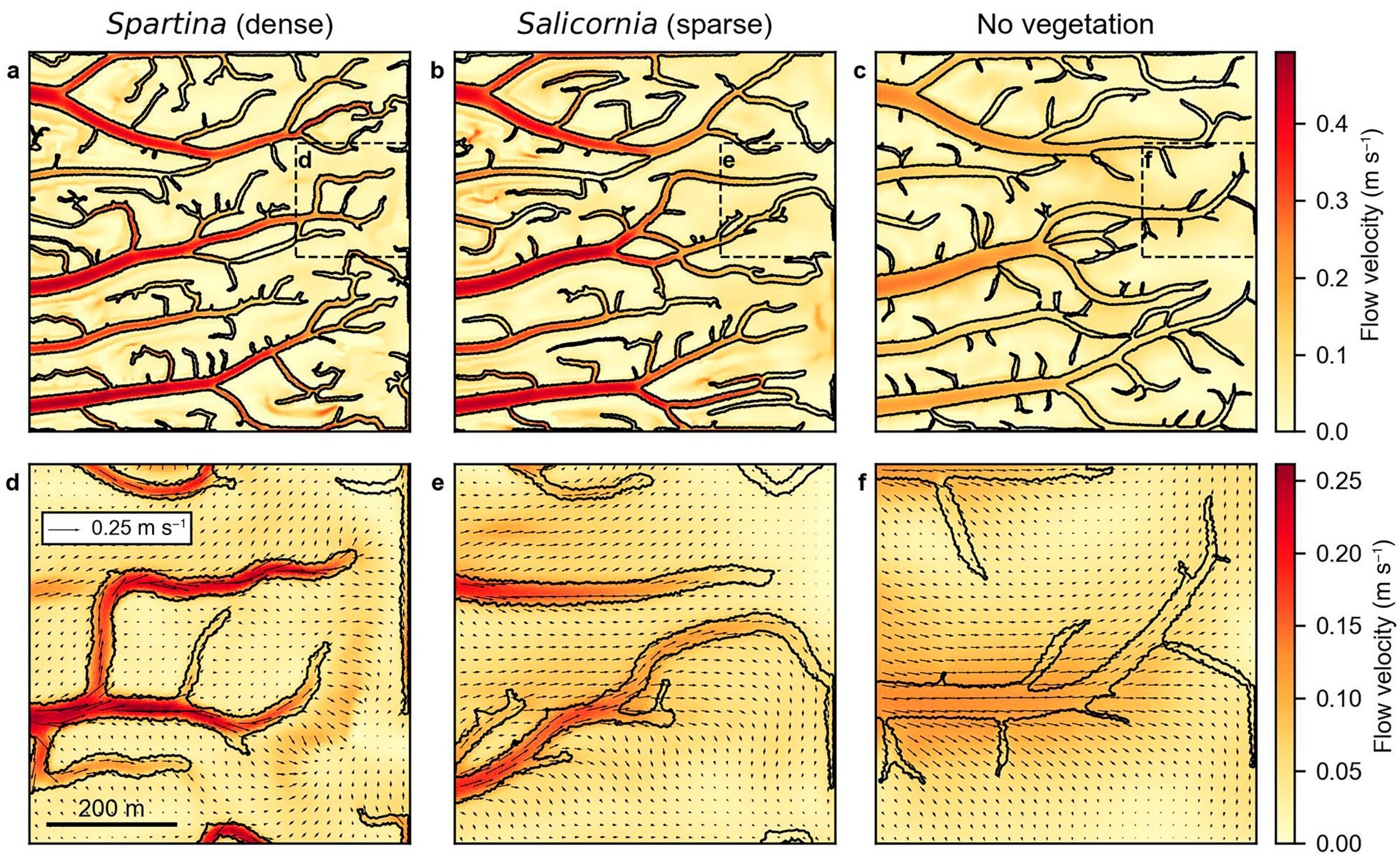

Fig. 3. (**a–c**) Flow velocities at the beginning of platform flooding (30 min before high tide in year 100) for *Spartina* marshes, *Salicornia* marshes and unvegetated mudflats. (**d–f**) Close-up view in the upstream part of the central channel. The black lines indicate channel edges. The black arrows represent flow velocity vectors.

approach (Gourgue et al. 2022), which is compared with field observations (Supporting Information Section S3) and able to represent centennial developments of tidal channel networks and spatial sediment accretion patterns with unmatched details (Fig. 1), under a constant contemporary rate of sea level rise. While present insights are largely based on the paradigm that dense vegetation promotes sediment accretion and marsh elevation gain in balance with sea level rise (Fagherazzi et al. 2012; Kirwan et al. 2016), we identify two key mechanisms through which dense vegetation also inhibits sediment accretion in saltmarsh interiors.

