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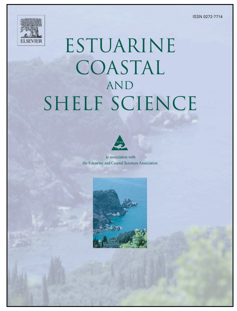

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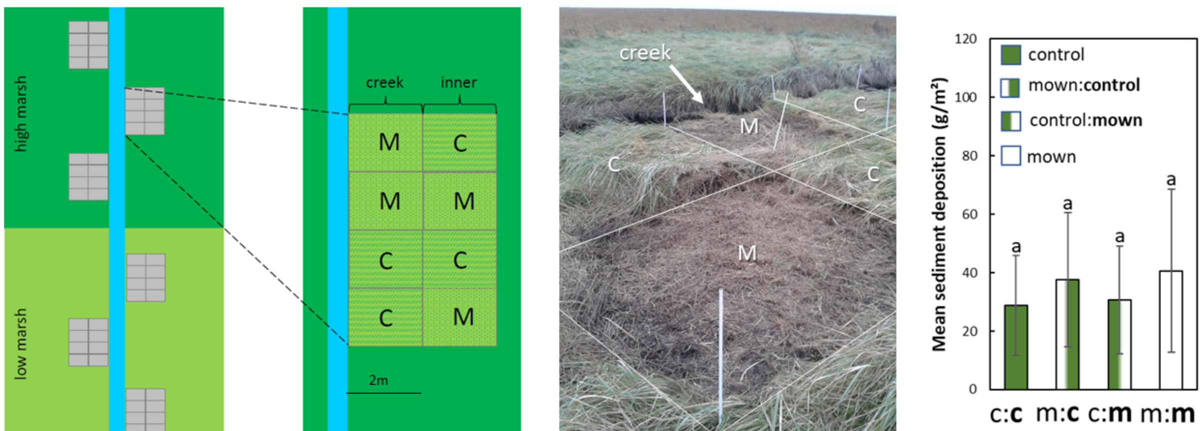
high marsh
low marsh
creek
inner
M
C
2m
creek
Mean sediment deposition (g/m²)
control
mown:control
control:mown
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a
c:c
m:c
c:m
m:m

Effects of small-scale patterns of vegetation structure on suspended sediment concentration and sediment deposition in a salt marsh

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Keywords:
Sedimentation; salt marsh vegetation; mowing; Wadden Sea; spatial pattern

Abstract

Salt marshes contribute to coastal protection by attenuating waves and reducing flow velocities. Nevertheless, coastal salt marshes are threatened by rising sea levels. In order to keep pace with rising sea levels, salt marshes need to grow vertically by sediment input. Although major processes contributing to sediment deposition in salt marshes are known, there is still a lack of understanding of the influence of canopy height and biomass on suspended sediment concentration and sediment deposition and on the spatial scale beyond which an influence of vegetation on sediment deposition comes into effect. Furthermore, vegetation can be heterogenous and little is known on the role of small-scale patterns of vegetation structure on suspended sediment concentration and sediment deposition. We investigated the effects of small-scale patterns of vegetation on suspended sediment concentration and sediment deposition in a field experiment with two vegetation types (i.e. *Spartina anglica* in the low marsh and *Elymus athericus* in the high marsh). Partial mowing of the vegetation resulted in a

pattern of mown subplots and control subplots with a size of 4 m^2 in various combinations adjacent to a creek. Based on the results, it can be concluded that on the spatial scale of 4 m^2, there is no effect of the vegetation on water flow as the sediment deposition between mown and control subplots did not differ in both the high and the low marsh. Furthermore, a mown or a control subplot next to the creek had no influence on the sediment deposition on a mown or control subplot behind. In summary, based on the results of our study, it can be concluded that the presence of salt marsh vegetation not automatically leads to higher sediment deposition on vegetated patches compared to mown patches in both the low and high marsh.

1. Introduction

Salt marshes are highly dynamic intertidal ecosystems at the coastlines of the world's temperate zone. They provide a unique habitat for many species and deliver important ecosystem services, such as coastal protection and carbon sequestration (Barbier et al., 2011). Because of their low elevation relative to sea level, a major future threat for salt marshes is habitat loss due to an accelerated sea-level rise (Horton et al., 2018; Spencer et al., 2016). As salt marsh landward migration is often prevented by seawalls, persistence of these ecosystems relies on sedimentation and vertical marsh accretion (Kirwan et al., 2016). Vertical accretion, defined as the vertical marsh growth including processes such as mineral sediment deposition, organic matter production and erosion (Cahoon et al., 1995; Nolte et al., 2013a), is therefore a key parameter for salt marsh persistence in times of climate change (Fagherazzi et al., 2020; Fitzgerald and Hughes, 2019). Generally, salt marshes can cope with rising sea level, when sea-level rise is lower than sedimentation rates and vertical marsh accretion (Nolte et al., 2013a). However, sedimentation processes are still not fully understood (Fagherazzi et al., 2020), as they are the result of complex bio-geomorphological interactions between marsh morphology (Brückner et al., 2019), sediment availability (Kirwan et al., 2010), hydrodynamics (Temmerman et al., 2005a), vegetation (Cahoon et al., 2020), and even plant-animal interactions (Williams and Johnson, 2021).

Many of these relevant factors can vary on a spatial scale from global to local and also within a single site (Cahoon et al., 2020). For example, on a global scale, North Sea salt marshes show a high sediment availability and are dominated by mineral sedimentation, whereas US East coast marshes, which are dominated by organogenic accretion, face eventual sediment starvation in the future (Peteet et al., 2018). These differences can be explained by environmental drivers of sediment availability such as sea-level rise and tidal amplitude, which differ globally (Brown et al., 2016). Due to the spatial and temporal variability of these factors, estimates of marsh development by modelling studies, field measurements and combination of both are challenging. Consequently, global predictions and observations of sedimentation and overall marsh development lead to contrasting results (Coleman et al., 2022; Wiberg et al., 2020). Depending on which processes are included, some studies indicate a widespread global marsh loss (Crosby et al., 2016; Spencer et al., 2016; Thorne et al., 2018), whereas other studies predict low marsh losses and even marsh expansion (Ganju, 2019; Kirwan et al., 2016; Schuerch et al., 2018). Additionally, some factors which are included in these predictions also differ regionally, locally or are even within a single marsh, leading to difficulties in forecasts on future marsh developments. On a within-marsh scale, sedimentation is spatially heterogeneous and depends on the distance to the sediment source (*i.e.* creek or marsh edge). When flooding occurs via the marsh edge or a creek, a large proportion of sediment is gravity-driven deposited on the first meters, leading to high sedimentation rates at the marsh edge or the creek edge and to lower deposition in the marsh interior (Temmerman et al., 2003b). While this pattern is generally accepted, it can interact with other processes defining spatial distribution of sediment on the marsh platform which are not fully understood (Marjoribanks et al., 2019; Wiberg et al., 2020). For example, understanding the role of complex vegetation-mediated sediment deposition still remains challenging (Fagherazzi et al., 2020).

