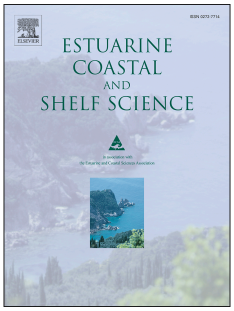

Livestock grazing reduces sediment deposition and accretion rates on a highly anthropogenically altered marsh island in the Wadden Sea

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PII: S0272-7714(21)00027-5

DOI: https://doi.org/10.1016/j.ecss.2021.107191

Reference: YECSS 107191

To appear in: *Estuarine, Coastal and Shelf Science*

Received Date: 25 March 2020

Revised Date: 7 December 2020

Accepted Date: 13 January 2021

Please cite this article as: Schulze, D., Jensen, K., Nolte, S., Livestock grazing reduces sediment deposition and accretion rates on a highly anthropogenically altered marsh island in the Wadden Sea, *Estuarine, Coastal and Shelf Science* (2021), doi: https://doi.org/10.1016/j.ecss.2021.107191.

CRediT author statement

Dennis Schulze: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data Curation, Writing - original draft, Writing - Review & Editing, Visualization, Project administration

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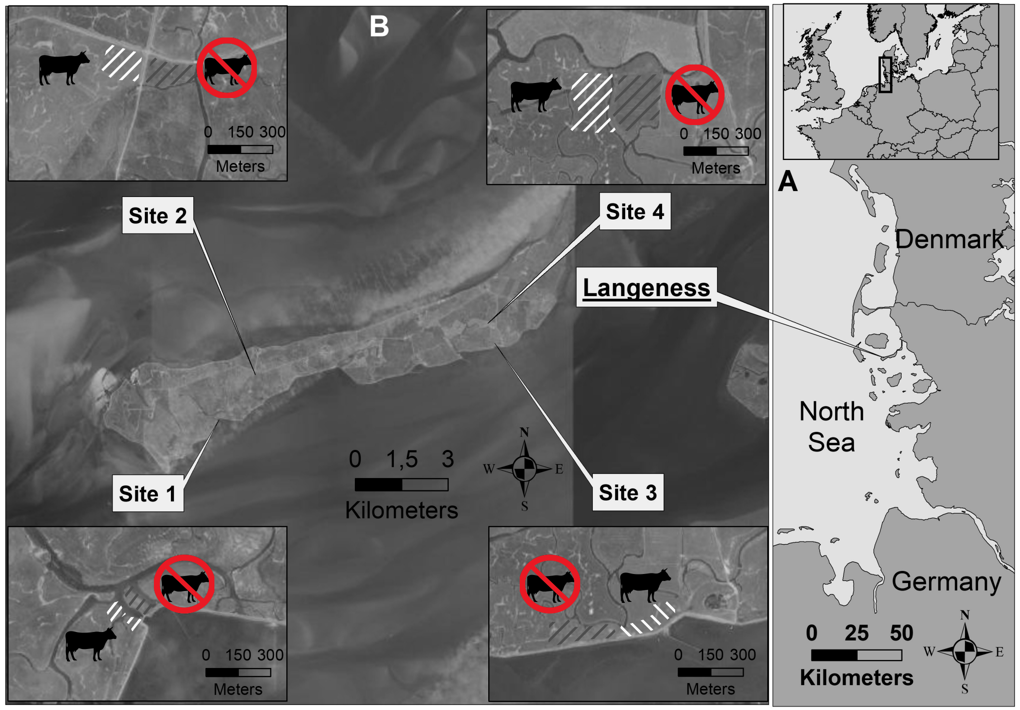
Stefanie Nolte: Conceptualization, Methodology, Validation, Formal analysis, Writing - Review & Editing, Funding acquisition, Supervision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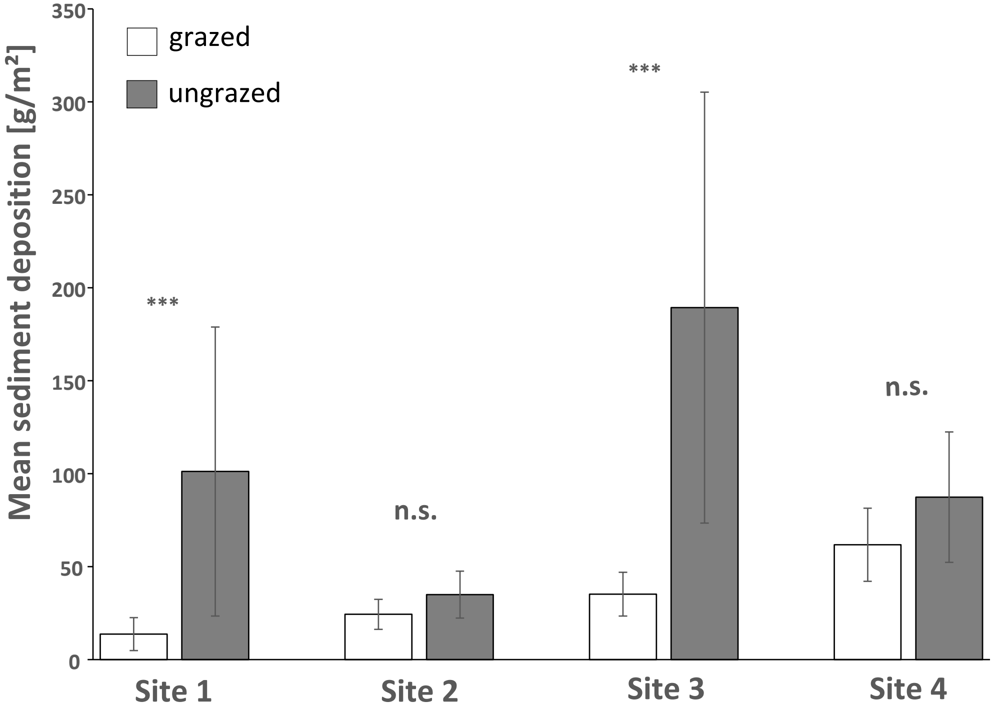
Mean sediment deposition [g/m²]
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100
150
200
250
300
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grazed
ungrazed
***
n.s.
***
n.s.
Site 1
Site 2
Site 3
Site 4

Title: Livestock grazing reduces sediment deposition and accretion rates on a highly anthropogenically altered marsh island in the Wadden Sea

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Key words: Sedimentation; Accretion; Sea-level changes; Salt marshes; Grazing; Wadden Sea