Reduced sediment supply and elevation deficit in saltmarsh interiors are well-established results confirmed by numerical models (D'Alpaos et al. 2007; Best et al. 2018) and field measurements (Coleman et al. 2020; Schepers et al. 2020). The novelty of our study is the thorough description of the mechanisms leading to these observations. In general, these observations are solely attributed to enhanced settling of suspended sediments on the saltmarsh platforms near the channel edges due to vegetation and increased friction. If that were the only significant mechanism at play, vegetated platforms would still on average accrete faster than unvegetated platforms, even more so considering that vegetation promotes dense, branching channel networks (Kearney and Fagherazzi 2016; Fig. 2a,b). Our results show a complete opposite trend: unvegetated platforms accrete on average faster than sparsely vegetated platforms, and even faster than densely vegetated platforms (Fig. 2c). These unexpected results in view of the current knowledge are explained by the fact that vegetation concentrates flow velocities (Fig. 3) and sediment transport (Fig. 4) inside the channels, hence reducing sediment supply toward platforms. Therefore, contrary to what is usually assumed implicitly in long-term platform accretion models with constant sediment supply from the channel (Kirwan et al. 2016; Duran Vinent et al. 2021), not all sediments in suspension inside tidal channels are available to supply the platforms, and hence saltmarshes are potentially more vulnerable to sea level rise than previously thought.

Previous studies highlight the positive effects of vegetation through biogeomorphic feedbacks on saltmarsh resilience to sea level rise (Morris et al. 2002; Kirwan et al. 2016): dense

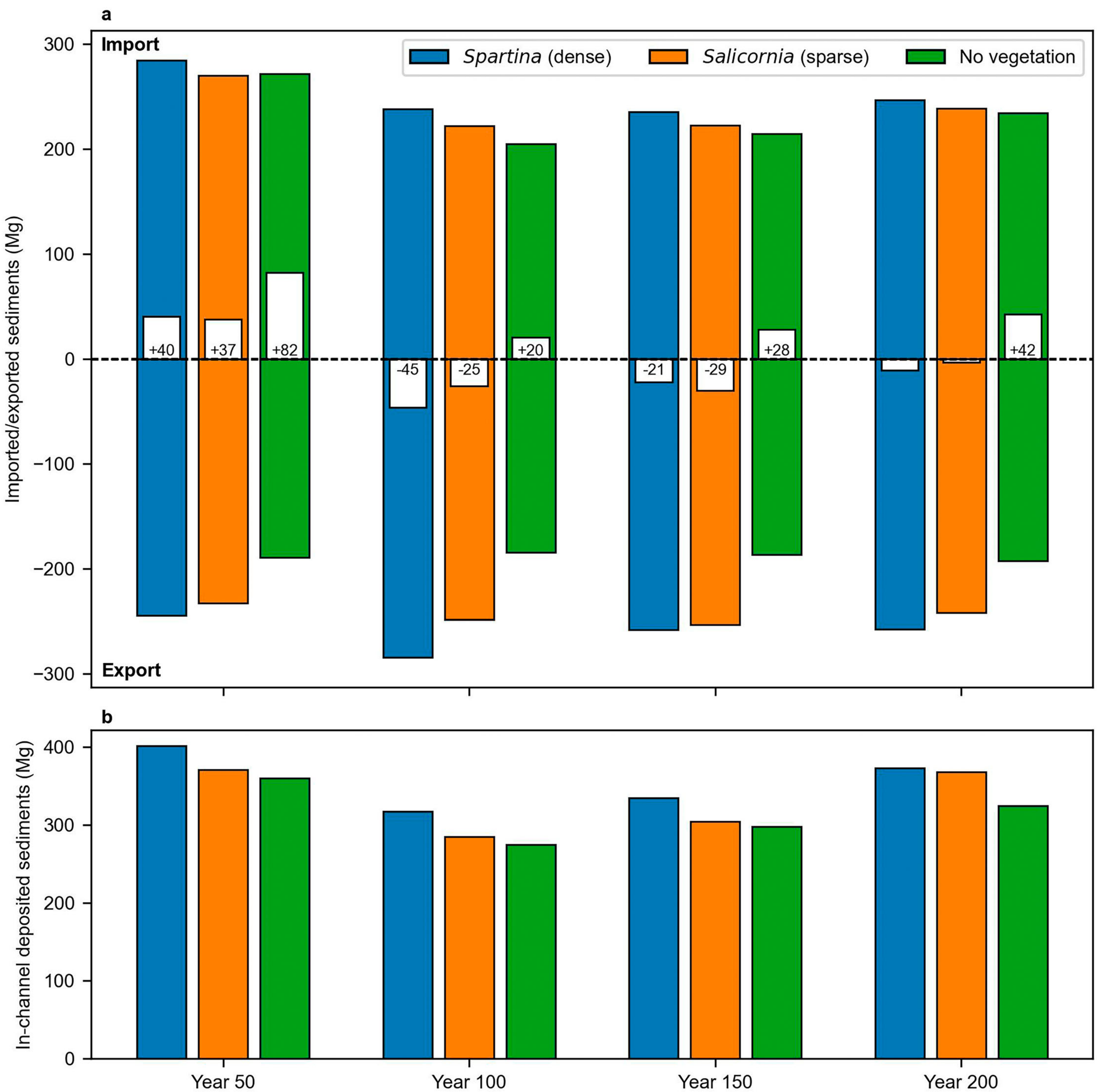

Fig. 4. (**a**) Total mass of sediments imported into and exported from the area of interest ($x > 0$; Supporting Information Fig. S2; white bars and numbers indicate net import balance), and (**b**) total mass of sediments deposited inside channels between two consecutive low tides, for *Spartina* marshes, *Salicornia* marshes and unvegetated mudflats.