Generally, it is assumed that vegetation enhances sediment deposition rates in minerogenic marshes by slowing down flow velocity as well as by directly trapping sediment particles on the plant surface (Fagherazzi et al., 2012; Kakeh et al., 2016; Li and Yang, 2009; Temmerman et al., 2005b). However, studies on this topic still show contrasting results and it is not fully understood under which conditions vegetation promotes sedimentation or might even cause erosion (i.e. “scouring”; Tinoco et al. 2020). Furthermore, results of field studies on the effects of salt marsh vegetation on sedimentation range from higher sedimentation rates in the presence of vegetation to higher sedimentation rates in the absence of vegetation (e.g. Morris et al. 2002; Silva et al. 2009; Reef et al. 2018). This simple question regarding presence or absence of vegetation is, however, further complicated by complex spatial patterns within the vegetated marsh caused by e.g. marsh zonation. A vegetation zonation along an elevational gradient is a key characteristic in many marshes (Bakker, 2014). This vegetation zonation is a spatial vegetation pattern consisting of coherent homogenous stands of single species or of a compound of different species with varying biophysical plant properties (Schulze et al., 2019; Zhu et al., 2019). These complex spatial patterns within the salt marsh vegetation further complicate the understanding of sedimentation (Fagherazzi et al., 2020).

Models and field studies often fail to incorporate the patterns and characteristics of salt marsh vegetation or tend to simplify vegetation properties (Wiberg et al., 2020). Therefore, understanding the effects of different plant species and the influence of within-marsh vegetation patterns on sediment transport and sediment deposition patterns is crucial for predictions of marsh development (Fagherazzi et al., 2020). However, predicting deposition on a vegetation-patch scale is difficult due to complex patch morphology and complex patch-flow interactions (Marjoribanks et al., 2019). In a recent field study on flow and sedimentation patterns, Schepers et al. (2019) found that, as expected, large vegetated plots (ca. 20 x 20m) positioned at a creek tended to show higher sedimentation rates compared to the vegetated plots located in the marsh. Surprisingly, mown plots of a similarly large size close to the sediment source showed lower sedimentation rates compared to interior located mown plots. Thus, the spatial positioning of vegetated and mown patches seems to influence spatial patterns of sediment deposition and accretion on this within marsh scale. However, most sediment is deposited on a distance of a few meters from a creek (Temmerman et al. 2003b) and little is known about patterns of sedimentation in vegetated and unvegetated plots on this considerably smaller scale. If small scale patches slow down the flow enough to increase sediment deposition on the surface as indicated by flume experiments (Wang et al., 2016), we would expect higher sedimentation in vegetated patches, as well as influence of vegetated patches on the inner marsh. Additionally, it should be tested whether the effect of small-scale vegetation patterns on sedimentation can be found in different salt marsh zones, as different plant species in these zones also differ in biophysical plant properties such as stem density and vegetation height (Schulze et al. 2019).

To answer the general question whether small scale spatial patterns within the salt marsh vegetation affect sediment deposition and suspended sediment concentration (SSC) (Bouma et al., 2007; Fagherazzi et al., 2012; Schepers et al., 2020) we conducted a mowing experiment adjacent to a tidal creek in a Wadden Sea low marsh and high marsh. More specifically we aim to answer the following questions: (I) Is the sediment deposition and suspended sediment concentration generally higher in tall compared to short vegetation?; (II) Do we find these vegetation effects on sedimentation in both the low and the high marsh?; (III) How does the spatial positioning of tall and short vegetation influence spatial patterns of sediment deposition and SSC on a small vegetation-patch scale ?

2. Methods

2.1 Study site

The study was conducted on a mainland salt marsh in the Wadden Sea. The Wadden Sea is Europe's largest intertidal ecosystem complex and includes 4500 km² of tidal flats, as well as approximately 400 km² of salt marshes. Mainland salt marshes encompass around 60% of this area (Reise et al. 2010) and are often characterized by a long history of anthropogenic interventions such as brushwood groynes and drainage ditches to facilitate sedimentation. The studied salt marsh is located in front of the 1935 embanked polder Dieksanderkoog (DSK) at 53.95°N, 8.89°E in Schleswig-Holstein, Germany (Fig. 1) and is a part of the outer Elbe estuary. The tidal range is approximately 3 m with a mean high tide (MHT) at 1.62 m above the German ordnance datum (Normalhöhennull NHN). The SSC for the outer Elbe estuary was found to be variable and ranges between 0.04 g/l and 0.1 g/l (Kappenberg and Grabemann, 2001). A study using ^{137}Cs dated cores found accretion rates in a close by site to vary between 8.7 – 10.1 mm yr^{-1}, an intermediate accretion rate compared to the other Wadden Sea sites included in Nolte et al. (2013b). The marsh stretches ca. 1100 m from the seawall to the tidal flats. As an originally man-made landscape, the study site was used for livestock grazing, which was abandoned in the early 1990s. Additionally, the maintenance of an artificial drainage ditch system was abandoned at the same time (Stock et al. 2005). The marsh shows a clear vegetation zonation from pioneer zone to the high marsh and is predominantly covered by *Elymus athericus* in the high marsh and by *Spartina anglica* in the pioneer zone (personal observations and the Trilateral Monitoring and Assessment Program, TMAP; Petersen et al. 2013).