Abstract

Coastal salt marshes and their provided ecosystem services are threatened by rising sea levels all over the world. In the Northern Wadden Sea region, a sea-level rise of 4 mm y^{-1} was recorded for recent years. Identifying and understanding factors that affect sediment deposition and determine vertical accretion of salt marshes is crucial for the management of these ecosystems. Even though major processes contributing to sedimentation and accretion have already been identified, the influence of reduced canopy heights due to livestock grazing is still debated. On a highly anthropogenically altered marsh island in the Wadden Sea, sediment deposition, accretion and suspended sediment concentration was analyzed on grazed and adjacent ungrazed plots both at the marsh edge and at the marsh interior. Due to a low seawall (a so-called ‘summer dike’), flooding frequency on the island is reduced and flooding mainly takes place during storm surges. After five flooding events within a year, mean sediment deposition and accretion were found to be up to seven times higher on ungrazed plots compared to grazed plots, but only at the marsh edges. This result was not explained by the overmarsh suspended sediment concentration (SSC), which was found to be twice as high on grazed plots compared to ungrazed plots. It is concluded that grazing has a negative effect on sediment deposition and accretion on Wadden Sea marsh islands and areas with similar conditions (e.g. presence of a summer dike) by reducing the sediment trapping capacity of those marshes. Overall, vertical marsh accretion ranged from 0.11 ± 0.09 mm y^{-1} on a grazed plot at the marsh edge to 1.12 ± 0.71 mm y^{-1} on an ungrazed plot at the marsh edge. By increasing the discrepancy between accretion and sea-level rise, livestock grazing can lead to higher inundation levels and in turn to increased hydrodynamic forces acting on these anthropogenically altered marshes.

1. Introduction

Coastal salt marshes are vegetated ecosystems which form a transition zone between the sea and the land (Bakker, 2014). They serve as habitats for specific plant and animal species adapted to salt stress and regular flooding. Furthermore, they provide several important ecosystem services such as climate regulation (Mcleod et al., 2011; Mueller et al., 2019) and coastal protection (Spalding et al., 2014; Temmerman et al., 2013). However, the persistence of salt marshes around the world is threatened by global warming and associated sea-level rise (Crosby et al., 2016). Global-scale assessments of sea-level rise within recent years show average rates of approx. 3 mm yr^{-1} (Chen at al., 2017; IPCC 2019). Nevertheless, varying regional conditions can lead to noticeable deviations from the global mean (Vermeersen et al., 2018). For northern parts of the Wadden Sea, Europe's largest area of salt marshes and mudflats, even higher sea-level-rise rates of up to 4 mm yr^{-1} are described for recent years (Wahl et al., 2013). Thus far, mainland salt marshes in the Wadden Sea were able to keep pace with sea-level rise as sediment deposition and accretion are sufficient (Butzeck et al., 2014; Nolte et al., 2013a; Suchrow et al., 2012). However, places with limited inundations and sediment load, such as the Wadden sea marsh islands, are more vulnerable due to an increasing imbalance of accretion rates and rising sea level (Schindler et al., 2014).

Sediment deposition on marsh surfaces (usually specified as g m^{-2} yr^{-1}) takes place during inundations and describes the process of sediments settling from the floodwater onto the soil surface (Nolte et al., 2013b). This process leads to a rise of elevation which then also affects plant colonization and vegetation succession (Olff et al., 1997). Established plants reduce hydrodynamic forces and flow velocity (Neumeier and Amos 2006; Peralta et al., 2008; Temmerman et al., 2012), leading to increased sediment deposition and consequently higher accretion rates (Van Hulzen et al., 2007). Accretion, describing vertical growth of the marsh platform by allochthonous sediment input and autochthonous organic production, also considers auto-compaction, compaction through trampling and erosion (Nolte et al., 2013b). When sediment deposition and long-term accretion rates cannot keep pace with sea-level rise, coastal wetlands, including salt marshes, will be in danger of being submerged permanently (Crosby et al., 2016; Spencer et al., 2016). Therefore, to predict the stability and persistence of salt marshes and to possibly adapt coastal management activities, knowledge on the influence of site-specific management and characteristics on sediment deposition accretion is crucial. The local elevation of the salt-marsh platform relative to the sea level determines the inundation parameters. Usually, higher inundation frequencies, flooding durations and water levels in low marshes compared to high marshes are related to higher sedimentation in low marshes (Temmerman et al., 2003). Higher elevations and decreased flooding frequencies or lower water levels in turn lead to lower sedimentation rates in high marshes. Additionally, with increasing distance to a certain sediment source, such as the marsh edge or a creek, sedimentation rates were found to decrease as sediment is removed from the water continuously (Temmerman et al., 2005a; Moskalski and Summerfield 2012). The overmarsh SSC is another major factor influencing sediment deposition and accretion as it determines the mass of sediment which can be deposited on the marsh platform (Nolte 2013b). Butzeck et al., (2015) found overmarsh SSC to be the main predictor for sediment deposition rates in freshwater marshes, brackish marshes and Wadden Sea mainland marshes. Thus, the question whether sediment deposition and accretion rates are sufficient in outpacing the rising sea level, largely depends on those local characteristics of the respective marshes.

Additionally, biophysical properties of marsh vegetation differ spatially (Schulze et al., 2019) and could thus affect flow velocity, wave energy and sediment parameters such as SSC and sediment deposition. For example, high stem densities, stiff canopies and high aboveground biomass (Fagherazzi et al., 2012; Peralta et al., 2008) were found to increase gravity-related sediment deposition on the marsh surface by slowing down flow velocities. Furthermore, suspended sediment particles can be intercepted by a dense vegetation and are likely to be deposited directly on parts of the canopy thus leading to potentially lower SSC over ungrazed sites compared to grazed sites. This direct trapping effect of vegetation on sediment has been described before and depends, similar to sediment deposition processes, on biomass, stem density, surface roughness of the vegetation type and surface area of the whole foliage system (Fagherazzi et al., 2012; Kakeh et al., 2016; Li and Yang, 2009; Schuerch et al., 2014; Yang et al., 2008).