vegetation attenuates tidal flow and wind waves, which is widely considered to enhance trapping of mineral sediments (Mudd et al. 2010; Fagherazzi et al. 2012) and reduce shoreline erosion (Möller et al. 2014; Schoutens et al. 2019). Although this is locally true, our results show that larger landscape-scale effects of vegetation on sediment distribution are more complex (Figs. 4, 5a–c), and that vegetation density is not necessarily positively correlated with platform accretion

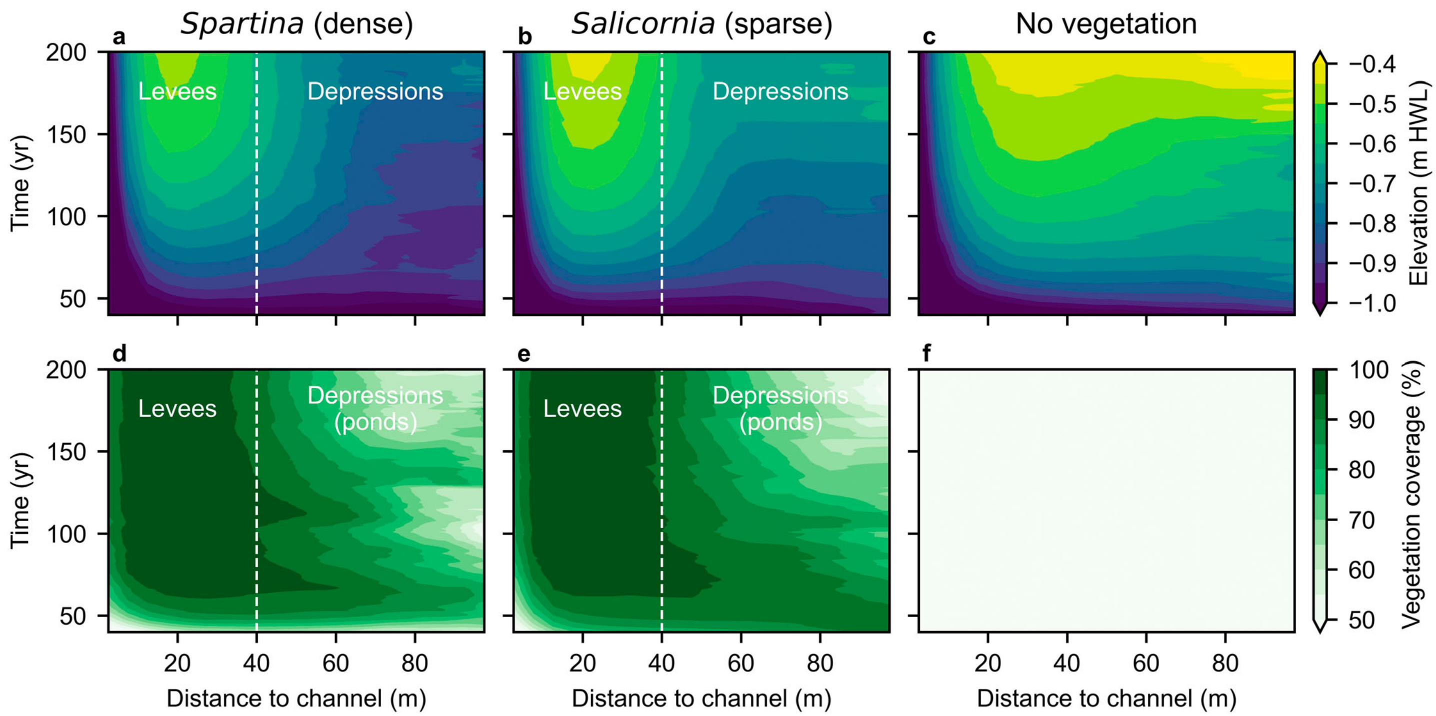

Fig. 5. Evolution of mean platform elevation (**a–c**) and mean vegetation coverage (**d–f**) as functions of the distance to the closest channel, for *Spartina* marshes, *Salicornia* marshes and unvegetated mudflats. The platform elevation is expressed with respect to the high-water level (HWL). The vegetation coverage is the percentage of vegetated pixels. Profiles are computed by classifying distances to the closest channels in bins of 5 m and averaging the considered variable within each bin.

rates (Fig. 2c). Similar vegetation effects are also observed in river-dominated settings (Nardin and Edmonds 2014; Hiatt and Passalacqua 2017; Wright et al. 2018; Albernaz et al. 2020; Xu et al. 2022; Beltrán-Burgos et al. 2023). Furthermore, previous studies focus on vegetation effects on tidal channel network characteristics, arguing that vegetation promotes the development of dense, branching, and meandering channel networks, which are claimed to be more efficient at draining coastal wetlands and delivering sediments to platform interiors (Kearney and Fagherazzi 2016; Schwarz et al. 2018, 2022). Our results reveal that vegetation density has a bigger impact on reduced sediment supply to saltmarsh interiors, and that tidal channel self-organization only plays a secondary role (Fig. 2).