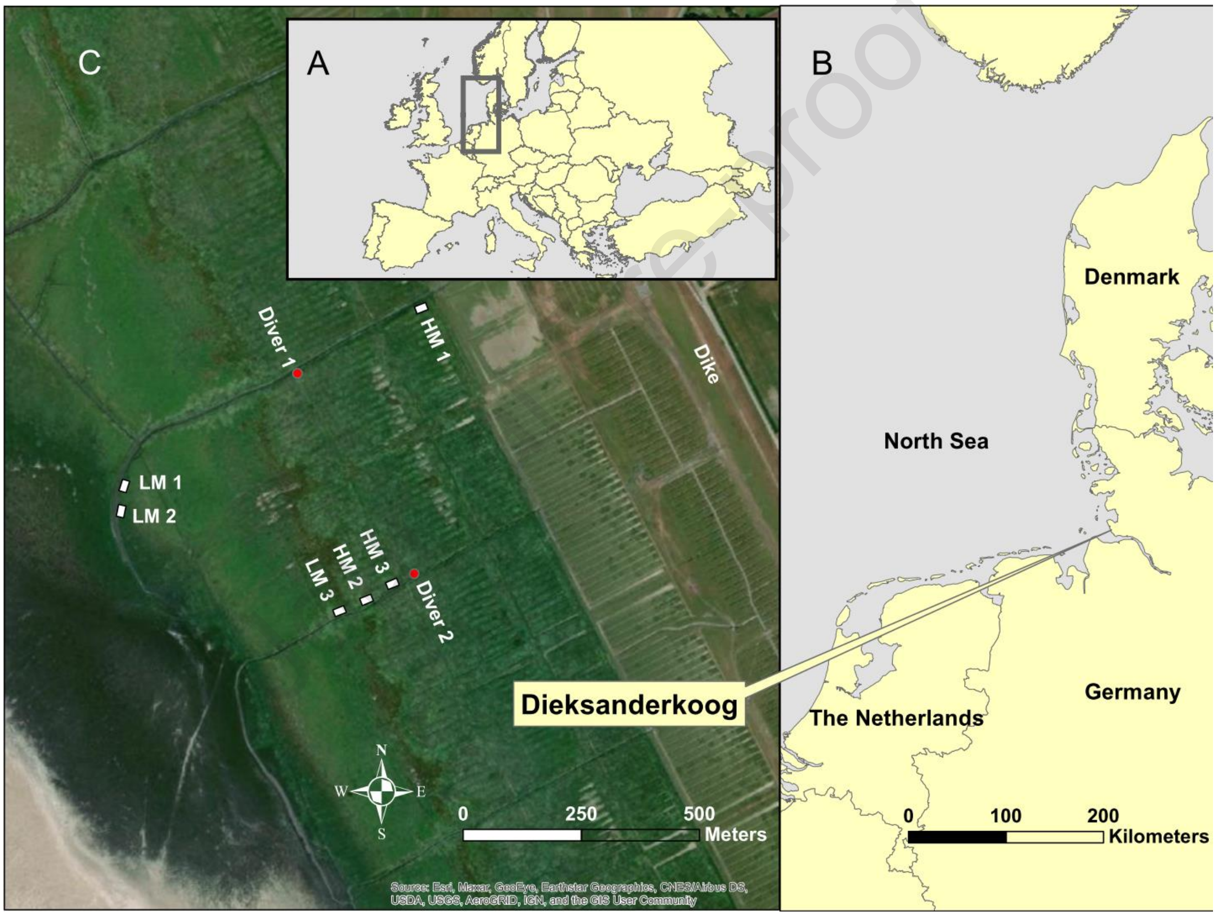

Fig. 1 (A) Location of the study region (grey rectangle) in Europe; (B) Location of the study site in the study region with the Wadden Sea National Park Schleswig–Holstein at the German North Sea coast; (C) Satellite image of the study site with the research plots. Shown are the high marsh plots (HM 1 – HM 3) and the low marsh plots (LM 1 – LM 3). The red dots show the locations of two divers. The map was created using a base map in ArcGIS © Desktop: Release 10, ESRI 2014, Redlands, CA: Environmental Systems

2.2 Experimental design

To study how sediment deposition and suspended sediment concentration (SSC) are affected by a small-scale pattern of vegetation patches, a field experiment was established. Three replicate plots (4 m x 8 m) were placed in the low marsh dominated by *Spartina anglica* and three plots in the high marsh dominated by *Elymus athericus* (Fig. 2 a) along a major creek. Each plot was subdivided into eight 2 m x 2 m subplots. Four of these subplots were situated directly adjacent to the creek ('creek') (Fig. 2b). We placed the four 'inner' subplots parallel and directly adjacent to the 'creek' subplots (Fig 2b). Subplots were either mown ('mown') or the vegetation was left intact ('control'). A full-factorial design with four different treatment-combinations (creek=mown/inner=mown, creek=mown/inner=control, creek=control/inner=mown and creek=control/inner=control) was randomly assigned to the six plots. Mowing was repeated several times in order to keep the vegetation as short as possible.

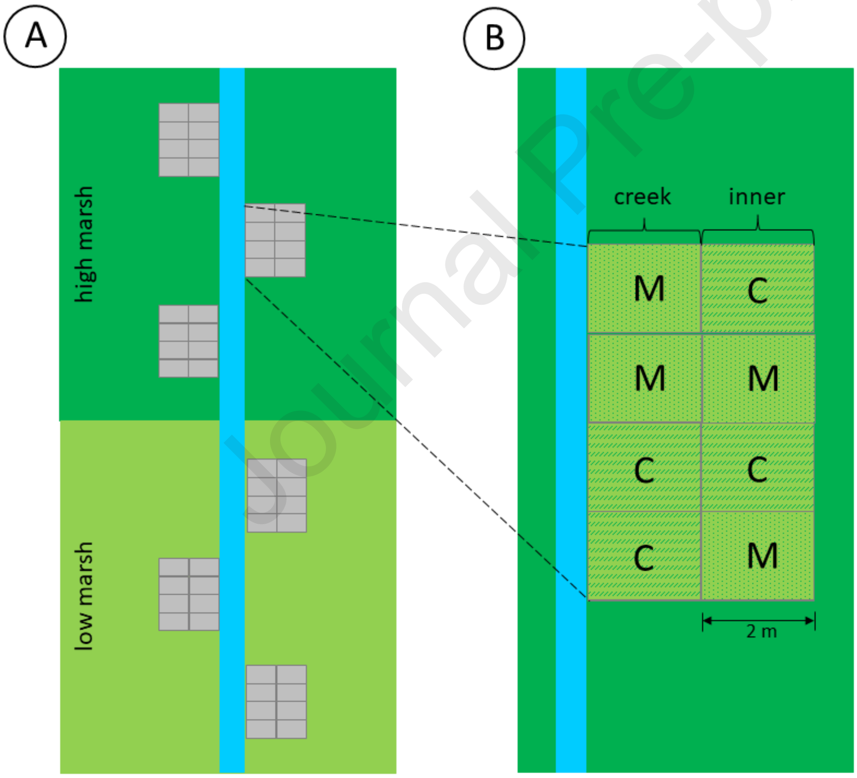

Fig. 2 Experimental setup: A) Within the low and high marsh zone six experimental plots were established directly adjacent to the creek. B) Each experimental plot is subdivided into eight sub-plots with one half close to the creek ('creek') and the other further away from the creek ('inner'). The treatments mown ('M') and control ('C') are assigned to achieve a full factorial design within both zones.