The vegetation structure in many salt marshes, however, is largely affected by anthropogenic influences such as livestock grazing for agricultural and nature conservation purposes. Livestock grazing results in reduced aboveground biomass and shorter canopies (Esselink et al., 2000; Nolte et al., 2013a; 2015). Furthermore, livestock grazing can increase soil bulk density by trampling (Nolte et al., 2015) and thus potentially reduce accretion. Therefore, sedimentation and accretion rates are expected to be lower in grazed marshes. However, field studies on the effects of grazing and vegetation on sediment deposition and accretion rates are still scarce and show contradicting results with positive correlations between the presence of vegetation and sediment deposition on the one hand (e.g. Morris et al., 2002) and negative correlations (e.g. Silva et al., 2009) on the other hand. In Wadden Sea mainland salt marshes, Andresen et al., (1990) and Neuhaus et al., (1999) found sedimentation rates to be higher on ungrazed sites compared to grazed sites. More recently, Elschot et al., (2013) and Nolte et al., (2013a) did not find differences in accretion between grazed and ungrazed areas, albeit they found a trampling-driven higher soil bulk density in grazed marshes. However, these marshes show comparatively high sediment deposition, and it is unknown whether a grazing effect may potentially be more pronounced at sites with low rates of sediment deposition due to e.g. artificially reduced flooding frequencies.

Marshes with limited sediment input can be found on the so called ‘Hallig’ islands, which are remnants of the former mainland marshes of the Northern German Wadden Sea. The islands are largely consisting of salt marshes which have been used for livestock grazing for a long time. Further human modifications, such as a ‘summer dike’ (comparatively low seawalls preventing marsh surfaces to be flooded during spring tides), ‘stone revetments’ of island margins (serving as erosion protection) and straightening of creeks for drainage, have turned the Hallig islands into highly anthropogenically altered marshes. Particularly due to the summer dike, which is still common in some parts of the North Sea area (Ahlhorn and Kunz, 2002), inundation does only occur during storm surges when the summer dike is overtopped. Therefore, the reduced inundation frequencies ranging between zero and 28 events per year have in turn led to low accretion rates (Schindler et al., 2014). Vulnerability of the specific Hallig marsh type results from the increasing discrepancy between sea-level rise and overall accretion rates, which over time results in higher inundation height and in turn go along with increased hydrodynamic forces to the marsh surfaces (Schindler et al., 2014).

However, it is unknown how these already low sediment deposition and accretion rates are affected by livestock grazing and how this will affect their capability to keep up with sea-level rise in the long term. In this study, it was therefore aimed to investigate the effects of livestock grazing on sediment deposition and accretion rates on a marsh island in the Wadden Sea with a reduced flooding frequency and a reduced sediment input. It was hypothesized (I) that sediment deposition and accretion rates are higher on ungrazed plots than on grazed plots because of flow velocity reductions due to changes in vegetation structure. It was also hypothesized (II) that SSC is lower over ungrazed marshes than over grazed marshes as suspended sediment is prone to be filtered out of the water by a dense vegetation canopy. Regarding the spatial distribution of sediment, it was hypothesized (III) that the total sediment deposition and accretion rates are higher at the edge of the marsh island compared to inner parts.

2. Methods

2.1 Study area

The study was conducted on the marsh island ‘Langeness’ in the Northern German Wadden Sea region. It is the largest island of the Hallig marsh-island group (9.2 km²) and is located off the mainland coast of the state of Schleswig-Holstein (Fig.1 A). All marsh islands in this area are remnants of the former mainland marshes and were separated by a severe storm surge event in 1634 (Ahrendt, 2007). Today, they are part of the biosphere reserve ‘Schleswig-Holsteinisches Wattenmeer’. At the beginning of the 20th century, Langeness was encompassed by a stone revetment to prevent erosion of the island margins and by a summer dike with an average height of 1 m above mean high tide. In this way, flooding is mostly prevented from April to October when a large proportion of the marsh is used for cattle grazing by the permanent inhabitants of the island. The summer dike contains several tide gates connecting the marsh creeks to the Wadden Sea. These gates, however, automatically close during rising tides and prevent flooding of the island via the creeks. Tidal flooding thus only occurs as a sheet flow coming from the marsh edge and is induced by strong westerly winds and spring tides. The marsh topography is characterized by an elevational gradient from the higher elevated areas at the edges behind the summer dike towards the lower elevated inner parts of the marsh. Averagely, the marsh platform is elevated 0.17 m above mean high water (Schindler et al. 2014). Generally, the Hallig marshes mostly represent high marsh vegetation (Kleyer et al., 2006; Esselink et al., 2017).

2.2 Study sites and study design

To investigate the influence of livestock grazing (factor ‘treatment’) on sediment deposition, accretion and overmarsh SSC, two sites were chosen at the island marsh edge and two sites further inwards (factor ‘position’). Each site included a grazed and an ungrazed plot adjacent to each other, resulting in a total number of eight different plots (Fig. 1 B). To test whether the expected treatment and position effects are consistent over the entire island, one pair of sites was positioned (inner, edge) in the east and one pair in the west, reflecting the longitudinal shape of the island. On the grazed plots, the livestock grazing (i.e. cattle) takes place during the summer season. Grazing resulted in a vegetation which mainly consists of the *Festuca rubra* vegetation type (see also Kleyer et al., 2006). The ungrazed plots consist of monospecific dense stands of the *Elymus athericus* type and have not been exposed to either grazing or mowing for several years. In each of the eight plots, eight sampling points were randomly chosen using a random point tool of QGIS 2.10 Pisa (QGIS Development Team 2015). At these points, sediment deposition was recorded during every inundation between October 2015 and March 2016. In this period, five inundation events occurred, which is only half of the average number of inundation events between 2001 and 2010 with ten events per year (Schindler and Willim, 2014).