Our results are in line with the paradigm that saltmarsh vegetation has a local positive impact on sediment trapping at the plant scale, but they reveal that saltmarsh vegetation also develops self-predatory mechanisms at the larger landscape scale, which can jeopardize their own survival. The potential die-back of vegetation due to increased water retention in densely vegetated saltmarshes is already reported in a prior study (Brückner et al. 2019). Here we also show that this is aggravated by the vegetation-induced formation of levees and topographic depressions (Fig. 5a,b), resulting from enhanced sedimentation on the vegetated platforms near the channels, and reduced sedimentation on their interiors. These topographic depressions can be temporarily converted into unvegetated ponds when disconnected from the channel network (Figs. 1, 5d,e) because of waterlogging and vegetation die-back. In the cases studied here, ponds get revegetated after a few decades once they reconnect to the channel network, a process also reported from observations (Wilson et al. 2014). Under less favorable conditions, however, pond formation can lead to considerable saltmarsh drowning (Schepers et al. 2017; Mariotti et al. 2020).

This study focuses on the specific case of a macrotidal system, with a moderate sediment supply and a contemporary rate of sea level rise. Current knowledge suggests that saltmarshes subject to lower tidal ranges, lower sediment supplies, or faster sea level rise are more vulnerable than the cases studied here (Kirwan et al. 2016; Duran Vinent et al. 2021) and we can reasonably expect that the mechanisms revealed in this study stay relevant in these conditions. In microtidal saltmarshes, platform elevation changes are also influenced by processes that are neglected in our model, such as local organic production (Temmerman et al. 2004; Kirwan et al. 2010) and storm surges (Goodbred and Hine 1995; Tognin et al. 2021). Although the tidal supply of inorganic sediments remains a key process determining accretion rates in such environments (Ganju et al. 2013, 2015; Belliard et al. 2023), we must acknowledge that our conclusions are especially relevant for mesotidal to macrotidal systems, where accretion is predominantly driven by inorganic material (French 2006). Additionally, low-tide rainfall runoff is a platform sediment removal mechanism that is neglected in our model, which could have a stronger effect on mudflats due to the absence of vegetation canopy to mitigate raindrop impact. However, this process is poorly quantified (Mwamba and Torres 2002). Another process that is neglected in our model is flocculation, a process by which suspended sediment particles come together to form larger aggregates or flocs, which impacts settling velocities. By testing the model sensitivity to settling velocities in a range that is consistent with observed values for flocs in similar environmental conditions (van Leussen 1999), we show that our conclusions are not impacted by such potential variations (Supporting Information Section S4). Finally, although our model also neglects the vegetation-induced reduction of turbulence (Leonard and Croft 2006), the latter enhances sedimentation on the platforms and therefore reinforce our conclusions.

Our model results are in good agreement with field observations of channel network characteristics and accretion history (Supporting Information Section S3). However, the specific mechanisms identified here, that vegetation concentrates flow velocities (Fig. 3) and sediment transport (Fig. 4) inside the channels, hence reducing sediment supply toward the platforms, remain difficult to observe in the field (Boldt et al. 2013). Our study calls for the development of new field techniques and the collection of new observational datasets, with the aim to validate these mechanisms and their influence on long-term saltmarsh dynamics. Healthy saltmarshes have managed to persist in many places for hundreds or more years. However, by identifying mechanisms by which saltmarsh vegetation hinders sediment transport from channels to platform interiors, our study cautions against potential overestimation of the capacity of densely vegetated saltmarshes to gain elevation and keep pace with sea level rise.

References

Albernaz, M. B., L. Roelofs, H. J. Pierik, and M. G. Kleinhans. 2020. Natural levee evolution in vegetated fluvial-tidal environments. Earth Surf. Process. Lanfdorms **45**: 3824–3841. doi:10.1002/esp.5003

Baptist, M. J., V. Babovic, J. R. Uthurburu, M. Keijzer, R. E. Uittenbogaard, A. Mynett, and A. Verwey. 2007. On inducing equations for vegetation resistance. J. Hydraul. Res. **45**: 435–450. doi:10.1080/00221686.2007.9521778

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

Belliard, J.-P., M. Toffolon, L. Carniello, and A. D'Alpaos. 2015. An ecogeomorphic model of tidal channel initiation and elaboration in progressive marsh accretional contexts. J. Geophys. Res. Earth Surf. **120**: 1040–1064. doi:10.1002/2015jf003445

Belliard, J.-P., O. Gourgue, G. Govers, M. L. Kirwan, and S. Temmerman. 2023. Coastal wetland adaptability to sea level rise: The neglected role of semi-diurnal vs. diurnal tides. Limnol. Oceanogr.: Lett. **8**: 340–349. doi:10.1002/lol2.10298

Beltrán-Burgos, M., C. R. Esposito, H. M. Nepf, M. M. Baustian, and D. R. D. Leonardo. 2023. Vegetation-driven seasonal sediment dynamics in a freshwater marsh of the Mississippi River Delta. J. Geophys. Res. Biogeosci. **128**: e2022JG007143. doi:10.1029/2022jg007143

Best, Ü. S. N., M. Van der Wegen, J. Dijkstra, P. W. J. M. Willemsen, B. W. Borsje, and D. J. A. Roelvink. 2018. Do salt marshes survive sea level rise? Modelling wave action, morphodynamics and vegetation dynamics. Environ. Model. Softw. **109**: 152–166. doi:10.1016/j.envsoft.2018.08.004

Boldt, K. V., C. A. Nittrouer, and A. S. Ogston. 2013. Seasonal transfer and net accumulation of fine sediment on a muddy tidal flat: Willapa Bay, Washington. Cont. Shelf Res. **60**: S157–S172. doi:10.1016/j.csr.2012.08.012

Brückner, M. Z. M., C. Schwarz, W. M. van Dijk, M. van Oorschot, H. Douma, and M. G. Kleinhans. 2019. Salt marsh establishment and eco-engineering effects in dynamic estuaries determined by species growth and mortality. J. Geophys. Res. Earth Surf. **124**: 2962–2986. doi:10.1029/2019jf005092

Coleman, D. J., N. K. Ganju, and M. L. Kirwan. 2020. Sediment delivery to a tidal marsh platform is minimized by source decoupling and flux convergence. J. Geophys. Res. Earth Surf. **125**: e2020JF005558. doi:10.1029/2020jf005558

D'Alpaos, A., S. Lanzoni, S. M. Mudd, and S. Fagherazzi. 2006. Modeling the influence of hydroperiod and vegetation on the cross-sectional formation of tidal channels. Estuar. Coast. Shelf Sci. **69**: 311–324. doi:10.1016/j.ecss.2006.05.002

D'Alpaos, A., S. Lanzoni, M. Marani, and A. Rinaldo. 2007. Landscape evolution in tidal embayments: Modeling the interplay of erosion, sedimentation, and vegetation dynamics. J. Geophys. Res. **112**: F01008. doi:10.1029/2006jf000537

Duran Vinent, O., E. R. Herbert, D. J. Coleman, J. D. Himmelstein, and M. L. Kirwan. 2021. Onset of runaway fragmentation of salt marshes. One Earth **4**: 506–516. doi:10.1016/j.oneear.2021.02.013

Fagherazzi, S., A. Bortoluzzi, W. E. Dietrich, A. Adami, S. Lanzoni, M. Marani, and A. Rinaldo. 1999. Tidal networks 1. Automatic network extraction and preliminary scaling features from digital terrain maps. Water Resour. Res. **35**: 3891–3904. doi:10.1029/1999wr900236

Fagherazzi, S., and others. 2012. Numerical models of salt marsh evolution: Ecological, geomorphic, and climatic factors. Rev. Geophys. **50**: RG1002. doi:10.1029/2011rg000359

Fagherazzi, S., G. Mariotti, N. Leonardi, A. Canestrelli, W. Nardin, and W. S. Kearney. 2020. Salt marsh dynamics in a period of accelerated sea level rise. J. Geophys. Res. Earth Surf. **125**: e2019JF005200. doi:10.1029/2019jf005200

Finotello, A., S. Lanzoni, M. Ghinassi, M. Marani, A. Rinaldo, and A. D'Alpaos. 2018. Field migration rates of tidal meanders recapitulate fluvial morphodynamics. Proc. Natl. Acad. Sci. USA **115**: 1463–1468. doi:10.1073/pnas.1711330115

French, J. 2006. Tidal marsh sedimentation and resilience to environmental change: Exploratory modelling of tidal, sea-level and sediment supply forcing in predominantly allochthonous systems. Mar. Geol. **235**: 119–136. doi:10.1016/j.margeo.2006.10.009

Ganju, N. K., N. J. Nidzieko, and M. L. Kirwan. 2013. Inferring tidal wetland stability from channel sediment fluxes: Observations and a conceptual model. J. Geophys. Res. Earth Surf. **118**: 2045–2058. doi:10.1002/jgrf.20143

Ganju, N. K., M. L. Kirwan, P. J. Dickhudt, G. R. Guntenspergen, D. R. Cahoon, and K. D. Kroeger. 2015. Sediment transport-based metrics of wetland stability. Geophys. Res. Lett. **42**: 7992–8000. doi:10.1002/2015gl065980

Ganju, N. K., Z. Defne, M. L. Kirwan, S. Fagherazzi, A. D'Alpaos, and L. Carniello. 2017. Spatially integrative metrics reveal hidden vulnerability of microtidal salt marshes. Nat. Commun. **8**: 14156. doi:10.1038/ncomms14156

Goodbred, S. L., and A. C. Hine. 1995. Coastal storm deposition: Salt-marsh response to a severe extratropical storm, March 1993, west-central Florida. Geology **23**: 679–682. doi:10.1130/0091-7613(1995)023<0679:csdsmr>2.3.co;2

Gourgue, O. 2022. Demeter (v2.0). doi:10.5281/zenodo.7101535

Gourgue, O., J. van Belzen, C. Schwarz, T. J. Bouma, J. van de Koppel, and S. Temmerman. 2021. A convolution method to assess subgrid-scale interactions between flow and patchy vegetation in biogeomorphic models. J. Adv. Model Earth Syst. **13**: e2020MS002116. doi:10.1029/2020ms002116

Gourgue, O., and I. Pelckmans. 2022. TidalGeoPro (v1.0). doi:10.5281/zenodo.7153257

Gourgue, O., and others. 2022. Biogeomorphic modeling to assess the resilience of tidal-marsh restoration to sea level rise and sediment supply. Earth Surf. Dyn. **10**: 531–553. doi:10.5194/esurf-10-531-2022

Gourgue, O., J.-P. Belliard, Y. Xu, M. G. Kleinhans, S. Fagherazzi, and S. Temmerman. 2023*a*. Dense vegetation hinders sediment transport towards saltmarsh interiors—Supporting data and source code (Part I: Pre-processing) (v1). doi:10.5281/zenodo.8262328

Gourgue, O., J.-P. Belliard, Y. Xu, M. G. Kleinhans, S. Fagherazzi, and S. Temmerman. 2023*b*. Dense vegetation hinders sediment transport towards saltmarsh interiors—Supporting data and source code (Part II: Main runs) (v1). doi:10.5281/zenodo.8256561

Gourgue, O., J.-P. Belliard, Y. Xu, M. G. Kleinhans, S. Fagherazzi, and S. Temmerman. 2024*a*. Dense vegetation hinders sediment transport towards saltmarsh interiors—Supporting data and source code (Part III: Extra runs) (v2). doi:10.5281/zenodo.11395640

Gourgue, O., J.-P. Belliard, Y. Xu, M. G. Kleinhans, S. Fagherazzi, and S. Temmerman. 2024*b*. Dense vegetation hinders sediment transport towards saltmarsh interiors—Supporting data and source code (Part IV: Post-processing) (v2). doi:10.5281/zenodo.11396904

Gourgue, O., J.-P. Belliard, Y. Xu, M. G. Kleinhans, S. Fagherazzi, and S. Temmerman. 2024*c*. Dense vegetation hinders sediment transport towards saltmarsh interiors—Supporting data and source code (Part V: Figures) (v3). doi:10.5281/zenodo.11401186

Hervouet, J.-M. 2007. *Hydrodynamics of free surface flows: Modelling with the finite element method*. Wiley. doi:10.1002/9780470319628

Hiatt, M., and P. Passalacqua. 2017. What controls the transition from confined to unconfined flow? Analysis of hydraulics in a coastal river delta. J. Hydraul. Eng. **143**: 03117003. doi:10.1061/(asce)hy.1943-7900.0001309

Jankowski, K. L., T. E. Törnqvist, and A. M. Fernandes. 2017. Vulnerability of Louisiana's coastal wetlands to present-day rates of relative sea-level rise. Nat. Commun. **8**: 14792. doi:10.1038/ncomms14792

Kearney, W. S., and S. Fagherazzi. 2016. Salt marsh vegetation promotes efficient tidal channel networks. Nat. Commun. **7**: 12287. doi:10.1038/ncomms12287

Kirwan, M. L., G. R. Guntenspergen, A. D'Alpaos, J. T. Morris, S. M. Mudd, and S. Temmerman. 2010. Limits on the adaptability of coastal marshes to rising sea level. Geophys. Res. Lett. **37**: L23401. doi:10.1029/2010gl045489

Kirwan, M. L., S. Temmerman, E. E. Skeehan, G. R. Guntenspergen, and S. Fagherazzi. 2016. Overestimation of marsh vulnerability to sea level rise. Nat. Clim. Change **6**: 253–260. doi:10.1038/nclimate2909

Leonard, L. A., and A. L. Croft. 2006. The effect of standing biomass on flow velocity and turbulence in *Spartina alterniflora* canopies. Estuar. Coast. Shelf Sci. **69**: 325–336. doi:10.1016/j.ecss.2006.05.004

Lesser, G. R., J. A. Roelvink, J. A. T. M. van Kester, and G. S. Stelling. 2004. Development and validation of a three-dimensional morphological model. Coast. Eng. **51**: 883–915. doi:10.1016/j.coastaleng.2004.07.014

Liu, Y., M. Zhou, S. Zhao, W. Zhan, K. Yang, and M. Li. 2015. Automated extraction of tidal creeks from airborne laser altimetry data. J. Hydrol. **527**: 1006–1020. doi:10.1016/j.jhydrol.2015.05.058

Liu, Z., O. Gourgue, and S. Fagherazzi. 2022. Biotic and abiotic factors control the geomorphic characteristics of channel networks in salt marshes. Limnol. Oceanogr. **67**: 89–101. doi:10.1002/lno.11977

Marani, M., E. Belluco, A. D'Alpaos, A. Defina, S. Lanzoni, and A. Rinaldo. 2003. On the drainage density of tidal networks. Water Resour. Res. **39**: 211. doi:10.1029/2001wr001051

Mariotti, G. 2020. Beyond marsh drowning: The many faces of marsh loss (and gain). Adv. Water Resour. **144**: 103710. doi:10.1016/j.advwatres.2020.103710

Mariotti, G., A. C. Spivak, S. Y. Luk, G. Ceccherini, M. Tyrrell, and M. E. Gonneea. 2020. Modeling the spatial dynamics of marsh ponds in New England salt marshes. Geomorphology **365**: 107262. doi:10.1016/j.geomorph.2020.107262

Möller, I., and others. 2014. Wave attenuation over coastal salt marshes under storm surge conditions. Nat. Geosci. **7**: 727–731. doi:10.1038/ngeo2251

Morris, J. T., P. V. Sundareshwar, C. T. Nietch, B. Kjerfve, and D. R. Cahoon. 2002. Responses of coastal wetlands to rising sea level. Ecology **83**: 2869–2877. doi:10.2307/3072022

Mudd, S. M., A. D'Alpaos, and J. T. Morris. 2010. How does vegetation affect sedimentation on tidal marshes? Investigating particle capture and hydrodynamic controls on biologically mediated sedimentation. J. Geophys. Res. **115**: F03029. doi:10.1029/2009jf001566

Murray, N. J., and others. 2019. The global distribution and trajectory of tidal flats. Nature **565**: 222–225. doi:10.1038/s41586-018-0805-8

Mwamba, M. J., and R. Torres. 2002. Rainfall effects on marsh sediment redistribution, North Inlet, South Carolina, USA. Mar. Geol. **189**: 267–287. doi:10.1016/s0025-3227(02)00482-6

Nardin, W., and D. A. Edmonds. 2014. Optimum vegetation height and density for inorganic sedimentation in deltaic marshes. Nat. Geosci. **7**: 722–726. doi:10.1038/ngeo2233

Oppenheimer, M., B. C. Glavovic, J. Hinkel, R. van de Wal, A. K. Magnan, A. Abd-Elgawad, R. Cai, M. Cifuentes-Jara, R. M. DeConto, T. Ghosh, J. Hay, F. Isla, B. Marzeion, B. Meyssignac, and Z. Sebesvari. 2019. Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N. M. Weyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 321–445. doi:10.1017/9781009157964.006

Rodríguez, J. F., P. M. Saco, S. Sandi, N. Saintilan, and G. Riccardi. 2017. Potential increase in coastal wetland vulnerability to sea-level rise suggested by considering hydrodynamic attenuation effects. Nat. Commun. **8**: 16094. doi:10.1038/ncomms16094

Roelvink, J. A. 2006. Coastal morphodynamic evolution techniques. Coast. Eng. **53**: 277–287. doi:10.1016/j.coastaleng.2005.10.015

Rogers, K., and others. 2019. Wetland carbon storage controlled by millennial-scale variation in relative sea-level rise. Nature **567**: 91–95. doi:10.1038/s41586-019-0951-7

Saintilan, N., N. S. Khan, E. Ashe, J. J. Kelleway, K. Rogers, C. D. Woodroffe, and B. P. Horton. 2020. Thresholds of mangrove survival under rapid sea level rise. Science **368**: 1118–1121. doi:10.1126/science.aba2656

Schepers, L., M. Kirwan, G. Guntenspergen, and S. Temmerman. 2017. Spatio-temporal development of vegetation die-off in a submerging coastal marsh. Limnol. Oceanogr. **62**: 137–150. doi:10.1002/lno.10381

Schepers, L., P. Brennand, M. L. Kirwan, G. R. Guntenspergen, and S. Temmerman. 2020. Coastal marsh degradation into ponds induces irreversible elevation loss relative to sea level in a microtidal system. Geophys. Res. Lett. **47**: e2020GL089121. doi:10.1029/2020gl089121

Schoutens, K., M. Heuner, V. Minden, T. S. Ostermann, A. Silinski, J.-P. Belliard, and S. Temmerman. 2019. How effective are tidal marshes as nature-based shoreline protection throughout seasons? Limnol. Oceanogr. **64**: 1750–1762. doi:10.1002/lno.11149

Schuerch, M., and others. 2018. Future response of global coastal wetlands to sea-level rise. Nature **561**: 231–234. doi:10.1038/s41586-018-0476-5

Schwarz, C., and others. 2018. Self-organization of a biogeomorphic landscape controlled by plant life-history traits. Nat. Geosci. **11**: 672–677. doi:10.1038/s41561-018-0180-y

Schwarz, C., F. van Rees, D. Xie, M. G. Kleinhans, and B. van Maanen. 2022. Salt marshes create more extensive channel networks than mangroves. Nat. Commun. **13**: 2017. doi:10.1038/s41467-022-29654-1

Temmerman, S., G. Govers, S. Wartel, and P. Meire. 2004. Modelling estuarine variations in tidal marsh sedimentation: Response to changing sea level and suspended sediment concentrations. Mar. Geol. **212**: 1–19. doi:10.1016/j.margeo.2004.10.021

Temmerman, S., T. J. Bouma, J. van de Koppel, D. Van der Wal, M. B. D. Vries, and P. M. J. Herman. 2007. Vegetation causes channel erosion in a tidal landscape. Geology **35**: 631–634. doi:10.1130/g23502a.1

Temmerman, S., E. M. Horstman, K. W. Krauss, J. C. Mullarney, I. Pelckmans, and K. Schoutens. 2022. Marshes and mangroves as nature-based coastal storm buffers. Ann. Rev. Mar. Sci. **15**: 95–118. doi:10.1146/annurev-marine-040422-092951

Tognin, D., A. D'Alpaos, M. Marani, and L. Carniello. 2021. Marsh resilience to sea-level rise reduced by storm-surge barriers in the Venice Lagoon. Nat. Geosci. **14**: 906–911. doi:10.1038/s41561-021-00853-7

Tucker, G. E., F. Catani, A. Rinaldo, and R. L. Bras. 2001. Statistical analysis of drainage density from digital terrain data. Geomorphology **36**: 187–202. doi:10.1016/s0169-555x(00)00056-8

van Leussen, W. 1999. The variability of settling velocities of suspended fine-grained sediment in the Ems estuary. J. Sea. Res. **41**: 109–118. doi:10.1016/s1385-1101(98)00046-x

Vandenbruwaene, W., T. J. Bouma, P. Meire, and S. Temmerman. 2013. Bio-geomorphic effects on tidal channel evolution: Impact of vegetation establishment and tidal prism change. Earth Surf. Process. Landforms **38**: 122–132. doi:10.1002/esp.3265

Vandenbruwaene, W., C. Schwarz, T. J. Bouma, P. Meire, and S. Temmerman. 2015. Landscape-scale flow patterns over a vegetated tidal marsh and an unvegetated tidal flat: Implications for the landform properties of the intertidal floodplain. Geomorphology **231**: 40–52. doi:10.1016/j.geomorph.2014.11.020

Wang, D., J. Bai, C. Gu, W. Gao, C. Zhang, Z. Gong, and B. Cui. 2021. Scale-dependent biogeomorphic feedbacks control the tidal marsh evolution under *Spartina alterniflora* invasion. Sci. Total Environ. **776**: 146495. doi:10.1016/j.scitotenv.2021.146495

Wilson, C. A., Z. J. Hughes, D. M. FitzGerald, C. S. Hopkinson, V. Valentine, and A. S. Kolker. 2014. Saltmarsh pool and tidal creek morphodynamics: Dynamic equilibrium of northern latitude saltmarshes? Geomorphology **213**: 99–115. doi:10.1016/j.geomorph.2014.01.002

Wright, K., M. Hiatt, and P. Passalacqua. 2018. Hydrological connectivity in vegetated river deltas: The importance of patchiness below a threshold. Geophys. Res. Lett. **45**: 10416–10427. doi:10.1029/2018gl079183

Xu, Y., C. R. Esposito, M. Beltrán-Burgos, and H. M. Nepf. 2022. Competing effects of vegetation density on sedimentation in deltaic marshes. Nat. Commun. **13**: 4641. doi:10.1038/s41467-022-32270-8

Acknowledgments

This project is funded by the European Union's Horizon 2020 research and innovation program (Marie Skłodowska-Curie Actions, global postdoctoral fellowship, grant no. 798222) and the Research Foundation—Flanders (FWO, fundamental research project, grant no. G031620N). J-PB is supported by the Research Foundation—Flanders (FWO, fundamental research project, grant no. G060018N). MGK is supported by the European Research Council (ERC Consolidator Grant, grant no. 647570). SF is supported by the National Science Foundation (NSF awards 2224608—PIE LTER—and 1832221—VCR LTER). The resources and services used in this work are provided by the VSC (Flemish Supercomputer Center), funded by the Research Foundation—Flanders (FWO) and the Flemish Government.

Submitted 30 January 2024
Revised 04 September 2024
Accepted 09 September 2024