We aimed to place all plots directly adjacent to a creek to ensure a comparable flooding regime for every subplot. Additionally, plots were chosen which have a homogenous vegetation and flat topography at the start of the experiment. However, as marsh setting is variable in terms of e.g. microtopography, vegetation cover, species composition and levee formation, it was highly challenging to find comparable conditions for every plot at one creek. We therefore had to choose plots at two adjacent creeks to ensure comparable microtopographic and vegetation-related conditions leading to an unbalanced design (Fig. 1).

2.3 Measurements of sediment deposition and SSC

Sediment deposition and SSC were assessed for one winter season (01/2017 to 03/2017) and one summer season (07/2017 to 10/2017). Within each subplot, we placed a circular plastic sediment trap (internal diameter: 19 cm; rim: 2.5 cm) with a floatable lid (Temmerman et al. 2003b; Nolte et al. 2019; Fig. 3). The sediment traps were attached to the ground with a plastic stick (1.5 m) and with metal wires. On a biweekly basis, the sediment was collected from the traps after each spring-neap cycle. The collected deposited sediment was rinsed with freshwater, transferred to plastic bags and further processed in the laboratory. Samples were sieved (mesh size: 500 μm), washed with deionized water and oven dried at 100°C until constant weight. Additionally, floodwater was collected to determine SSC at each subplot. For this purpose, plastic bottles (580 ml) with a 3 cm water inlet and a longer air outlet made of plastic tubes were buried at each sampling point (Fig. 3). These bottles allowed a controlled water inflow 3 cm above the marsh surface (Butzeck et al., 2015). The filled bottles were replaced after each spring-neap cycle. To determine SSC (g l^{-1}), water samples were resuspended and vacuum filtrated using cellulose nitrate filters (0.45 μm). Subsequently, samples were oven dried at 60°C until constant weight.

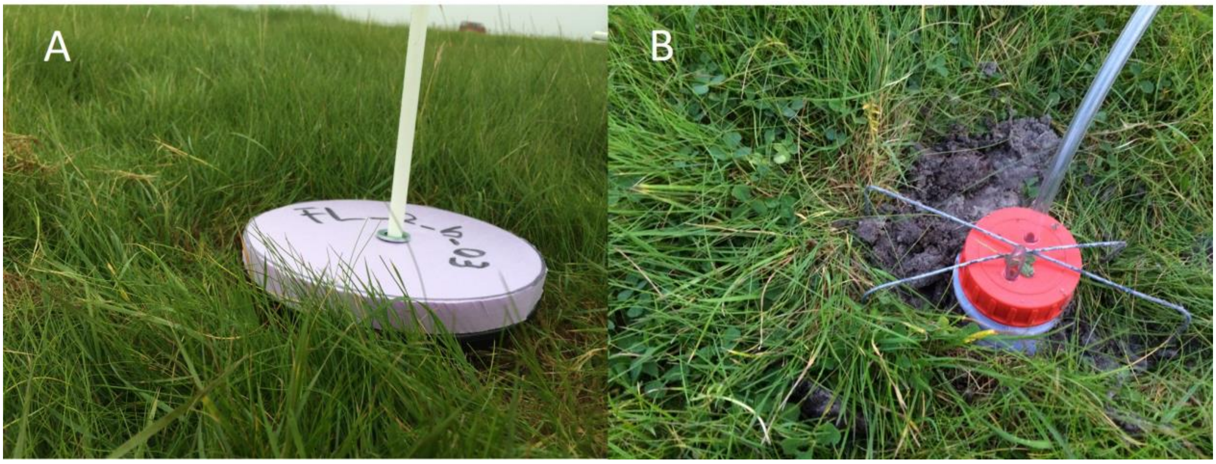

Fig. 3 Example photos of A) Sediment trap (internal diameter: 19 cm; rim: 2.5 cm) with floatable lid and B) SSC bottle (580 ml; plastic water inlet and air outlet allowing for a controlled water inflow 3 cm above the marsh surface. Photos were taken on the Hallig island Langeness in the framework of the study by Schulze et al. (2021).

2.4 Inundation measurements

Inundation height, frequency and duration were measured by installing one water level gauge in each creek, which allowed to determine inundation levels above each subplot relative to the gauges. A slitted plastic pipe containing a water pressure sensor (Schlumberger Cera diver, accuracy of measuring water level: ±1 cm), with a temporal resolution of 5 min, was inserted into the soil. An atmospheric pressure sensor (Baro Diver) was installed in a close by location behind the dike to compensate the water pressure measurements for the atmospheric pressure. Elevation of each sampling point was measured in relation to the respective water gauges using a Trimble LL500 precision laser and a Trimble HL 700 receiver (2.0 mm accuracy).

2.5 Data processing and statistics

The raw data set included 480 data points (6 plots x 8 subplots x 10 measurements). From these, we calculated total cumulative mean values of sediment deposition and SSC for each subplot, to compare overall effects of the treatments. Additionally, we calculated these cumulative values for the winter and summer season separately. We used two factorial analysis of variance with the total cumulative sediment deposition as response variable and the interaction of the factors creek and marsh zone to test whether the unbalanced design (e.g. two high marsh plots at creek 1 and only one high marsh plot at creek 2) affected the results. As a significant interaction was found, we split the dataset in a high marsh and a low marsh dataset to investigate treatment effects (sediment deposition ~ treatment) for each zone separately, thereby reducing unwanted creek effects in the model.

For each marsh zone, we first analysed the subplots adjacent to the creek ('creek') independently from the inner subplots to answer the question whether sediment deposition and SSC is generally higher in tall or short vegetation. We ran ANOVAs with sediment deposition or SSC as response variable and treatment as explanatory variable. To investigate how the spatial pattern of tall and short vegetation influences spatial patterns of sediment deposition and SSC, we then analysed sedimentation in the 'inner' subplots. The ANOVAs included both the treatment of the inner subplot and the treatment of the corresponding 'creek' subplot, as well as the interaction of both treatments. If necessary, data were log transformed to meet normality assumptions and to improve homogeneity of variances. Equal sample sizes in the study design assured robustness of parametric testing (McGuinness, 2002). As a post hoc test, Tukey's-HSD (honest significant difference) test was applied to determine pairwise differences. These tests were done for the total cumulative values, as well as for the winter and summer season. Furthermore, to assess the effect of maximum inundation height on sediment deposition and SSC, linear regressions were used. All analyses were performed using R version 3.5.3 (R Core Team, 2019; base package).