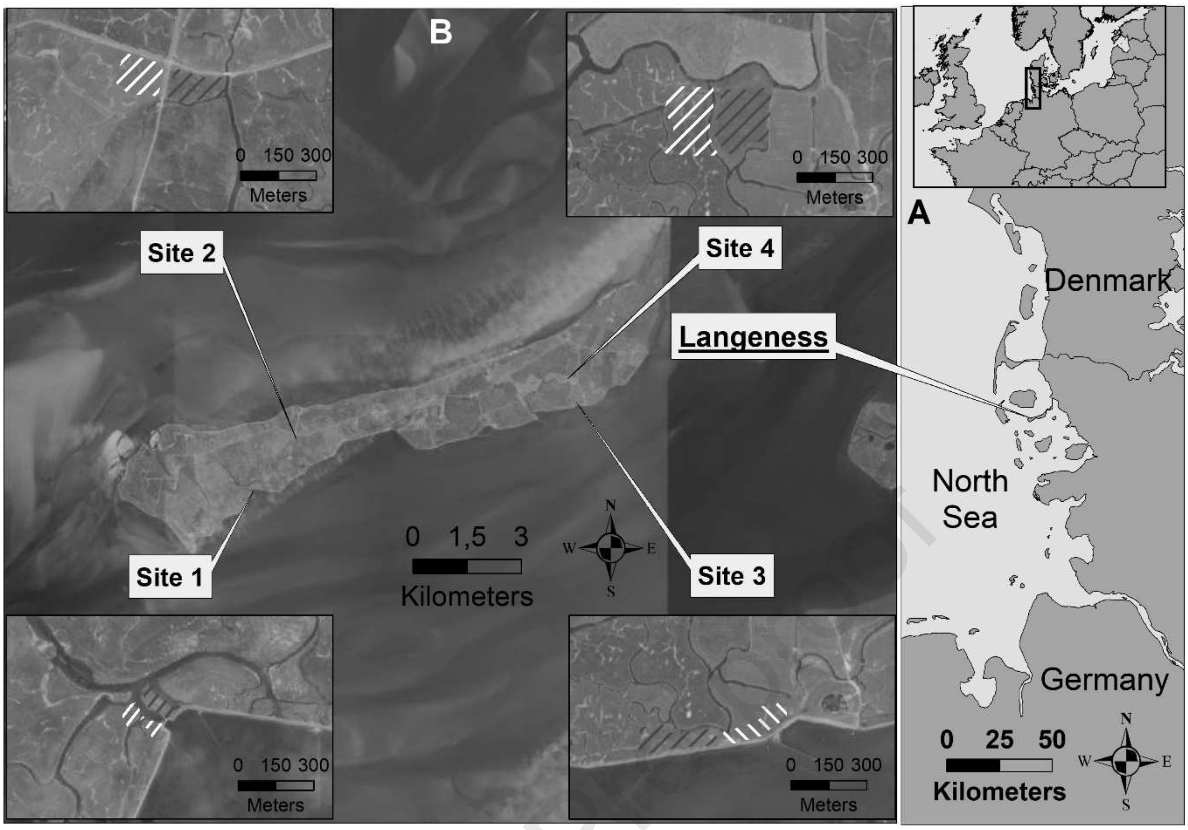

Figure 1: **A** Location of the marsh island Langeness in the Northern Wadden Sea region. **B** Satellite image of Langeness with the respective four study sites and the differently treated plots. Grazed plots are shown as white hatched whereas ungrazed plots are shown as dark grey hatched.

2.3 Measurements of sediment deposition and suspended sediment concentration

At each of the 64 sampling points, which had a minimum distance of three meters to each other, circular plastic plates (internal diameter: 19 cm; rim: 2.5 cm) were placed on the soil surface to trap the deposited sediment during inundations. The plates were attached to the ground with a plastic stick (1.5 m) and with metal wires. To prevent a washout of sediment by rain, every sediment trap was equipped with a floatable lid (Butzeck et al., 2014; Nolte et al., 2019; Temmerman et al., 2003). After each inundation, the collected 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. The dry weight provided information on the sediment deposition (g m^{-2}) for each flooding event. To convert the sediment deposition into accretion rates, soil bulk density was determined by taking a soil sample using a 100 cm^{-3} steel cylinder next to each sampling point from the uppermost (0-6 cm) soil layer. Bulk density was calculated by dividing the mass of the oven dried soil sample by the core volume. Accretion rates are based on five flooding events in the storm surge season from the beginning of autumn 2015 to the end of spring 2016 and were calculated as follows:

$$\text{Accretion (cm yr}^{-1}\text{)} = \text{Sediment deposition (g cm}^{-2}\text{ yr}^{-1}\text{)} / \text{Bulk density (g cm}^{-3}\text{)} \qquad [1]$$

Additionally, floodwater was collected to determine the suspended sediment concentration at each sampling point. 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. These bottles allowed a controlled water inflow 3 cm above the marsh surface (Butzeck et al., 2014). The filled bottles were replaced after each inundation event. To determine the suspended sediment concentration (g l^{-1}), water samples were resuspended and vacuum filtrated with cellulose nitrate filters (0.45 µm). Subsequently, samples were oven dried at 60 °C until constant weight.

2.4 Inundation and vegetation parameters

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). There was no significant difference in relative elevation between each of the corresponding plots. Information about inundation height, frequency and duration was obtained by installing a water gauge between the grazed and ungrazed plot at each of the four study sites, which allowed to determine absolute inundation levels above the plots. A slitted plastic pipe containing a water pressure sensor (Schlumberger Cera diver, accuracy of measuring water level: ± 1 cm), with a temporal resolution of five minutes, was inserted into the soil. An atmospheric pressure sensor (Baro Diver) was attached on one of the dwelling mounts on the island to compensate the water pressure measurements for the atmospheric pressure. The average canopy height for each plot was determined in late November by measuring the distance from the soil surface to a Styrofoam drop-disc (30 cm) at four points around each sediment trap.

2.5 Statistical analysis

Three-factorial analysis of variance (e.g. sediment deposition ~ treatment*position*location) was used to test whether each of sediment deposition, accretion and suspended sediment concentration were affected by treatment (grazed, ungrazed), position (inner, edge) and geographical location (east, west). To determine differences between the groups, Tukey's HSD tests were applied when the ANOVA revealed a significant effect ($p < 0.05$). If necessary, data were log transformed to meet normality assumptions and to improve homogeneity of variances (applied on sediment deposition, accretion and SSC). Equal sample sizes in the study design assured robustness of parametric testing (McGuinness 2002). Following the protocol by Zuur et al., (2009), no spatial autocorrelation of either raw data within plots or of residuals across all sampling points was detected, and therefore it is concluded that the assumption of independence is met. For each site, differences in inundation level, vegetation height and soil bulk density between grazed and ungrazed plots were analyzed with Bonferroni corrected t-tests for multiple testing. All analyses were performed using R version 3.5.3 (R Core Team, 2019; base package).

3. Results

Overall, five complete inundations of the island were recorded between early October 2015 and late March 2016. The mean maximum inundation height was slightly, but not significantly, higher on the ungrazed plot at site 1 (west, edge; t-test, p > 0.017, Table 1). At site 2 (west, inner, minimal distance to marsh edge: 350 m), 3 (east, edge) and 4 (east, inner, minimal distance to marsh edge: 250 m), the inundation was slightly, but not significantly, higher over the grazed plot (t-test, p > 0.017, Table 1). Mean maximum inundation height ranged from 86.36 cm (site 3, east, edge, ungrazed) to 164.1 cm (site 1, west, edge, ungrazed). At each site, vegetation height was significantly higher in ungrazed compared to grazed plots (p < 0.017, t-test for every site, Table 1). Soil bulk density did not differ between grazed and ungrazed plots, neither at the edges nor in the inner parts both in the east and west (t-test, p > 0.017, Table 1).

