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Salt marshes for nature-based flood defense: Sediment type, drainage, and vegetation drive the development of strong sediment beds

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ABSTRACT

In face of sea-level rise and increasing risks for storm impacts on shorelines, there is a growing demand for developing nature-based flood defenses, for example by restoring or creating salt marshes in front of engineered structures such as dikes. However, salt marshes can only optimally provide flood defense if their sediment beds are erosion resistant, even under very high flow velocities. It remains unknown how fast sediment strength develops in marshes restored or created for nature-based flood defense. Therefore, this study investigated how 1) sediment type, 2) tidal drainage depth and duration, and 3) pioneer vegetation species drive the development rate of sediment strength. A controlled experiment was set up with pots filled with two sediment types, which were either left bare or planted with *Spartina anglica* or *Scirpus maritimus*, two dominant salt marsh pioneers in NW Europe. All treatments were subjected to four different tidal regimes with different tidal drainage depth and duration. The results showed that sandy mud (with a 37% silt and clay fraction) led to much stronger sediments than fine mud (with a 77% silt and clay fraction). Sediment strength was higher in the treatments with deeper tidal drainage depth and longer drainage duration. The presence of vegetation increased sediment strength and this effect was stronger with *Scirpus maritimus* than with *Spartina anglica*. Plant roots increased sediment strength directly, and the presence of vegetation also seemed to increase sediment strength through enhanced evaporation and transpiration. From these results it can be concluded that to restore or create erosion resistant salt marshes for flood defense, it is essential to ensure that marshes can form at relatively high elevations from well-draining sand-mud mixtures, thereby also ensuring vegetation growth.

1. Introduction

As a result of climate change, sea levels are rising and storm intensity is increasing in certain regions (Bacmeister et al., 2018; IPCC, 2023; Leonardi et al., 2018). This will lead to significant increases in flood risks along coastal and estuarine shorelines. To protect shorelines from sea-level rise and increased storminess, current hard engineering structures for flood defense need to be heightened and strengthened. However, this maintenance is required regularly, hence is expensive and may become unsustainable (Temmerman et al., 2013; Vuik et al., 2019). Therefore, there is currently a growing interest in complementary measures for flood protection, such as the integration of nature-based solutions with engineered coastal defenses. In particular, salt marshes are considered highly valuable for nature-based flood risk mitigation (e.g. Leonardi et al., 2018; Temmerman et al., 2023). The active large-scale implementation is however awaiting resolving several knowledge questions (Bouma et al., 2014).

Salt marshes are intertidal wetlands that provide important ecosystem services, such as sequestering carbon, immobilizing pollutants, and offering recreational activities (Barbier et al., 2011; Brooks

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et al., 2021; Duarte et al., 2013). In addition, salt marshes in front of engineered flood defense, such as dikes, reduce the risk of failure of these flood defenses under critical storm conditions. Salt marshes reduce wave impact on dikes because the presence of the salt marsh vegetation and their elevated bed surface level attenuates waves more than unvegetated, lower elevated mudflats (Vuik et al., 2016). Salt marshes in front of a dike can also reduce dike breach dimensions if a dike breach happens, which in turn can lead to a shallower and slower inundation in the hinterland, hence reducing flood damage and allowing more time for evacuation (van den Hoven et al., 2023; Zhu et al., 2020a). Furthermore, salt marsh vegetation stimulates sediment accumulation by directly trapping sediment with their stems and leaves and by slowing down the water flow, and thus enhancing suspended sediment settlement (Fagherazzi et al., 2012; Mudd et al., 2010). Because of the resulting increase in surface elevation, marshes can keep up relatively well with sea-level rise, if there is sufficient sediment supply and accommodation space and if the tidal cycle allows for sufficiently high sedimentation rates (Belliard et al., 2023; Coleman et al., 2022; Schuerch et al., 2018). This natural sediment accumulation makes the protective effect of a hybrid approach, combining dikes and salt marshes in front of the dikes, cheaper, more sustainable and more climate-proof than conventional, hard engineering structures without salt marshes in front of them (Temmerman et al., 2023; Vuik et al., 2019).

As a result of these insights, there is a growing interest in salt marsh restoration or creation for nature-based coastal defense in estuaries. Knowledge gaps hampering large-scale implementation (Bouma et al., 2014) are increasingly addressed. For example, we increasingly start to understand the long-term biogeomorphic dynamics driving marsh width (Bouma et al., 2016; Willemsen et al., 2018, 2020, 2022) and the wave attenuating capacity under extreme conditions (Möller et al., 2014; Zhu et al., 2020a). It is obvious that salt marshes will only reduce flood discharge and damage after a dike breach if their sediment beds are strong and erosion resistant, even under the high flow velocities that are associated with dike breaches (Zhu et al., 2020a). Hence, important remaining questions are how long it takes to form an erosion resistant salt marsh sediment bed that can withstand dike breach flow velocities, and under which conditions this formation goes fastest. Answering these questions is crucial for the implementation of restored or created salt marshes as a component of coastal defense structures.

Salt marsh sediments typically consist of cohesive sediments due to the presence of a relatively high silt and/or clay fraction (Brooks et al., 2021; Grabowski et al., 2011). The development of erosion resistance of cohesive sediments is expected to be affected by both biotic and abiotic processes (Brooks et al., 2021; Chen et al., 2012). An important abiotic process that affects sediment erosion resistance is consolidation (i.e. strengthening of the sediment bed; Chen et al., 2012). Under the weight of accumulating sediment, self-weight consolidation expels pore water from the sediment matrix (Barciela-Rial et al., 2020; Torfs et al., 1996). This dewatering decreases the sediment volume and thereby increases bulk density (Torfs et al., 1996; Zhou et al., 2016). In turn, these changes increase the cohesive strength and hence the erosion resistance of cohesive sediment beds (Chen et al., 2012; Grabowski et al., 2011). In addition, consolidation can also result from drying of the sediment, called drying-induced consolidation (Dong et al., 2020). Sediment water losses through drainage (Cao et al., 2021; Van Putte et al., 2022) and evaporation (Barciela-Rial et al., 2023) are therefore expected to lead to consolidation, and in turn enhance marsh sediment erosion resistance.