3. Results

3.1 Inundation characteristics

Over the course of the experiment, the mean maximum inundation height over the creek subplots ranged from 0.55 m ± 0.13 m (mean ± standard deviation) in the high marsh to 0.80 m ± 0.1 m in the low marsh. The mean maximum inundation height over inner located subplots ranged from 0.56 m ± 0.11 m in the high marsh to 0.82 m ± 0.08 in the low marsh. For subplots located at the creek, there were no differences in inundation height between the control treatment and the mown treatment neither in the high marsh nor in the low marsh (HM control: 0.56 m ± 0.13 m vs. HM mown: 0.55 m ± 0.13 m; LM control: 0.80 m ± 0.1 m vs. LM mown: 0.79 ± 0.1 m). Similar results were observed for the inner located subplots (HM control: 0.56 m ± 0.11 m vs. HM mown: 0.56 m ± 0.11 m; LM control: 0.82 m ± 0.08 m vs. LM mown: 0.81 m ± 0.08 m).

3.2 Sediment deposition and SSC

In both marsh zones as well as all datasets (total, summer, winter), there was no consistent trend or significant difference in sediment deposition between the mown treatment and the untreated control for subplots located at the creek (Fig. 4, Table 1, Appendix 1). The mowing treatment also had no significant effect on SSC (Fig.5, Table 1, Appendix 1). However, in both zones SSC was slightly higher on mown subplots compared to the control subplots. In the high marsh, SSC was approximately 40% higher on mown subplots compared to control subplots whereas in the low marsh SSC was approximately 30% higher. For inner located subplots, there was no trend detectable across all treatment combinations indicating that treatment combination (control:control, mown:control, control:mown, mown:mown) had no significant effect on sediment deposition (Figure 4, Table 1). SSC did not differ significantly but tended to be higher on mown inner subplots compared to control inner subplots (Figure 5, Table 1). In the high marsh, SSC on mown subplots was approximately 45% higher compared to control subplots and in the low marsh SSC was 55% higher on mown subplots compared to control subplots.

3.3 Relationship between inundation and sedimentation

Regressions revealed a significant and strong positive linear relationship between maximum inundation height and sediment deposition (Fig. 6 A,B), as well as SSC (Fig. 6 C,D). However, on control subplots this correlation was slightly stronger compared to mown subplots for sediment deposition and SSC both in the high and low marsh. For sediment deposition, the strongest correlation with maximum inundation height occurred on control subplots in the high marsh (R^2=0.687) while the lowest correlation occurred on mown subplots in the low marsh (R^2=0.636). For SSC, the strongest correlation with maximum inundation height occurred on control subplots in the high marsh (R^2=0.782) while the lowest correlation occurred on mown subplots in the low marsh (R^2=0.602)

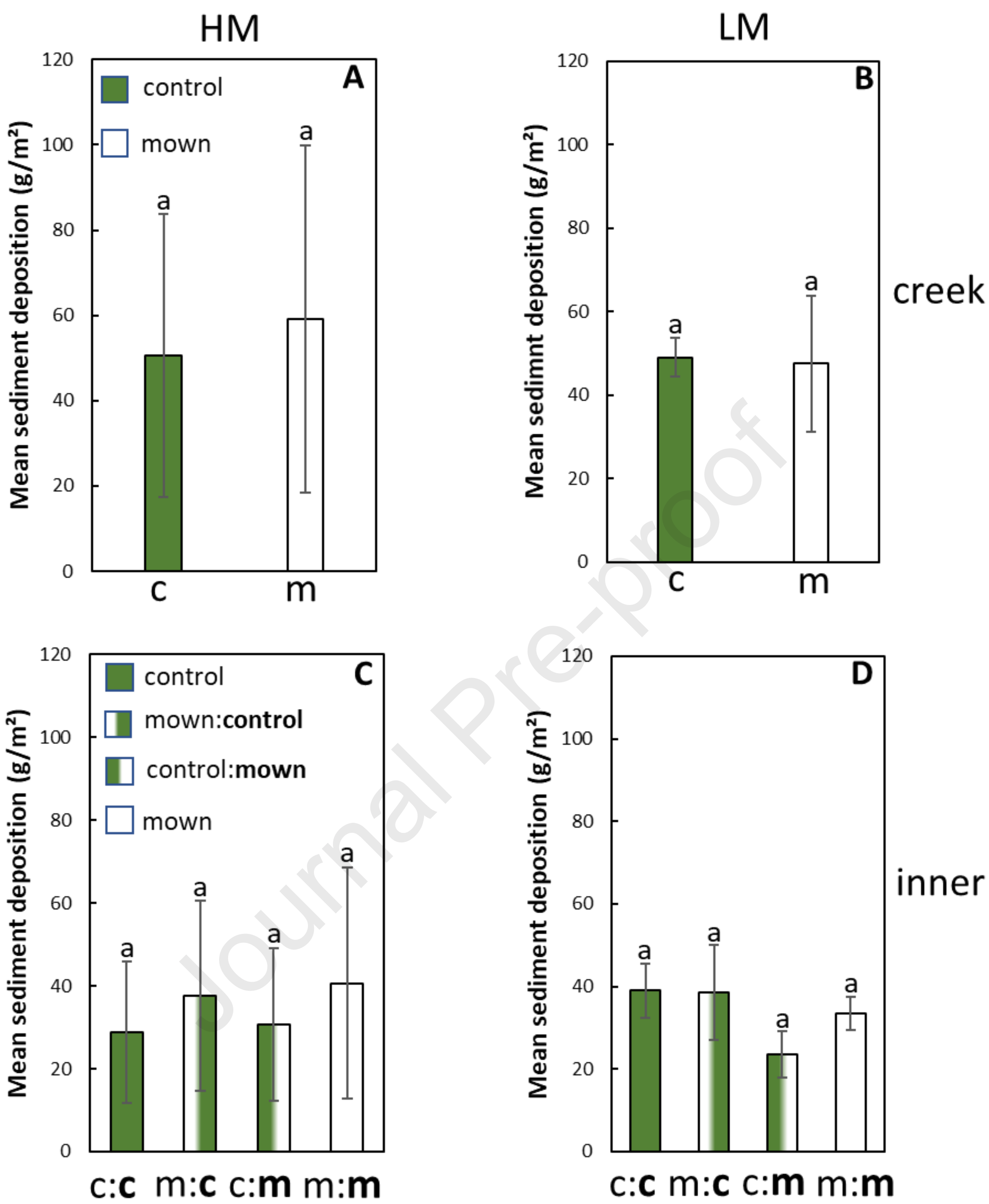

Fig. 4 Sediment deposition at subplots located at the creek (panel A, B) and of inner located subplots (panel C, D) in the high (panel A,C) and low marsh (panel B,D). Green bars show control subplots, white bars show mown subplots. Bars with a colour shift from white to green show inner control subplots, which are located behind a mown subplot and bars with a colour shift from green to white show inner mown subplots, which are located behind a control subplot. Values are means and the error bars indicate standard deviation. Treatment and treatment combination of at the creek and inner located subplots had no effect on sediment deposition (illustrated by equal lowercase letters following ANOVA and Tukey's tests).

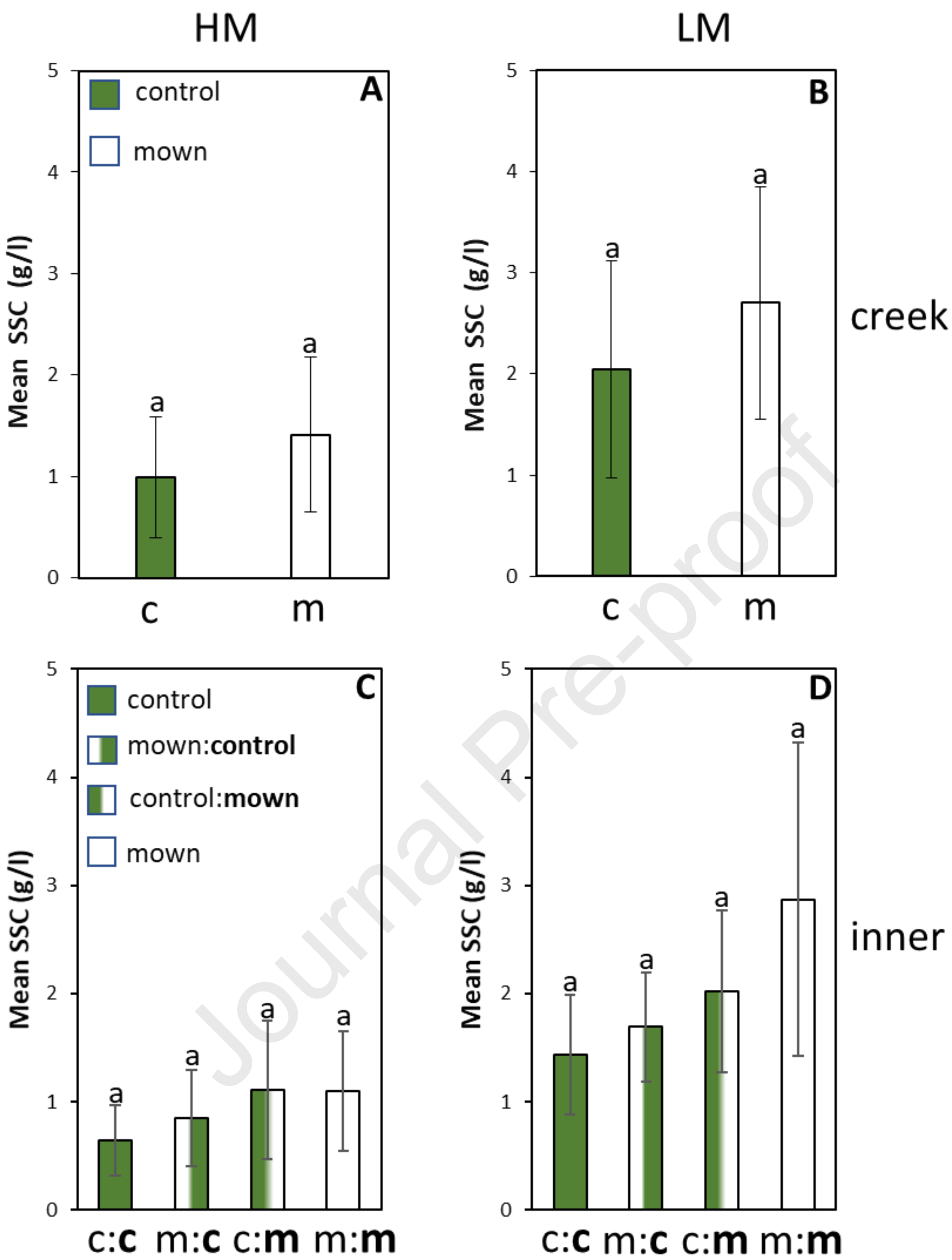

Fig. 5 SSC of at the subplots located at the creek (panel A, B) and of inner located subplots (panel C,D) in the high (panel A, C) and low marsh (panel B, D). Green bars show control subplots, white bars show mown subplots. Bars with a colour shift from white to green show inner control subplots, which are located behind a mown subplot and bars with a colour shift from green to white show inner mown plots, which are located behind a control subplot. Values are means and the error bars indicate standard deviation. Treatment and treatment combination of at the creek and inner located subplots had no effect on SSC (illustrated by equal lowercase letters following ANOVA and Tukey's tests).

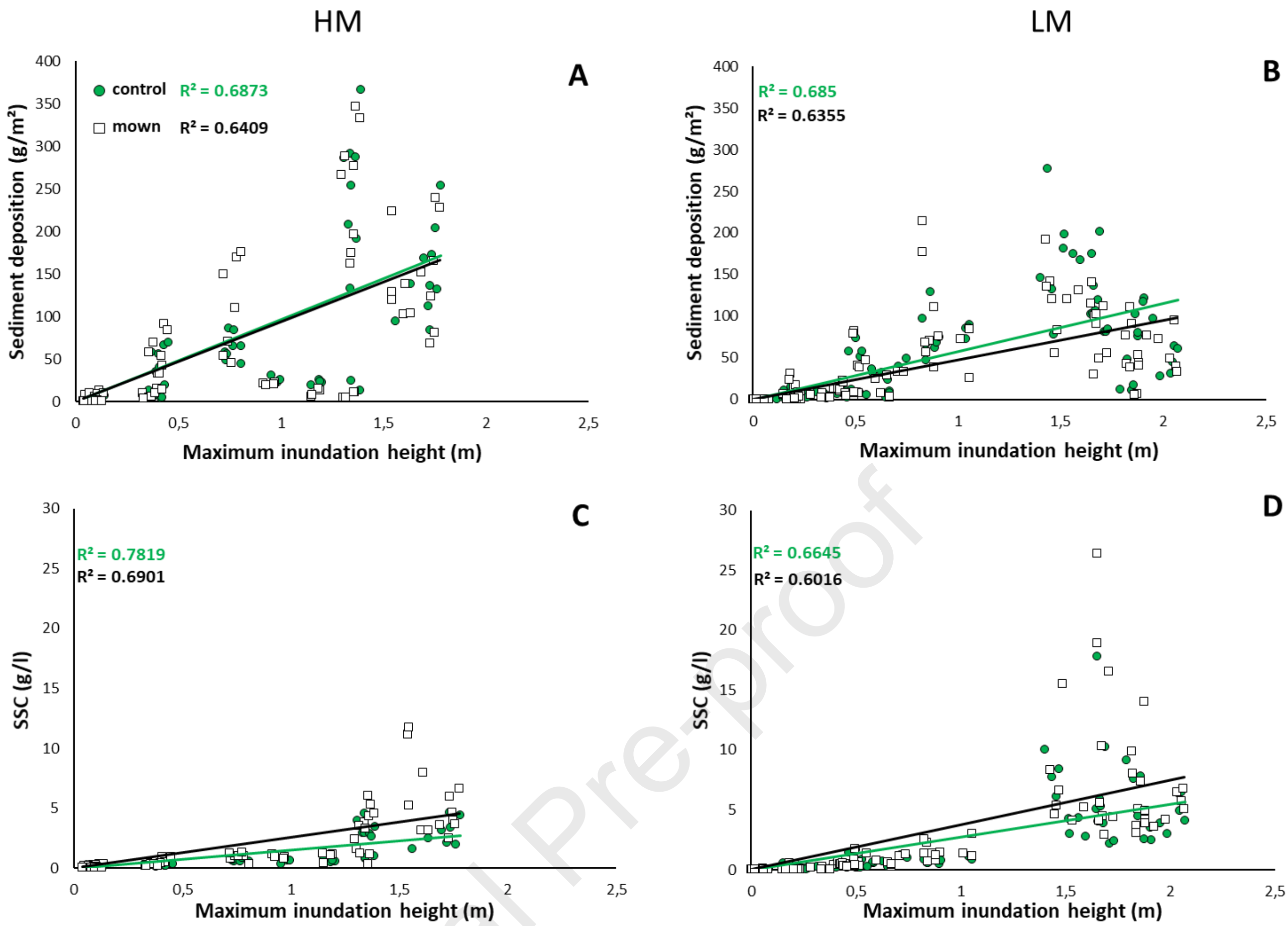

Fig. 6 Sediment deposition (panel A, B) and SSC (panel C, D) as a function of maximum inundation height in the high (panel A, C) and low (panel B, D) marsh. White squares show mown subplots with a corresponding black regression line. Green circles show control plots with a corresponding green regression line. All relationships between maximum inundation height and SSC or sediment deposition are linear and significant.

Table 1: ANOVA table of the effects of treatment (mown, control) on total sediment deposition and SSC on at the creek located subplots in the high and low marsh and of treatment combination on sediment deposition and SSC on inner located subplots in the high and low marsh. Given are F-values and p-values.

	Sediment deposition HM		Sediment deposition LM		SSC HM		SSC LM	
	F	P	F	p	F	p	F	p
Treatment	0.722	n.s.	0.043	n.s.	0.933	n.s.	0.862	n.s.
Treatment creek x Treatment inner	0.001	n.s.	0.883	n.s.	0.087	n.s.	0.311	n.s.
Treatment creek	0.364	n.s.	0.732	n.s.	0.076	n.s.	0.618	n.s.
Treatment inner	0.024	n.s.	3.440	n.s.	1.005	n.s.	1.694	n.s.

4. Discussion

Vegetation-induced sedimentation is an important factor for coastal marsh maintenance under sea-level rise (Baustian et al., 2012; Zhang et al., 2020). Yet even though it is often assumed that vegetation has a positive effect on sediment deposition, there were no differences in sediment deposition and SSC between patches of control and mown vegetation in both the high marsh and the low marsh. We also did not find evidence for an influence of different spatial positioning of vegetated control and mown subplots on patterns of sediment deposition and SSC.

This study adds to a body of research showing contrasting results on the influence of tall and short marsh vegetation on sediment deposition and SSC (e.g. Morris et al. 2002; Neumeier and Ciavola 2004; Temmerman et al. 2005; Silva et al. 2009; Elschot et al. 2013; Nolte et al. 2013b; Reef et al. 2018; Schulze et al. 2021). Within a marsh, on a small vegetation-patch scale, it is assumed that a patch of vegetation represents an obstacle to the water flow, leading to altered hydrodynamic conditions within, between, and around the vegetation patch. A small vegetation patch adjacent to a creek or marsh edge experiences high drag forces (Bouma et al., 2010), dissipates wave energy and reduces flow velocity causing lower hydrodynamic energy behind the patch and therefore conditions for enhanced sediment deposition (Marjoribanks et al., 2019). However, these previous studies investigating flow-patch interactions mostly focus on isolated vegetated patches (i.e. tussocks) on an unvegetated tidal flat, which are not necessarily comparable to patches and patterns within a vegetation canopy. The difference between isolated patches and patterns in the vegetation canopy might be a reason why we did not observe the expected higher sedimentation in the vegetated control plots in both positions (inner and creek).

Previous studies have found, that a considerable amount of hydrodynamic energy (~40-50%) is effectively attenuated on the first five to ten meters of a vegetated marsh (Leonard and Croft, 2006; Möller and Spencer, 2002; Ysebaert et al., 2011), but it stays unclear what happens on shorter distances comparable to those studied here. Our results indicate that substantial attenuation of hydrodynamic energy and enhanced sediment deposition probably only takes place on coherent vegetation patches which are larger than 2x2 m or 4x4 m. In a tidal marsh study on flow and sediment deposition patterns, it was shown that larger fully vegetated plots adjacent to the sediment source showed a higher sediment deposition compared to the 10 m interior located vegetated plots (Schepers et al., 2020). In contrast, mown plots close to the sediment source showed less sediment deposition compared to interior located mown plots. It was shown that sediment deposition not only depends on the treatment of the vegetation (e.g. grazed/ungrazed, mown/unmown) but also on the distance of the plot to the source of the sediment and on the spatial scale. However, it should also be taken into account that Schepers et al., (2020) studied a tidal freshwater marsh dominated by *Phragmites australis*, a plant that grows considerably taller than the vegetation in some salt marshes and might therefore lead to clearer vegetation effects. While our study included at least two vegetation types (*Spartina anglica* and *Elymus athericus*), future studies should further investigate the influence of differences in vegetation properties on sedimentation processes.

We did find a linear relationship between inundation height and SSC as well as between inundation height and sediment deposition across treatments and thus conclude that inundation height seems to be the control mechanism for SSC and sediment deposition in this study. This is in line with previous studies showing a linear increase of initial floodwater SSC with increasing inundation height (Temmerman et al., 2003a, 2003b). However, this correlation seems to be slightly, but consistently, more pronounced on control subplots (higher R^2 on control subplots compared to mown subplots). This indicates that a slightly greater part of the variation in the data is explained by the maximum inundation height in the control treatment compared to the mown treatment. If vegetation density would have played a role mediating the effect of inundation height on sediment deposition and SSC, we would have expected a lower R2 in the control treatment, as there is a higher variability of vegetation density in this treatments than it is in the more uniform mown treatment. This underlines the lack of influence of vegetation on sediment deposition in this study, as sediment deposition is more strongly affected by inundation height on vegetated plots than on mown plots. We thus assume that in the patches we studied here there is no effect of vegetation structure, while in larger patches consisting of dense vegetation this has previously been found. For example Schulze et al. (2021) who found a significantly higher sediment deposition on large ungrazed plots (>100 m²) compared to large grazed plots (>100 m²).

Interestingly, we found a consistent, but non-significant, trend of SSC being higher over mown subplots compared to control subplots. This trend could indicate additional explanations for the unexpected results on sediment deposition. Firstly, the slightly lower SSC over control subplots could suggest that a certain amount of suspended sediment is directly trapped by the vegetation, which is a well described process (e.g. Fagherazzi et al. 2012b; Li et al. 2014; Kakeh et al. 2016). This process (Fig 7), in contrast to the above-described passive deposition mechanism, is not reflected in our results as the lid of the sediment traps prevented uptake of sediment sticking to vegetation. During an inundation, the lid first moves up allowing sediment in the water column to settle and then shuts when water level moves down thus preventing washout of trapped sediment by rain (Nolte et al., 2019). However, during rainfalls, sediment sticking on the vegetation surface can be rinsed and accumulated on the marsh surface leading to underestimation of total sediment deposition. We therefore suggest that considering this mechanism in future studies would substantially increase our knowledge on the influence of salt marsh vegetation on SSC and sediment deposition. This could be achieved by measuring the accretion rates on longer timescales using e.g. a SET approach (Nolte et al., 2013a). Secondly, our study did not include the process of resuspension, which could be another explanation for the trend of slightly, but not significantly higher SSC on mown plots. We positioned the traps in the middle of the subplots, and therefore sediment might have been resuspended from the marsh surface in front of the SSC-bottle (Fig. 7). This process could have been reduced in control plots as both aboveground canopy (Ros et al., 2014) and roots (Chirol et al., 2021; De Battisti et al., 2019) reduce resuspension (Fig. 7), leading to slightly lower SSC compared to the mown subplots. However, it should be taken into account that in contrast to a natural unvegetated mudflat, our mown treatments removed only aboveground biomass and left belowground structures intact. We are unable to corroborate this hypothesis, so we would suggest future studies should include measurements of SSC throughout the water column and during the entire inundation cycle using automated sampling devices or OBS sensors (see e.g. Reef et al., 2018). In addition, we would suggest to measure flow velocity and direction (Schepers et al., 2020) in at least some of the plots. This would allow some conclusion on whether the marsh is flooded predominantly via the creeks or whether sheet flow via the marsh edge occurs. Based on personal observations we assume that during intermediate flooding events and at the beginning of inundations the salt marsh is flooded via the creek. However, we cannot rule out that sheet flow occurred during the higher inundations. This could have led to less clear results, as our study was designed based on the assumption of inundations via the creek.

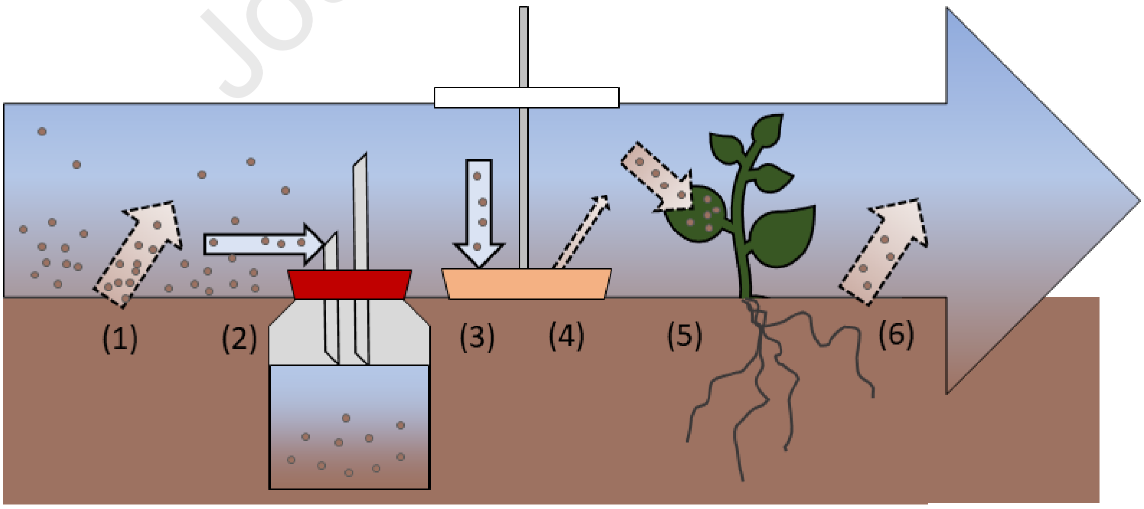

Fig. 7 Processes which were measured in the present study (solid line arrows) include (2) the SSC in the water column (at the height of the bottle opening) and (3) the sediment deposition in sediment traps. Other processes which should be considered in future studies (dashed line arrows) include the resuspension of sediment from the soil surface in (1) unvegetated (i.e. mudflat) and (6) vegetated areas. It would also be relevant to compare these to (4) resuspension from sediment traps. Finally, (5) the direct trapping of sediments on the vegetation should be assessed.

In summary, based on the results of our study, it can be concluded that the presence of salt marsh vegetation not automatically leads to higher sediment deposition on vegetated patches compared to mown patches in both the low and high marsh. Furthermore, we found that the vegetation pattern on the patch size created in the experiment did not affect sediment deposition or SSC. To provide comprehensive information on scale dependency of vegetation-mediated sediment deposition, future studies should include measurements of flow velocity, sediment transport, sediment deposition, resuspension of sediment as well as vegetation behaviour on patches of different sizes in order to find critical thresholds for effects of vegetation on sediment deposition (Fagherazzi et al., 2020). However, the fact that biophysical plant properties are highly variable spatially and seasonally (Schulze et al., 2019) and hydrodynamic attenuation follows non-linear relationships makes research in this field challenging and explains the scarcity of studies (Friess et al., 2012; Koch et al., 2009; Wiberg et al., 2020).

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- We investigated effects of small-scale marsh vegetation patterns on sedimentation.
- The experiment included mowing and control plots.
- Vegetation did not increase sediment deposition on this small scale.

Declaration of interests

☐ 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.

☒ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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