Table 1: Relative elevation, max. inundation heights and vegetation heights of the grazed and ungrazed plots at the islands marsh edges and the marsh interior in the east and west. After Bonferroni corrections for multiple testing, statistical significance was determined as p < 0.017. Different letters indicate significant differences among the treatments.

Site	Location	Position	Treatment	Mean max. inundation [cm]	Vegetation height [cm]	Soil bulk density [g/cm³]
1	West	Edge	Grazed	137.62 ± 16.68 **a**	5.69 ± 1.56 **a**	0.66 ± 0.09 **a**
			Ungrazed	164.12 ± 21.93 **a**	12.56 ± 2.17 **b**	0.75 ± 0.07 **a**
2	West	Interior	Grazed	142.19 ± 4.85 **a**	6.63 ± 0.61 **a**	0.55 ± 0.09 **a**
			Ungrazed	141.64 ± 6.33 **a**	11.97 ± 1.08 **b**	0.57 ± 0.08 **a**
3	East	Edge	Grazed	87.86 ± 7.16 **a**	4.81 ± 0.94 **a**	0.82 ± 0.07 **a**
			Ungrazed	86.36 ± 13.12 **a**	12.56 ± 1.87 **b**	0.83 ± 0.11 **a**
4	East	Interior	Grazed	147.33 ± 6.94 **a**	4.72 ± 0.79 **a**	0.58 ± 0.08 **a**
			Ungrazed	137.06 ± 13.38 **a**	9.88 ± 1.73 **b**	0.46 ± 0.11 **a**

Highest mean sediment deposition occurred on the ungrazed plot at site 3 (east, edge; 189.35 g m^{-2} yr^{-1}) while the lowest mean sediment deposition occurred at the grazed plot of site 1 (west, edge; 13.75 g m^{-2} yr^{-1}, Fig. 2). A significant interaction between the treatment and the position indicated that differences in sediment deposition between ungrazed and grazed plots were more pronounced at the island marsh edges (Fig 2; Table 2). At the marsh edges, sediment deposition was roughly 7 times (site 1, west, edge) and 5 times (site 3, east, edge) higher on the ungrazed plot compared to the grazed plot. The effect of the treatment and the position on sediment deposition was found both in the eastern and the western part of the island. Overall, sediment deposition was twice as high in the east as in the west and 60% higher at the marsh edge compared to the sites located further inwards. The mean accretion showed similar results as the sediment deposition rates with a significant interaction between treatment and position revealing that accretion was higher on ungrazed compared to grazed plots at the island marsh edges (Fig.3, Table 2). Overall, accretion was twice as high in the east as in the west. Furthermore, sediment deposition and accretion on at the edge positioned ungrazed plots was found to be slightly higher than on interior positioned ungrazed plots and vice versa for grazed plots (Figure 2, Figure 3, Supplementary Table 1).

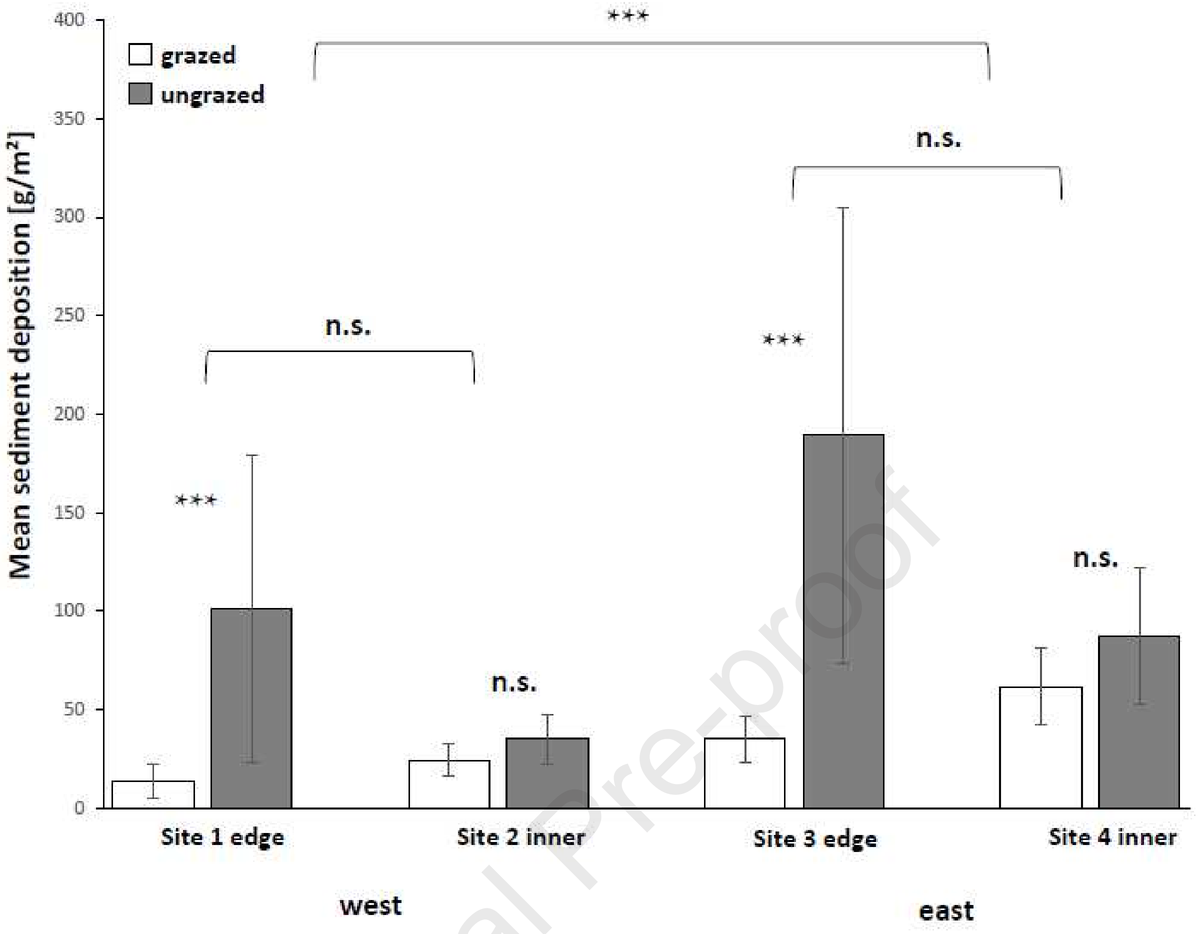

Figure 2

Mean sediment deposition on grazed and ungrazed plots at the marsh edges and marsh interior in the east and west of the island after five inundation events. Every bar represents the average of eight sampling points. Given are the mean and the standard deviation. For comparisons between sites, the grazed and ungrazed plot were combined. The difference between the eastern and western location was determined by comparing total sediment deposition in the east and in the west. Significant differences between treatments, sites and geographic locations are indicated as resulting from post-hoc tests following ANOVA (*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$).