An important biotic process that influences the formation of erosion resistant sediment beds is vegetation growth. Generally, lower erosion rates are observed in vegetated areas than in bare areas (Lo et al., 2017; Wang et al., 2017). Plants can increase erosion resistance directly with their belowground biomass, but also indirectly by modifying sediment properties (Fagherazzi et al., 2012; Feagin et al., 2015). Roots directly increase aggregate stability and cohesion, leading to increased erosion resistance with increasing root biomass (Brooks et al., 2021; Gyssels et al., 2005). At the same time, root growth is influenced by sediment properties (Gyssels et al., 2005), illustrating the feedbacks between biological and physical factors in salt marshes. Vegetation indirectly increases sediment erosion resistance by capturing fine, cohesive sediments and accumulating sediment organic matter (Fagherazzi et al., 2012; Feagin et al., 2015), which will increase cohesion (Brooks et al., 2021). Vegetation also enhances evapotranspiration of sediment pore water (Barciela-Rial et al., 2023), and thereby contributes to drying-induced consolidation and sediment erosion resistance.

Until now, it remains unknown how the development rates of sediment strength and erosion resistance in salt marshes are influenced by sediment type, tidal drainage depth and duration, and pioneer vegetation species. Gaining insight in these effects will enable the possibility to determine how fast a vegetated and erosion resistant marsh can develop under the conditions at a specific location, and thus if this location is suitable for marsh development for flood defense. Therefore, the aim of this study was to improve our understanding of how 1) sediment type, 2) tidal drainage depth and duration, and 3) pioneer vegetation species drive the development rates of sediment strength and erosion resistance using a controlled experiment. By monitoring sediment properties and strength and vegetation biomass over time, the rates of sediment strength development and vegetation growth were estimated, improving the understanding of interactions between marsh sediment and vegetation.

2. Methods

2.1. Experimental design

A controlled experiment was carried out in an outdoor mesocosm facility. Sixteen tidal mesocosms (Cao et al., 2018) were filled with brackish water (5 ppt) obtained by mixing water taken from the Eastern Scheldt estuary (30 ppt) and fresh tap water. The salinity used in the experiment aimed to simulate the conditions in the middle reaches of the Western Scheldt estuary where *Scirpus maritimus* can survive. Each tidal mesocosm consists of two 1.11 × 0.93 × 0.60 m tanks on top of each other and a pump in the bottom tank is connected to a timer (Fig. 1A). To simulate high tide, the pump brings water up from the bottom tank to the upper tank. The pump stops during low tide, which lets the water freely flow back to the lower basin for storage. Thereby a tidal regime is simulated in the upper tank. The transitions between high and low tide take ±5 min, simulating a tidal regime as a sequence of high and low water levels that are maintained constant for a prescribed time. This mesocosm set-up does not allow for a natural, sinusoidal water level variation in the upper tank, but this simplification was necessary for the technical execution of this experiment. It was assumed that the effect of this simplification on the main results would be small, since sediment drainage is a slow process. However, it might have affected the experimental results to some extent on the small scale. Four different tidal regimes were simulated (Fig. 1B) to test the effect of tidal drainage depth and duration, with four tidal mesocosms per tidal regime. High water levels reached ±1 cm above the rim of the pots for all tidal regimes, while low water levels and duration varied per tidal regime. The different low water levels allow simulating different sediment pore water drainage depths. These different drainage depths mimic differences in distance from tidal creeks, with locations closer to creeks draining deeper (Van Putte et al., 2020, 2022), and differences in sediment type, since sandy sediments drain much easier than fine clay sediments (Cao et al., 2021). Different low water level durations were selected to simulate marsh locations with different emergence times (drainage durations): a low-lying pioneer marsh with short emergence duration (6 h) and a high-lying mature marsh with long emergence duration (11.5 h). Neap-spring tidal cycles were excluded from this experiment to exclusively study the effects of tidal drainage depth and duration.

720 cylindrical PVC pots with a height of 25 cm and a diameter of 12.5 cm were used for this experiment. Lids were glued to the bottom of

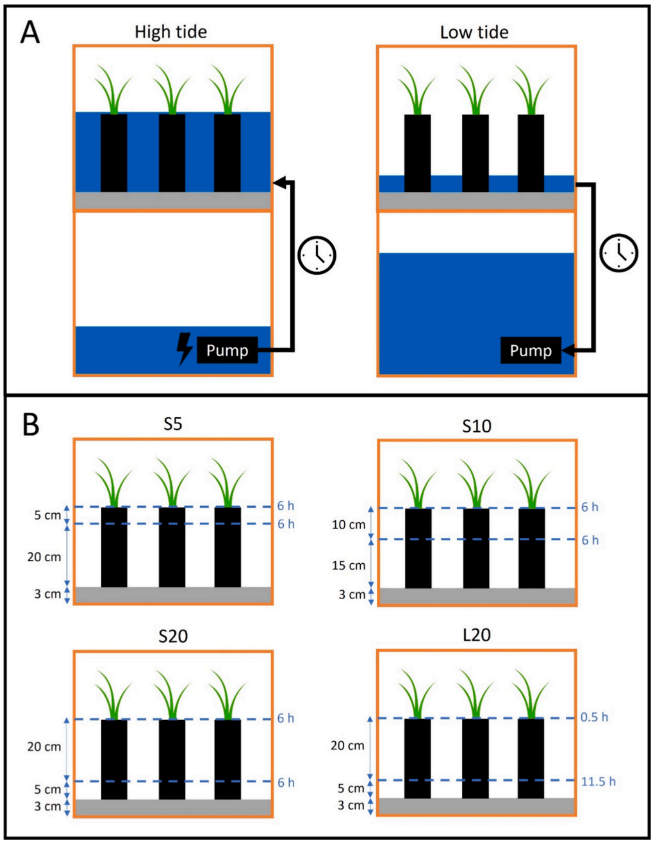

Fig. 1. A) The mesocosm set-up simulating semidiurnal high (left, pump on) and low (right, pump off) tides, controlled by timers. B) The four tidal regimes of the experiment: S5 with a difference of 5 cm between high and low tide and a short (6 h) low tide, S10 with a difference of 10 cm and a short low tide, S20 with a difference of 20 cm and a short low tide, and L20 with a difference of 20 cm and a long (11.5 h) low tide.

the pots and sixteen holes (diameter of 4 mm) were drilled in the lids to enable sediment drainage. To prevent sediment from leaking, some cotton wool was placed in the bottom of the pot. Two types of sediment were used, which are referred to as: 1) fine mud (77% silt and clay fraction <63 μm, D_{50} = 22 μm) and 2) sandy mud (37% silt and clay fraction <63 μm, D_{50} = 109 μm). Both sediment types were sieved over a 5 mm sieve to remove large shell fragments. 360 pots were filled to the rim with fine mud and 360 pots were filled to the rim with sandy mud. Seeds from *Spartina anglica* (herein referred to as *Spartina*) and *Scirpus maritimus* (herein referred to as *Scirpus*), two frequently occurring pioneer vegetation species in NW European salt marshes, were harvested from salt marshes in the Western Scheldt estuary (The Netherlands). *Spartina* is dominant in the saline parts of the Western Scheldt and *Scirpus* in the brackish parts (Zhu et al., 2020b). *Spartina* seeds were stored in salt water at 4 °C and *Scirpus* seeds were first stratified in tap water at 4 °C. After this pretreatment, all seeds were placed in small greenhouses filled with a layer of sand and kept wet. During the night, the small greenhouses with *Scirpus* seeds were placed in a 30 °C oven to speed up the germination process. Once the seeds germinated, they were planted in the pots. Per sediment type, 120 pots were planted with three *Spartina* seedlings, 120 pots with three *Scirpus* seedlings, and 120 pots were left bare as control. All naturally sprouting plants were removed from the control pots, all sprouting non-*Spartina* plants from the *Spartina* pots, and all sprouting non-*Scirpus* plants from the *Scirpus* pots. To enable drainage through the holes in the bottom of the pots, the tidal mesocosms were filled with ±3 cm of gravel and the pots were placed on top of the gravel bed. All pots were distributed over the tidal mesocosms with four different tidal regimes, resulting in 30 pots per treatment. The experiment started in May 2021 and lasted until October 2022. If sediment in the pots compacted during the runtime of the experiment, resulting in space between the rim of the pot and sediment surface, holes (diameter of 4 mm) were drilled in the side of the pots above the new sediment surface to enable drainage of water that would otherwise be pooling on top of the sediment surface. Salinity of the tidal mesocosm water was measured at least once a month. Fresh or saline water was added to keep the salinity approximately the same throughout the experiment.

2.2. Measurements on vegetation growth and sediment strength

Compaction (as a measure of consolidation), defined here as the distance between the top of the pots and sediment surface, was monitored of all pots in the experiment over the runtime of the experiment. Since most compaction occurred during the first month, measurements were done weekly during the first month. Between the first and second month, compaction was measured once every two weeks. Between the second and fifth month, compaction was measured monthly. From then onwards, compaction was measured once every two months.

After the growing season of 2021 (October) and before and after the growing season of 2022 (April and October, respectively), sediment strength proxies (i.e., compaction, penetration resistance, bulk density, and shear strength) and vegetation variables (i.e., above- and belowground biomass) (Table 1) were measured in five pots per treatment. To do the measurements, the five pots per treatment were taken out of the experiment and brought to the laboratory. All measurements were done within four hours after the pots were taken out of the experiment, preventing them from drying out too much, which could change the sediment properties. Since the measurements were destructive, the measured pots were kept out of the experiment afterwards, reducing the number of pots in the experiment over time. From the 'harvested' pots, compaction and the number of shoots and shoot heights were measured, and the shoots were clipped. The clipped shoots were dried in a 60 °C oven for two weeks to determine dry aboveground biomass. A bulk density core (diameter of 4 cm and length of 25 cm) was pushed into the sediment and left in the sediment until the penetration resistance measurement was performed. Penetration resistance can be used as a measure of sediment strength, if grain sizes are similar (Marin-Diaz et al., 2021). Penetration resistance was measured in this study with an INSTRON Testing System controlled with INSTRON Bluehill 3 software. The INSTRON was equipped with a cone with a surface area of 5 cm^2 and a tip angle of 60°. Penetration resistance was measured until a depth of approximately 20 cm. The cone was lowered with a speed of 100 mm min^{-1} next to the bulk density core, while recording penetration resistance with an interval of 0.05 mm. After this measurement, the bulk density core was pulled out and the sediment was sliced per 2 cm. The bulk density samples of 0–2, 4–6, and 10–12 cm deep were freeze dried and dry weight was divided by slice volume to calculate bulk density of the different depth layers. To extract the root biomass, the remaining sediment was taken out of the pot, cut in 2 cm slices and every slice washed out over a 3 mm sieve. The roots were placed in a 60 °C oven for two weeks, after which dry biomass was weighed.

Besides penetration resistance, sediment shear strength was also considered as a measure of sediment strength (Amer et al., 2017; Watts et al., 2003). Shear strength was measured in October of 2022, after the growing season (Table 1). This was done with a field inspection shear vane tester (Eijkelkamp, The Netherlands) at 0–5 and 10–15 cm depth, after pushing in the bulk density core and before the penetration resistance measurements.

2.3. Statistical analyses

All statistical analyses were performed in R, version 4.3.0 (R core team, 2023). To study the effect of the different treatments on sediment strength development and vegetation growth, data were analyzed using

Table 1
The measurements taken in the 'harvested' pots and when these were done. The number of months between brackets indicates how long after the start of the experiment the measurements took place.

	Compaction	Penetration resistance	Shear strength	Bulk density	Aboveground biomass	Belowground biomass
Measurement depth		Continuous with depth	0–5 & 10–15 cm depth	0–2, 4–6 & 10–12 cm depth		In slices of 2 cm up to bottom of pot
October 2021 (5 months)	X	X		X	X	X
April 2022 (10 months)	X	X		X	X	X
October 2022 (17 months)	X	X	X	X	X	X

multi-factor ANOVA and Tukey Honest Significant Differences tests. In these tests, sediment type, tidal regime, vegetation treatment, and time were used as factors. The dplyr package (Wickham et al., 2022) was used to calculate means of the response variables for the different treatments. To test relationships between compaction, sediment strength proxies (penetration resistance, shear strength, and bulk density), and vegetation variables (above- and belowground biomass), the Pearson's correlation coefficient was calculated and linear regressions performed. Log-transformations were applied to skewed data of some parameters to conform to normality before performing the statistical tests, namely compaction, depth-averaged penetration resistance, shear strength between 0 and 5 cm and 10– and 15 cm depth, aboveground biomass, and depth-averaged belowground biomass.

3. Results

3.1. Sediment, tidal regime, vegetation, and time effects on compaction, sediment strength, and vegetation biomass

3.1.1. Sediment type

The pots with sandy mud had significantly lower compaction and significantly higher penetration resistance, shear strength, and bulk density than the pots with fine mud (all $p < 0.001$; Table 2; Fig. 2). The pots with sandy mud also had significantly higher vegetation biomass than the pots with fine mud ($p < 0.001$ for both above- and belowground biomass; Table 2).

3.1.2. Tidal regime

Tidal regime significantly affected compaction, penetration resistance, shear strength at 0–5 and 10–15 cm, and belowground biomass ($p = 0.025$ for shear strength at 0–5 cm, $p = 0.019$ for belowground biomass, and p < 0.001 for the other variables), but not bulk density and aboveground biomass ($p > 0.050$; Table 2). Compaction significantly increased with deeper drainage (from S5 to S20, p < 0.001) and with a longer drainage duration (from S20 to L20, p < 0.001). According to a Tukey HSD test, penetration resistance did not change when only drainage duration was increased (from S20 to L20, $p = 0.16$), but did increase with deeper drainage (from S5 to S20, all $p < 0.050$). Shear strength at 0–5 cm was only significantly higher in tidal regime L20 than in S5 ($p = 0.031$), while shear strength at 10–15 cm was significantly higher in tidal regime S20 than in S5 ($p = 0.002$), in L20 than in S5 (p < 0.001), and in L20 than in S10 ($p = 0.003$; Fig. 2). Belowground biomass was highest in tidal regime S10, followed by S20, S5 and L20, although only the individual difference between tidal regimes S10 and L20 was significant (p = 0.025).

3.1.3. Vegetation presence & species

Vegetation treatment (*Spartina*, *Scirpus*, or unvegetated) significantly affected all variables (all p < 0.001) except for aboveground biomass ($p = 0.089$; Table 2). However, Tukey HSD tests showed that for compaction and shear strength at 0–5 cm this difference is only significant between vegetated and unvegetated (p < 0.001 for both variables), and not between the two vegetation species ($p = 0.31$ for compaction, $p = 0.10$ for shear strength at 0–5 cm). Compaction was higher in the unvegetated pots than in the vegetated ones. Penetration resistance was highest for *Scirpus*, followed by *Spartina* and then by the unvegetated pots. Shear strength at 0–5 cm was higher in the vegetated pots than in the unvegetated pots and shear strength at 10–15 cm was highest in the *Scirpus* pots, followed by the *Spartina* pots and the unvegetated pots (Fig. 2). Bulk density was highest in the *Scirpus* pots and did not differ significantly between the *Spartina* and unvegetated pots. Belowground biomass was higher for *Scirpus* than for *Spartina*.

3.1.4. Time

All variables significantly increased over time between 5 and 17 months ($p = 0.027$ for compaction, p < 0.001 for all other variables, Table 2). Most compaction took place within the first ten weeks of the experiment (Appendix A: Fig. A.1).

Table 2
p-values and F-values of multi-factor ANOVA tests (n = 5) for all variables that were measured in the harvested pots. The factors include the sediment type, tidal regime, vegetation treatment, and time. The used vegetation treatments were unvegetated, vegetated with *Spartina*, and vegetated with *Scirpus*. Data of all variables, except for bulk density, were log transformed before applying multi-factor ANOVA, since they were log-normally distributed. Penetration resistance, bulk density, and belowground biomass are depth-averaged. *** indicates a p-value < 0.001, ** a p-value < 0.010, * a p-value < 0.050, and. a p-value < 0.100.

		Sediment	Tidal regime	Vegetation	Time
Compaction	p	< 2.2E-16 ***	< 2.2E-16 ***	2.2E-11 ***	0.027 *
	F	283	92	26	4
Penetration resistance	p	< 2.2E-16 ***	7.8E-15 ***	< 2.2E-16 ***	< 2.2E-16 ***
	F	2770	25	148	*84*
Shear strength 0–5 cm	p	< 2.0E-16 ***	0.025 *	< 2.0E-16 ***	
	F	325	3	111	
Shear strength 10–15 cm	p	< 2.2E-16 ***	1.6E-05 ***	< 2.2E-16 ***	
	F	467	9	87	
Bulk density	p	< 2.2E-16 ***	0.66.	7.1E-5 ***	9.0E-6 ***
	F	10,052	1	10	12
Aboveground biomass	p	1.9E-9 ***	0.20.	0.089.	< 2.2E-16 ***
	F	39	2	3	689
Belowground biomass	p	< 2.0E-16 ***	0.019 *	< 2.0E-16 ***	< 2.0E-16 ***
	F	132	3	161	201

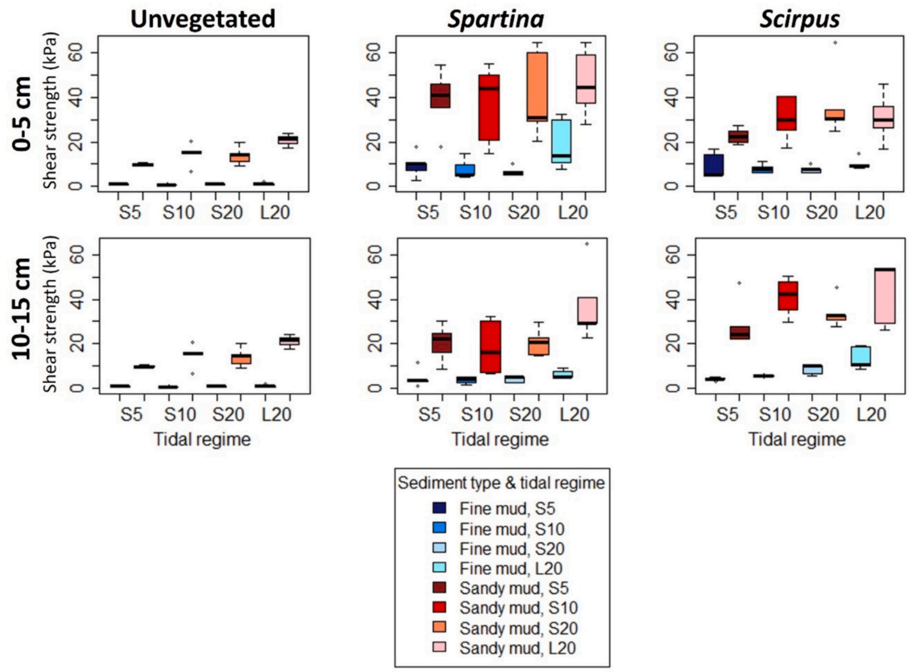

Fig. 2. Shear strength of sediment at the end of the experiment, after 17 months, for the unvegetated, *Spartina* and *Scirpus* pots. The top row shows shear strength from 0 to 5 cm and the bottom row from 10 to 15 cm. Measurements in fine mud are indicated in blue colors, those in sandy mud in red colors. Different shades of blue and red indicate the different tidal regimes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. Relationships between compaction, sediment strength, and vegetation biomass

Penetration resistance increased with shear strength at both depths, for both fine and sandy mud (Fig. 3; Appendix A: Table A.1). Penetration resistance also increased with aboveground and belowground biomass. Not surprisingly, aboveground and belowground biomass were positively correlated (Fig. 3; Appendix A: Table A.1). Compaction was not significantly related to any of the sediment strength and vegetation variables, likely resulting from the sediment and vegetation effects on compaction (this will be further elaborated on in sections 4.1 and 4.3). Bulk density did not strongly relate to any of the other variables and

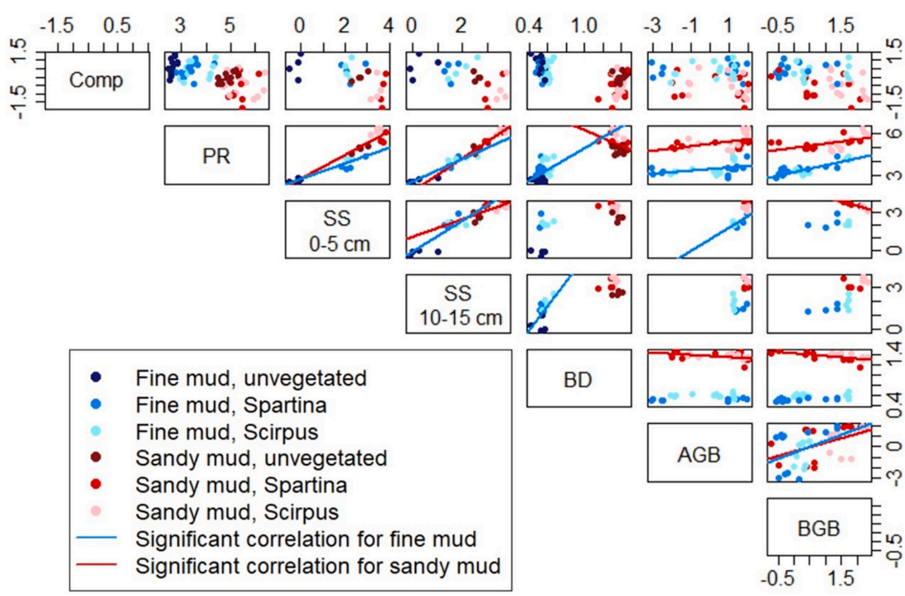

Fig. 3. Relationships between compaction (Comp), penetration resistance (PR), shear strength from 0 to 5 cm (SS 0–5 cm), shear strength from 10 to 15 cm (SS 10–15 cm), bulk density (BD), aboveground biomass (AGB), and belowground biomass (BGB). Data of all variables, except for bulk density, were log transformed, since they were log-normally distributed. Penetration resistance, bulk density, and belowground biomass are depth-averaged. Points represent an average of five replicates at one moment in time (5, 10, or 17 months after the start of the experiment). A linear regression line indicates a significant ($p < 0.05$) correlation between two variables, the absence of a line indicates a non-significant correlation. Blue colors indicate measurements in the pots with fine mud, red colors in the pots with sandy mud. Different shades of blue and red indicate the different vegetation treatments. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

relationships between shear strength and vegetation biomass were often also absent (Fig. 3; Appendix A: Table A.1).

3.3. Sediment, tidal regime, and vegetation effects on depth profiles of penetration resistance and belowground biomass

There was a peak in penetration resistance around 4 cm depth in the pots with *Spartina*, and a peak between 5 and 10 cm depth in the pots with *Scirpus* (Fig. 4). The penetration resistance peaks in the vegetated pots were not present in the unvegetated pots (for fine mud) or had a higher penetration resistance value than in the unvegetated pots (for sandy mud) (Fig. 4). In the unvegetated pots, penetration resistance did not significantly increase over time ($F_{2,113} = 0$, $p = 0.64$; Appendix A: Fig. A.2). In contrast, penetration resistance in the pots with *Spartina* and *Scirpus* did significantly increase over time (*Spartina*: $F_{2,113} = 25$, $p < 0.001$; *Scirpus*: $F_{2,113} = 252$, $p < 0.001$; Appendix A: Fig. A.2). However, a Tukey HSD test showed that the difference between 5 and 10 months is not significant ($p = 0.74$ for *Spartina*; $p = 0.36$ for *Scirpus*), while it is significant between 10 and 17 months ($p < 0.001$ for both species). This indicates that the strongest increase took place during the second growing season (between 10 and 17 months).

Tidal regime affected the depth distribution of *Scirpus* roots. The belowground biomass reached its maximum relatively close to the surface in the tidal regime with the shallowest drainage depth, while more roots grew in the deeper sediment layers in the tidal regimes with deeper drainage depth (Fig. 4). *Spartina* roots grew close to the surface, while *Scirpus* roots grew deeper. Roots of Spartina mainly grew in the top 2 cm of the pots, and roots of *Scirpus* showed a peak between 2 and 10 cm depth (Fig. 4). For both species, total belowground biomass was still relatively small after one growing season (5 months) but strongly increased during the second growing season (17 months) (Appendix A: Fig. A.3).

By comparing the depth profiles of belowground biomass and penetration resistance it becomes clear that the peaks in belowground biomass correspond to some extent to the peaks in penetration resistance (Fig. 4). However, the peaks of penetration resistance seem to lie somewhat deeper than the peaks of belowground biomass for both species and sediment types. Differences in belowground biomass, found between tidal regimes, were not always found in penetration resistance and vice versa.

4. Discussion

To gain more insight in the conditions that are necessary to quickly develop a strong salt marsh sediment bed, this study investigated how the development rate of sediment strength is affected by sediment type, tidal drainage depth and duration, and pioneer vegetation species in a tidal mesocosm experiment. It was found that sandy mud (37% silt and clay fraction) led to much stronger sediments than fine mud (77% silt and clay fraction). Our results also showed that sediment strength was higher in the tidal regimes with deep drainage depth and long drainage duration than in the tidal regimes with shallow drainage depth and short drainage duration. Lastly, the presence of vegetation can significantly increase sediment strength within 17 months after vegetation establishment under controlled conditions (Fig. 5).

4.1. How sediment type affects biomass and sediment strength

Sediment type influenced both vegetation growth and development of sediment strength. Below- and aboveground biomass were significantly higher in the sandy mud than in the fine mud (Table 2; Fig. 4). This may be explained as the coarser particles of sandy mud allow faster drainage (Brooks et al., 2021), which will in turn lead to better conditions for vegetation growth (Crooks et al., 2002; Mendelssohn and Seneca, 1980).

The higher compaction in fine mud than sandy mud (Table 2; Appendix A: Fig. A.1) can be ascribed to the higher clay and silt content (i.e. fraction <63 μm) in the fine mud, since sediment compressibility increases with clay and silt content (Bradley and Morris, 1990; Brooks et al., 2021). Sandy mud had a significantly higher penetration resistance and shear strength than the fine mud (Fig. 2; Fig. 4). Although erosion resistance was shown to increase with increasing clay and silt content in many previous studies (Feagin et al., 2009; Houwing, 1999; Lo et al., 2017; Marin-Diaz et al., 2022), erosion thresholds start to decrease with increasing clay and silt content when sediments contain >30–50% clay and silt, due to the decrease in bulk density (Grabowski et al., 2011; Houwing, 1999; Mitchener and Torfs, 1996). Besides, the coarser grain size of sandy mud led to lower water contents because of better drainage (Brooks et al., 2021; Cao et al., 2021). These combined effects of bulk density and water content likely led to higher sediment strength of the sandy mud than of the fine mud (Da Silva et al., 2016; Grabowski et al., 2011; Vaz et al., 2001; Weaich et al., 1992; Fig. 5).

4.2. How drainage depth and duration affect biomass and sediment strength

No significant differences between tidal regimes for aboveground biomass were found and only between two tidal regimes for belowground biomass (Table 2). The lack of strong effects of tidal drainage depth or duration on above- or belowground biomass indicates that the range of drainage depths and durations that were tested are all suitable for *Spartina* and *Scirpus* survival and growth of roots and shoots. Van der Wal et al. (2008) showed that *Spartina* occurs at salt marshes in the Western Scheldt with a wide range of inundation durations between 11.8 and 46.2% of the time. Our tested inundation durations of 0.5 and 6 h per tidal cycle (4 and 50% of the time, respectively) lie somewhat outside this range, but this confirms that the tested pioneer species can withstand a wide range of inundation durations.

Tidal regime did affect the depths at which *Spartina* and *Scirpus* roots grew, with more superficial roots in the tidal regimes with shallower drainage depth and shorter drainage duration and deeper roots in the tidal regimes with deeper drainage depth and longer drainage duration (Fig. 4). Apparently, a constant relatively high water level, as in tidal regime S5, does not require deep root growth, because sufficient water level is available at the surface. However, especially in tidal regime L20 with a long drainage duration, roots need to grow deeper in the pots to take up sufficient water (Fan et al., 2017; Naumburg et al., 2005).

A drier tidal regime with a deeper drainage depth or with a longer drainage duration increased compaction and depth-averaged penetration resistance (Table 2; Fig. 4; Appendix A: Fig. A.1). Sediment drying leads to increased compaction and thus consolidation (Dong et al., 2020), and in addition to that, dry sediments have a higher penetration resistance than wet ones (Da Silva et al., 2016; Vaz et al., 2001; Weaich et al., 1992; Fig. 5). It is striking that no effect of tidal regime on bulk density was observed (Table 2), since an increase in compaction was expected to cause an increase in bulk density. Two possible explanations for this are 1) that the bulk density measurements were not accurate enough, or 2) that compaction only slightly and non-significantly increases bulk density. The significant effect of tidal regime on penetration resistance might thus only be caused by drying of the sediment and not by an increased bulk density.

4.3. How vegetation affects sediment strength

It was hypothesized that the presence of vegetation would increase sediment compaction, because evaporation and transpiration of a marsh sediment bed with vegetation are higher than only evaporation of a bare sediment bed (Barciela-Rial et al., 2023). The increased sediment drainage and water uptake could speed up sediment compaction and thereby drying-induced consolidation (Barciela-Rial et al., 2023; Dong et al., 2020). However, less compaction was measured in the vegetated pots than in the unvegetated ones (Table 2). In the vegetated pots an

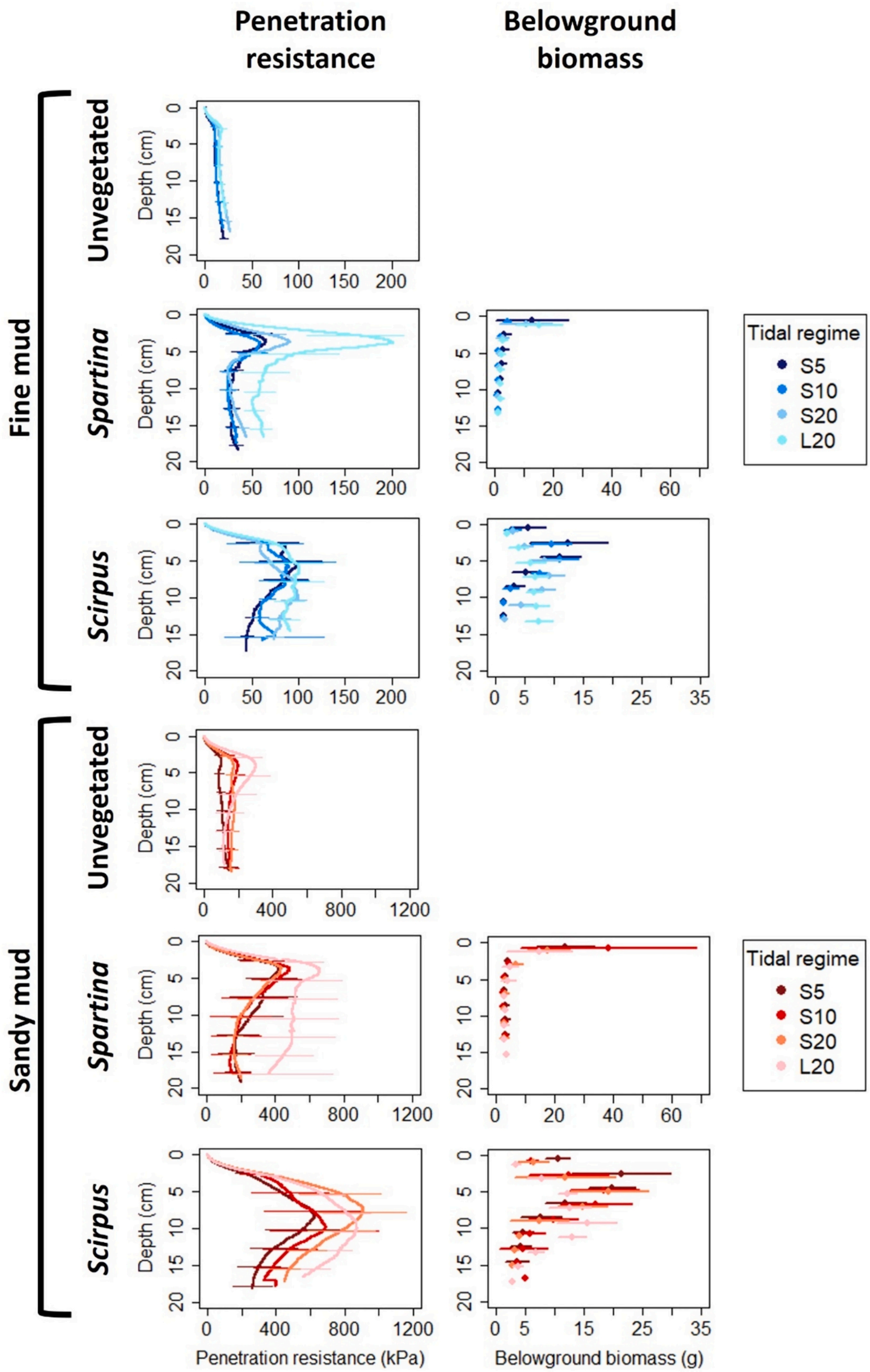

Fig. 4. Depth profiles of penetration resistance and belowground biomass of the unvegetated, *Spartina*, and *Scirpus* pots 17 months after the start of the experiment. Measurements in fine mud are indicated in blue colors, those in sandy mud in red colors. Different shades of blue and red indicate the different tidal regimes. Please note that the x-axis scale of penetration resistance differs between fine and sandy mud, and that of belowground biomass between *Spartina* and *Scirpus*. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

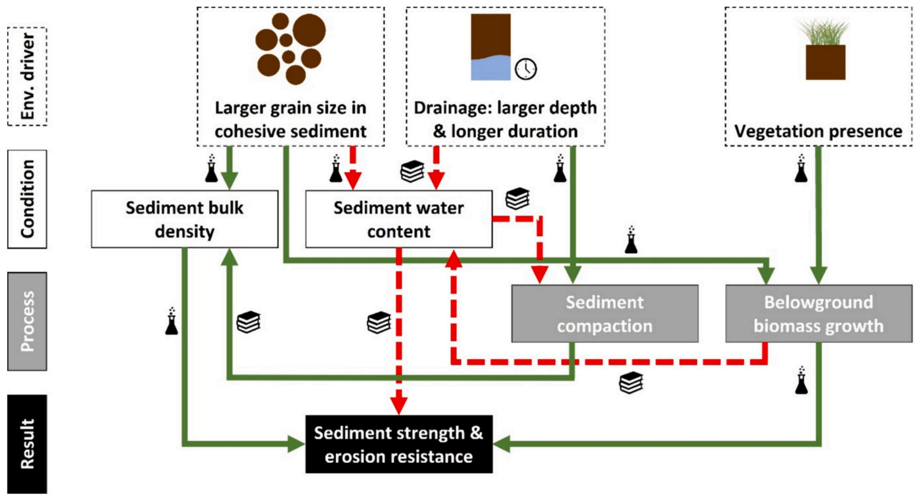

Fig. 5. Conceptual framework showing the effect of environmental drivers (dashed boxes; tested in this study using different treatments) on sediment strength and erosion resistance (black box). The white and grey boxes indicate the conditions and processes, respectively, through which the environmental drivers affect sediment strength and erosion resistance. Green, continuous arrows indicate positive effects, while red, dashed arrows indicate negative effects. Erlenmeyer symbols indicate relationships of which this study advanced the understanding or established a quantitative relationship, book symbols indicate relationships known from existing literature. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

extensive root system was observed, which was often visible on the sediment surface. Due to the confined space in the pots, the roots might have pushed the sediment upwards by taking up space themselves, resulting in a smaller distance between sediment and pot rim for the vegetated pots than for the unvegetated ones. Field studies have also found that belowground biomass production and organic matter accumulation lead to marsh surface accretion (Blum et al., 2021; Callaway et al., 1997; Nyman et al., 2006). This effect is the likely reason for a lack of significant relationships between compaction and the sediment strength parameters.

The presence of vegetation significantly increased penetration resistance and shear strength (Table 2; Fig. 2; Fig. 4), which is expected to be mainly caused by the root system which increases sediment strength (Brooks et al., 2021; Gyssels et al., 2005; Lo et al., 2017; Wang et al., 2017; Fig. 5). This hypothesis is partly confirmed by Fig. 4, since the peaks in penetration resistance correspond relatively well with the peaks in belowground biomass. However, the penetration resistance peak for both species was located somewhat deeper in the sediment profile than the belowground biomass peak. Besides, differences in penetration resistance between the tidal regimes cannot always be explained by differences in belowground biomass between the tidal regimes. This discrepancy suggests that the presence of vegetation also affects penetration resistance by modifying the sediment properties, and not only by growing roots. As explained by Barciela-Rial et al. (2023), vegetation can enhance sediment drainage and water uptake, and thus decrease sediment water content and increase bulk density (through drying-induced consolidation; Fig. 5). This study indeed showed that the *Scirpus* pots with higher belowground biomass than the *Spartina* pots also had higher bulk density. This will lead to a higher penetration resistance (Da Silva et al., 2016; Vaz et al., 2001; Weaich et al., 1992) and could thus explain the increased penetration resistance in the vegetated pots at depths without significant amounts of belowground biomass.

In general, sediment strength was species-dependent, with significantly higher depth-averaged penetration resistance and shear strength between 10 and 15 cm in the *Scirpus* pots than in the *Spartina* pots (Fig. 2; Fig. 4). This is expected to at least be partly caused by the higher belowground biomass in the *Scirpus* pots than in the *Spartina* pots. In contrast to depth-averaged penetration resistance and shear strength between 10 and 15 cm, shear strength between 0 and 5 cm did not significantly differ between *Spartina* and *Scirpus* (Fig. 2). This might result from the general presence of roots of both species in the upper centimeters.

4.4. Vegetation growth and development of sediment strength

Plant biomass, compaction, penetration resistance, and bulk density all significantly increased over time (Table 2). Especially during the second growing season (between April and October 2022) a strong increase in belowground biomass was observed (Appendix A: Fig. A.3), and as well in penetration resistance in the vegetated pots (Appendix A: Fig. A.2). New seedlings can thus already significantly affect sediment strength within the first 1.5 years after establishment under controlled conditions. Watts et al. (2003) showed that within six years after vegetation establishment at a managed realignment marsh, vegetated sediment beds became highly resistant to erosion. This illustrates that the development of sediment strength in the field can also happen relatively fast.

The vegetation in the controlled experiment of this paper was confined by the pot edge, which might have reduced their growth rate compared to a natural, open system. On the other hand, the vegetation and sediment of the experiment were not exposed to any waves or currents (except for the slow water movement due to the water circulation during high tide). This might have increased the vegetation growth rate compared to a natural system with more hydrodynamic forces, as higher waves have been shown to cause more damage to vegetation (Reents et al., 2022). The effect of these differences between controlled and natural conditions on vegetation growth and development of sediment strength should be further studied.

Important to note is that the effect of vegetation on the development of sediment strength does not immediately lead to erosion resistant sediments. Especially for fine mud, shear strength values at the end of the experiment were still relatively low, often below 20 kPa (Fig. 2). Such sediments with low shear strength are likely to also have low erosion thresholds. Hence, the context of such vegetation-induced differences in sediment strength are important to consider for the use of salt marshes to reduce dike breach depths, for which their sediment beds should remain erosion resistant under dike breach flow velocities (Schoutens et al., 2022; Zhu et al., 2020a).

4.5. Implications for salt marsh restoration and creation

The results of this study indicate that abiotic and biotic factors can have strong effects on the development of sediment strength in salt marshes over time. For the restoration or creation of marshes that are both erosion resistant under currents and waves, but also under the high flow velocities associated with dike breaches (Schoutens et al., 2022; Zhu et al., 2020a), it is necessary to make a detailed assessment of environmental conditions at sites with planned marsh restoration or creation. It can then be determined if these conditions will enable fast formation of an erosion resistant marsh.

In this experiment, large differences in sediment strength between the two sediment types were found. Sandy mud was much stronger than fine mud, which is expected to be a result of the much higher bulk density and lower moisture content of the sandy mud (Grabowski et al., 2011). The very small particles of the fine mud likely impaired drainage (Cao et al., 2021). The higher sediment strength of sandy mud than fine mud is in accordance with previous studies that showed that sand-mud mixtures have a higher erosion resistance than very clayey sediments above a certain clay content threshold (Grabowski et al., 2011; Winterwerp and Van Kesteren, 2004). Therefore, it can be expected that a salt marsh of a sand-mud mixture, with a relatively high bulk density and large enough sediment particles to enable proper drainage but also enough cohesive particles, will lead to the highest erosion resistance. The aim should thus be to restore or create salt marshes for flood defense at locations with sufficient availability of such sediment grain sizes.

A drier tidal regime with deeper drainage depth or longer drainage duration led to an increase in penetration resistance and shear strength, but not in bulk density. The effect of tidal regime on shear strength was significant, but weaker than the effects of vegetation and sediment type. It is expected that the differences in drainage depth and duration that were simulated might have been too small to observe an effect on bulk density and a stronger effect on shear strength. From the effect on penetration resistance, it can be expected that a higher elevated and longer draining salt marsh will form a stronger sediment bed than a lower elevated and shorter draining one, as was also shown before by e.g., Marin-Diaz et al. (2022). A high location and proper development of tidal creeks will lead to better drained sediments and more consolidation, and thereby to more erosion resistant salt marshes (Crooks et al., 2002; Dong et al., 2020; Van Putte et al., 2020, 2022).

The presence of pioneer vegetation species increases sediment strength, already within 1.5 years after sprouting of the seeds. Vegetation enforces the sediment matrix by root growth (Brooks et al., 2021; Gyssels et al., 2005; Lo et al., 2017; Wang et al., 2017), but also by drying out the sediment due to enhanced evaporation and transpiration (Barciela-Rial et al., 2023). Therefore, it is important to facilitate the chances for vegetation establishment at a site if the aim is to restore or create erosion resistant salt marshes. A site with higher location in the intertidal zone will experience less and shorter tidal inundations, and thereby improve conditions for vegetation establishment and growth (Fivash et al., 2023). Other conditions such as tidal range, wave exposure, salinity, bioturbation, herbivory, and soil anoxia are also important to consider when estimating suitable elevations for marsh establishment (Balke et al., 2016; Callaghan et al., 2010; He et al., 2015; van Wesenbeeck et al., 2007).

In conclusion, to restore or create erosion resistant salt marshes for flood defense, some conditions should apply. At the large scale, salt marshes should form at relatively high elevations and drain properly through a developed tidal creek system. Conversely, at the small scale, salt marshes should consist of well-draining sand-mud mixtures contributing to vegetation establishment and growth. The morphodynamic equilibrium of the target estuary for marsh restoration or creation projects should be studied before restoration of creation, to ensure sustainability of the newly formed marshes in the long term (Lanzoni and Seminara, 2002; Zawadzka, 1996). Marsh sediment beds will not immediately be erosion resistant, and thus the timescales of sediment consolidation and vegetation growth should be considered, in addition to how the development of sediment strength can potentially be sped up for the use of marshes for flood defense.

5. Conclusions

This study investigated how 1) sediment type, 2) tidal drainage depth and duration, and 3) pioneer vegetation species drive the development rate of sediment strength in salt marshes, using a controlled experiment. It was shown that sandy mud (with a 37% silt and clay fraction) led to much stronger sediments than fine mud (with a 77% silt and clay fraction). Sediment strength was higher in the treatments with deeper tidal drainage depth and longer drainage duration. The presence of vegetation increased sediment strength and this effect was stronger with *Scirpus maritimus* than with *Spartina anglica*. Plant roots increased sediment strength directly, and the presence of vegetation also seemed to increase sediment strength through enhanced evaporation and transpiration. For the restoration or creation of erosion resistant salt marshes for flood defense, we can conclude that it is essential to ensure that marshes can form at relatively high elevations from well-draining sand-mud mixtures, thereby also ensuring vegetation growth. Since marsh sediment beds need time to become erosion resistant, it is crucial to plan ahead for the use of tidal marshes for nature-based flood defense in the future.

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CRediT authorship contribution statement

Marte M. Stoorvogel: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Jim van Belzen:** Writing – review & editing, Methodology, Conceptualization. **Stijn Temmerman:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Lauren E. Wiesebron:** Writing – review & editing, Formal analysis. **Gregory S. Fivash:** Writing – review & editing, Methodology, Formal analysis. **Lennart van IJzerloo:** Methodology, Conceptualization. **Johan van de Koppel:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Tjeerd J. Bouma:** Writing – review & editing, Supervision, Methodology, Funding acquisition, 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.

Data availability

The data of this study are openly available in the research repository 4TU: https://doi.org/10.4121/408021f9-8576-4175-924f-9ad81866b8cf.

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Appendix A. Supplementary data

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