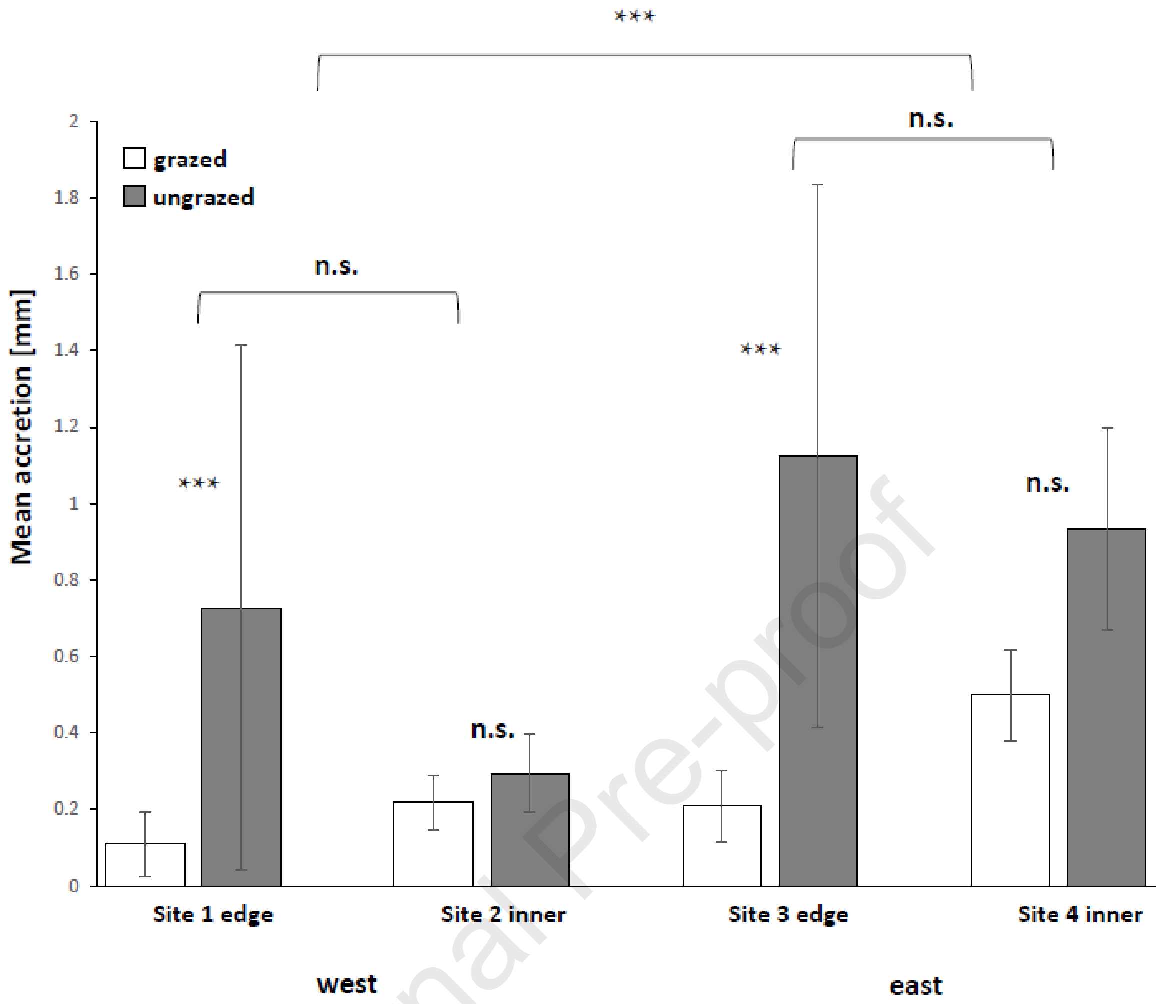

Figure 3

Mean annual accretion on grazed and ungrazed plots at the marsh edges and marsh interior in the east and west of the island. Every bar represents the average of eight sampling points. Given is the mean and the standard deviation. For comparisons between sites, the grazed and ungrazed plot were combined. The difference between the eastern and western location was determined by comparing total accretion in the east and in the west. Significant differences between plots, sites and geographic locations are indicated as resulting from post-hoc tests following ANOVA (*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$).

SSC in the floodwater showed an opposite pattern with higher concentrations over the grazed plots compared to the ungrazed plots. Highest SSC occurred over the grazed plot at site 3 (east, edge; 0.81 g liter^{-1} yr^{-1}, Fig. 4) while lowest SSC occurred over the ungrazed plot at site 2 (west, inner; 0.15 g liter^{-1} yr^{-1}, Fig. 4). SSC was found to be significantly affected by the interaction between treatment and location and between location and position (Table 2). The treatment effect was less pronounced in the west than in the east as at site 1 (west, edge), where SSC was only slightly, but not significantly, higher over the grazed than over the ungrazed plots. At site 2 (west, inner), 3 (east, edge) and 4 (east, inner), SSC was approx. twice as high on the grazed compared to the ungrazed plots. Differences in SSC between the island marsh edge and the marsh interior were more pronounced in the east than in the west with SSC being approx. 90% higher at the marsh edge compared to the marsh interior in the east. In the west, SSC was 40% higher at the marsh edge compared to the marsh interior. SSC was approx. 60 % higher in the east than in the west (Fig. 4).

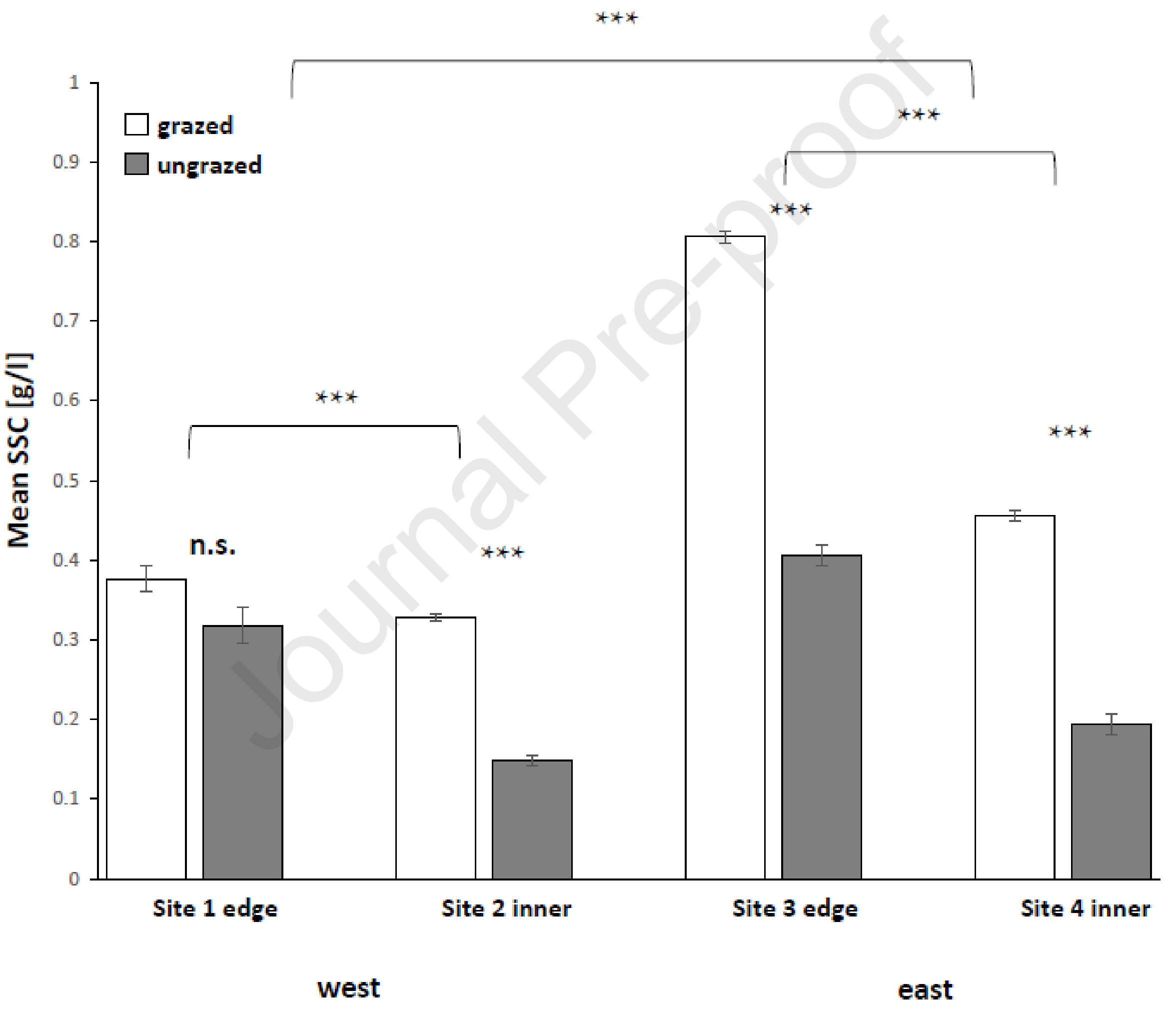

Figure 4

Mean suspended sediment concentration on grazed and ungrazed plots at the marsh edges and marsh interior in the east and west of the island after five inundation events. Every bar represents the average of eight sampling points. Given is the mean and the standard deviation. For comparisons between sites, the grazed and ungrazed plot were combined. The difference between the eastern and western location was determined by comparing the total SSC in the east and in the west. Significant differences between treatments, sites and geographic locations are indicated as resulting from post-hoc tests following ANOVA (*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$).

Table 2: ANOVA table of the effects of treatment (grazed, ungrazed), position (marsh edge, marsh interior), location (east, west) and the respective interactions on sediment deposition, accretion rates and SSC rates. Given are F-values and p-values. Significant effects are symbolized as the following: *** p < 0.001, ** p < 0.01, * p < 0.05.

	Sediment deposition		SSC		Accretion	
	F	p	F	p	F	p
Treatment	60.75	***	106.01	***	54.83	***
Position	0.17	n.s.	78.13	***	4.22	*
Location	42.69	***	46.28	***	31.04	***
Treatment x Position	26.82	***	12.26	***	17.92	***
Position x Location	0.25	n.s.	3.65	n.s.	0.13	n.s.
Treatment x Location	1.05	n.s.	6.41	*	0.92	n.s.
Treatment x Position x Location	0.93	n.s.	4.22	*	0.22	n.s.

4. Discussion

The results show a significant negative effect of livestock grazing on sediment deposition and accretion at the marsh edge with reduced sediment deposition and accretion on grazed plots compared to ungrazed plots, which is therefore in concordance with the first hypothesis. The same general, but non-significant, trend was found at the marsh interior. The suspended sediment concentration showed a contrasting pattern with lower SSC over ungrazed plots and thus the results confirm the second hypothesis of high-marsh vegetation reducing overmarsh SSC. Furthermore, total sediment deposition and accretion rates were expected to be higher at the marsh edges compared to inner parts of the marsh but the results did not support this third hypothesis. The effects of grazing on sediment deposition, accretion and SSC were similar in the east and in the west of the island. Furthermore, the results confirm findings of Schindler et al., (2014) indicating low accretion on Langeness leading to an increasing discrepancy between sea-level rise and accretion, which over time likely results in higher inundations and in turn increased hydrodynamic forces acting on the marsh surfaces. High hydrodynamic forces were found to cause high folding and breakage rates for *Elymus* canopies (Möller et al., 2014; Rupprecht et al,. 2017). As a consequence, losses in biomass and surface elevation might threat the *Elymus* dominated ungrazed areas of the island.

Higher sedimentation and accretion rates on ungrazed plots at the island marsh edge, as found in this study, most likely indicate an interaction effect of vegetation and flow velocity. Vegetation characteristics such as high biomass, high stem densities and tall canopies of marsh vegetation have long been known to reduce flow velocity (Leonard and Croft, 2006; Widdows et al., 2008) and to potentially increase sediment deposition and accretion on the marsh platform (Boorman et al., 1998; Morris et al., 2002). The findings of the study presented are supported by observations of Suchrow et al., (2012) who, probably as a result of lower sediment deposition, found a decreased surface-elevation change on grazed areas compared to ungrazed areas in high marshes of the Wadden Sea. Contrastingly, other studies on the influence of reduced canopy height (e.g. by grazing) on sediment deposition and accretion show no difference between non-manipulated areas and areas with decreased canopy height and biomass (Elschlot et al., 2013; Nolte et al., 2013a). Furthermore, Reef et al., (2018) found no effect of an experimentally reduced canopy height on the sediment budget in a southeastern British salt marsh and assume that the missing effect could have been caused by calm hydrodynamic conditions with inundation depths between 0.14 m and 0.54 m. A vegetation-mediated sediment deposition thus may not become effective when flow velocities are low. This assumption is supported by Nolte et al., (2015) who only found an effect of vegetation structure on accretion in a study period with increased storminess (see also Schuerch et al., 2012). Neumeier and Ciavola (2004) even described a negative correlation between the presence and density of vegetation and sediment deposition rates during fair weather conditions which was explained by a smaller water volume and therefore lower sediment load above vegetated areas. On the contrary, Elschot et al., (2013) and Temmerman et al., (2005b) expect vegetation structure to have no or only limited impact on sediment deposition when vegetation is overtopped by water. Under storm conditions and during high tides, sediment deposition can indeed be higher on unvegetated areas compared to fully vegetated areas as found by Silva et al., (2009). If the flow is relocated above the canopy as skimming flow, sediment deposition might be reduced (Neumeier and Amos, 2006; Peralta et al., 2008). As average inundation levels in our study ranged between 0.86 m and 1.64 m and thus overtopped the canopy (Table 1), evidence for a positive effect of vegetation and accordingly a negative effect of grazing on sediment deposition and accretion under these conditions is provided.

Focusing on the investigation of different canopy heights (short, long) as a result of grazing and their impact on SSC, it was hypothesized that SSC was lower over ungrazed plots compared to grazed plots. Indeed, SSC data show a significant trend of lower SSC over ungrazed plots compared to grazed plots. This result could be explained by a direct trapping effect of the *Elymus* vegetation on ungrazed plots as *Elymus* shows relatively high winter and spring biomass stocks of approx. 1 kg/m² (dry biomass) and high stem densities (>1000 stems/m²) in the Wadden Sea (Schulze et al., 2019). Additionally, resuspension of deposited sediment may be reduced on ungrazed plots, therefore leading to lower SSC in the water column over ungrazed plots (Yang et al., 2008). These observations are supported by Coulombier et al., (2012) who found SSC to be the highest when vegetation was minimal. A similar pattern was also found for a brackish marsh in Georgia, USA (Coleman and Kirwan, 2019). As the amount of suspended sediment in the floodwater as well as the amount that deposits, largely depends on the biophysical plant properties (Fagherazzi et al., 2012; Schuerch et al., 2014), these properties and their spatio-temporal variability should therefore be considered in studies investigating sedimentation patterns in salt marshes.

Contradicting the third hypothesis, total sediment deposition and accretion at the edges and the inner parts of the marsh did not differ significantly but still showed slightly higher rates at the edges. While sediment deposition and accretion on ungrazed plots was slightly higher at the edges than at the inner sites, which supports this hypothesis, the contrary was found for grazed plots. A similar pattern was found in a mowing experiment in the Scheldt Estuary (Schepers et al., 2019). In their study, fully vegetated plots close to the sediment source showed a higher sediment deposition compared to the interior located vegetated plots. In contrast, unvegetated plots nearby the sediment source showed less sediment deposition compared to interior located unvegetated 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 relative position of the plot to the source of the sediment and on respective flow velocities (see also Temmerman et., 2012). At the Langeness study site, tide gates prevent flooding of the creeks resulting in water coming from the island edge being the only source for sediment. Already a small vegetation patch near the marsh edge can reduce flow velocities (Schepers et al., 2019) and therefore favor sediment deposition. Allowing for higher flow velocities, grazed areas at the marsh edge might thus lead to higher sediment transport rates to the inner parts where sediment can deposit.

Conclusion

The pattern of overmarsh SSC and sediment deposition rates observed in this study reveals the general complexity of sedimentation in salt marshes on the one hand, and the significant importance of vegetation for overmarsh SSC and sedimentation rates on the other hand. In contrast to the literature, sediment deposition in this study does not mainly depend on the SSC recorded close to the sediment traps but rather on the management and characteristics of the plots and on the position of plots relative to the sediment source. Based on the data presented, it is shown that overall mean accretion of 0.5 mm yr^{-1} (based on five inundations) is not sufficient to keep pace with sea-level rise. This result is supported by Schindler et al., (2014) who found similar accretion rates and suggest the removal of summer dikes to increase the number of flooding events and therefore accretion rates on this marsh island. Adding to this suggestion, this study moreover shows that non-grazing favors sediment deposition and accretion in salt marshes with low flooding frequencies. Comparing grazed and ungrazed plots of the marsh island, the results show an up to seven times higher sediment deposition and accretion on the ungrazed plots with accretion rates of up to 1.1 mm yr^{-1}. Therefore, a reduction or abandonment of grazing can increase accretion rates considerably and should be incorporated into future management plans for the studied island and for other similar areas in the Wadden Sea or elsewhere. Additionally, occasional mowing of the marsh edges could increase accretion rates in inner parts of the island by allowing higher suspended sediment concentrations in the floodwater reaching inner parts of the island.

Acknowledgements

The study was funded by the WWF in the framework of the ‘PiKKoWatt’ project. We thank Jannes Fröhlich and Dr. Hans-Ulrich Rösner from the WWF Wadden Sea office for support. D. Schulze was partly funded by the DFG project ‘WAMM’ (NO 1256/1-1) in the framework of the priority program ‘SPP 1889 - Regional Sea Level Change and Society’. We thank Björn Marten Phillips and the *Schutzstation Wattenmeer* for hospitality in their field station and field work support. Furthermore, we are grateful to the inhabitants of Langeness for allowing us to conduct our study on their marshes. The manuscript profited from the thoughtful and constructive anonymous reviews.

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Highlights:

1. Accretion rates on a Wadden Sea marsh island cannot keep pace with rising sea level
2. Ungrazed plots showed significantly higher sediment deposition and accretion rates
3. Suspended sediment concentration was higher under grazing treatment
4. Natural marsh vegetation is thought to have a considerable sediment trapping effect
5. Accretion rates can be improved by abandonment of grazing

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: