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RESEARCH ARTICLE

Using salt marshes for coastal protection: Effective but hard to get where needed most

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Abstract

1. Salt marshes fronting coastal structures, such as seawalls and dikes, may offer important ecosystem-based coastal defence by reducing the wave loading and run-up levels during storms. We question (i) how the long-term salt marsh development in the Dutch Wadden Sea relates to the tidal-flat foreshore bathymetry and (ii) how the wave run-up onto dikes, which enhances the risk of dike failure, depends on foreshore bathymetry, the presence/absence of marshes, marsh vegetation properties, tidal range and wind exposure.
2. We analysed 15 years of vegetation and bathymetry maps along the entire Dutch Wadden Sea coast, in combination with detailed process-based measurements at five locations during 3 years, to understand where salt marshes naturally form and what features determine their contribution to coastal protection.
3. The horizontal extent of marshes along the dikes remained relatively stable over the past decade. The presence of marshes was associated with higher elevations of adjacent tidal flats (above ~0.5 m NAP), while landward-directed marsh retreat was associated with surface erosion of the fronting tidal flats.
4. Wave run-up during storms was lower at sites with wider marshes and higher foreshore elevations. This was attributed to the marsh attenuation effect, which led to a reduction in wave heights at the dike toe. As the tidal range varies across the Dutch Wadden Sea, areas to the East with generally higher water levels experienced higher wave run-up.
5. *Synthesis and applications*. We found that (i) marshes, where present, effectively protected the dikes from wave loading and (ii) the sites where marshes typically do not develop spontaneously were the most vulnerable to high wave run-up.

This catch-22 problem implies that increasing reliance on nature-based coastal defences along soft-bottom coasts may require human interventions to stimulate marsh formation at the locations where it is most needed. Alternatively, 'hard engineering' solutions may remain necessary where implementing nature-based solutions are either too costly, unachievable, or at the expense of other ecological values, such as causing the loss of mudflats that are important for migratory birds.

KEYWORDS

beach wrack, flotsam, grazing, nature-based coastal protection, overtopping, sediment dynamics, wave attenuation, wind exposure

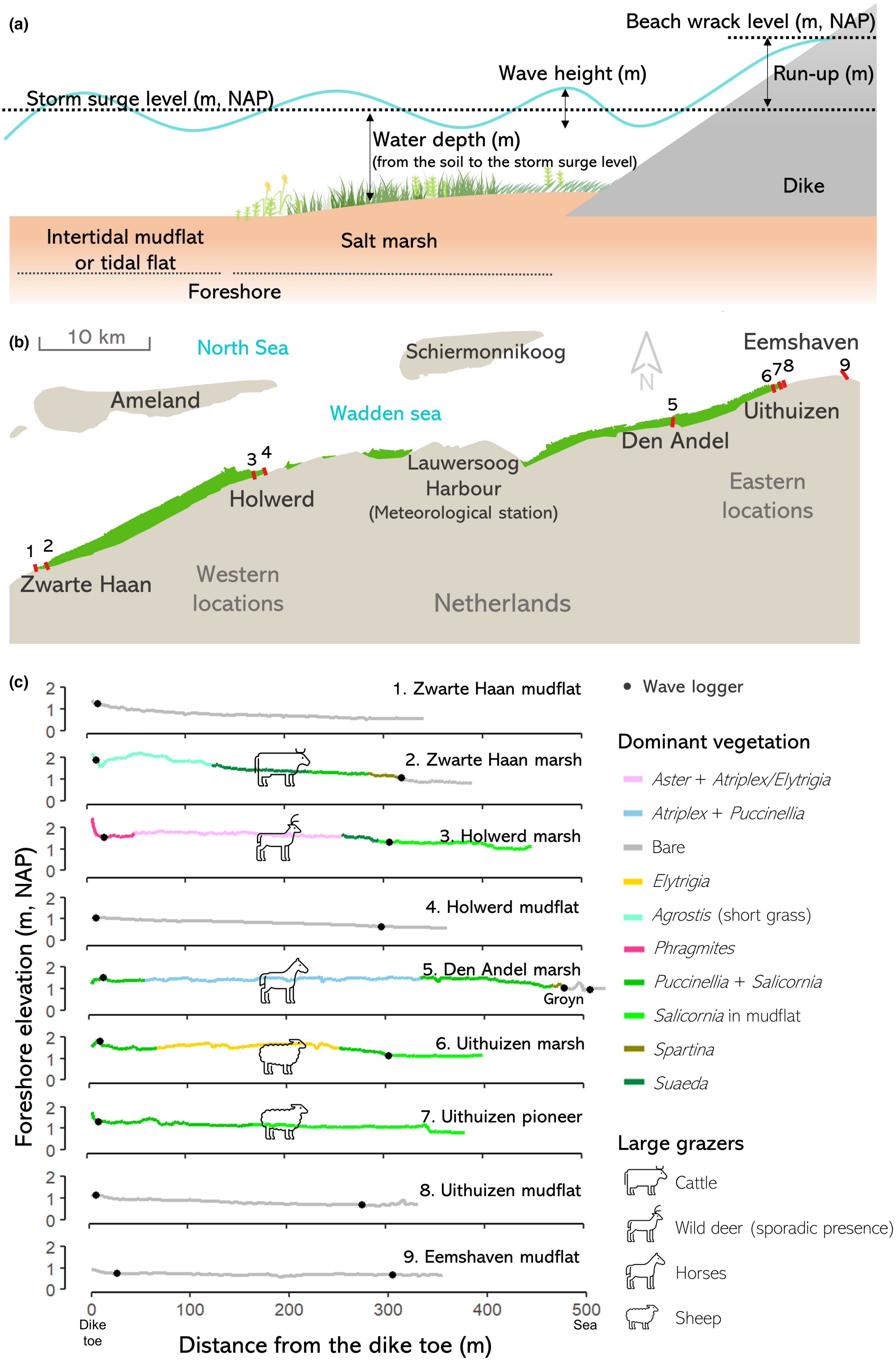
1 | INTRODUCTION

Salt marshes provide valuable ecosystem services such as carbon sequestration, water purification and coastal protection (Barbier et al., 2011; Duarte et al., 2013; Shepard et al., 2011). The combination of these natural ecosystems with hard engineering like seawalls or dikes for the purpose of coastal protection is known as ecosystem-based coastal defence (Figure 1a). Considering the projected rise in sea level and increase in storm intensity (IPCC, 2014; Morris et al., 2020), ecosystem-based coastal defence may offer a more sustainable and cost-effective solution to ensuring coastal safety, compared to hard engineering alone (Schoonees et al., 2019; Temmerman et al., 2013; Vuik et al., 2019). However, the implementation of these solutions requires an in-depth understanding of (i) where salt marshes can be established, based on environmental characteristics; and (ii) how effective salt marshes are in reducing the uprush of water onto the dike due to storm waves, referred to as wave run-up.

The applicability of marshes for ecosystem-based coastal defence strongly depends on their effectivity in attenuating waves. Dike overtopping, where wave run-up reaches and passes over the dike crest, forms a major flood-safety risk, as it may induce sea-wall breaching by eroding the back of the dike (Schüttrumpf & Oumeraci, 2005; Zhu et al., 2020). Hence, the seawall or dike height is typically designed to resist high water levels during a storm surge and the corresponding wave run-up height or overtopping volume (EurOtop, 2018; Lashley, Jonkman, et al., 2021). Elevated foreshores fronting a dike will reduce the water depth so that large incident waves will be depth limited and forced to break (Bouma et al., 2014). The wave shoaling and breaking induced by shallow foreshores leads to several nearshore processes, including a rise in mean water level, known as wave setup and the growth of long-period infragravity waves, also known as 'surfbeat' (Keimer et al., 2021; Lashley, Jonkman, et al., 2021; Lashley, van der Meer, et al., 2021). Lashley, Jonkman, et al. (2021) and Lashley, van der Meer, et al. (2021) examined these effects in detail and concluded that shallow foreshores have a net positive effect on coastal safety by reducing the extent to which waves run-up and overtop the structure behind them. Salt marshes will be more effective in wave attenuation compared to bare tidal flats as a result of having a higher and more stable bathymetric elevation, combined with imposing vegetation friction to the orbital water motion (e.g. Bouma et al., 2014; Leonardi et al., 2018; Möller et al., 2014; Vuik et al., 2016). The magnitude of vegetation friction may vary depending on the species, seasonality and grazing, as it depends on vegetation characteristics such as plant height, biomass, structural complexity (leaves or branches complexity), stem density and stiffness (Bouma et al., 2005, 2010; Maza et al., 2022; Möller, 2006; Ysebaert et al., 2011). Locations with higher storm surge levels may be expected to attenuate less waves during storms, ultimately resulting in higher wave run-up (Keimer et al., 2021). Finally, locations that are directly exposed to the wind direction of a storm are likely to experience higher waves (Vuik et al., 2016). Hence, it would be logical to expect higher wave run-up at wind-exposed than at more sheltered locations.

The applicability of marshes for ecosystem-based coastal defence also strongly depends on where the marshes can develop. Marsh presence depends on the soil elevation relative to the mean sea level (Balke et al., 2016), the sediment supply (Fagherazzi et al., 2020; Ladd et al., 2019; Liu et al., 2021) and the local wind exposure (Wang et al., 2017). Bed-level change and inundation period will drive the marsh edge location: at lower elevations with longer inundation periods, a more stable bed will be needed to preserve seedlings (Bouma et al., 2016; Willemsen et al., 2017). As wind-driven waves can cause sediment dynamics, they may impede seedling establishment, causing marshes to be restricted to higher elevations at exposed locations and sometimes even causing cliff formation and retreat (Bouma et al., 2014, 2016; Wang et al., 2017). Despite the growing understanding of marsh establishment, we lack quantitative landscape-scale analyses relating the long-term marsh

FIGURE 1 (a) Illustration of the terms utilized in this study. (b) Location of the study sites. Red lines indicate the transects with wave loggers. (c) Elevation profiles of the transects with wave loggers, including the dominant vegetation and grazing. The wave logger transect at Den Andel was longer because of the marsh width. Marsh plateau edge was considered as the limit of the dense pioneer vegetation (*Spartina* or dense *Salicornia* with *Puccinellia*).


(a)
Beach wrack level (m, NAP)
Wave height (m)
Run-up (m)
Storm surge level (m, NAP)
Water depth (m)
(from the soil to the storm surge level)
Dike
Intertidal mudflat
or tidal flat
Salt marsh
Foreshore
(b)
10 km
North Sea
Schiermonnikoog
N
Eemshaven
Ameland
Wadden sea
Uithuizen
Den Andel
Lauwersoog
Harbour
(Meteorological station)
Holwerd
Eastern
locations
Zwarte Haan
Western
locations
Netherlands
(c)
1. Zwarte Haan mudflat
2. Zwarte Haan marsh
3. Holwerd marsh
4. Holwerd mudflat
5. Den Andel marsh
Groyn
6. Uithuizen marsh
7. Uithuizen pioneer
8. Uithuizen mudflat
9. Eemshaven mudflat
Foreshore elevation (m, NAP)
0
Dike
toe
100
200
300
400
500
Sea
Distance from the dike toe (m)
Wave logger
Dominant vegetation
Aster + Atriplex/Elytrigia
Atriplex + Puccinellia
Bare
Elytrigia
Agrostis (short grass)
Phragmites
Puccinellia + Salicornia
Salicornia in mudflat
Spartina
Suaeda
Large grazers
Cattle
Wild deer (sporadic presence)
Horses
Sheep

occurrence at the regional scale to the long-term morphological development of bare foreshores.

Currently, we lack measurements on how wave run-up varies at the regional scale, due to variation in foreshore properties such as bathymetry, vegetation characteristics, tidal range and wind exposure. To our knowledge, most work is modelled (e.g. Vuik et al., 2016), tested in wave flumes using artificial vegetation (Keimer et al., 2021), or applied to beaches (e.g. Didier et al., 2020; Polidoro, 2014). Field measurements regarding the effects of marsh foreshores on wave run-up also remain scarce not making it possible to perform regional-scale analyses (Spencer et al., 2015; Zhu et al., 2020). Moreover, run-up measurements have not been related to the ability of marshes to establish across locations. To deepen our insight in the applicability of marshes for ecosystem-based coastal defence, we investigated at the regional scale (i) how the long-term salt marsh development in the Dutch Wadden Sea relates to the tidal-flat foreshore bathymetry and (ii) how the wave run-up onto dikes depends on foreshore bathymetry, the presence/absence of marshes, marsh vegetation properties, tidal range and wind exposure.

2 | MATERIALS AND METHODS

2.1 | Description of the field location: Dutch Wadden Sea coast

The Wadden Sea is a large intertidal area sheltered by barrier islands (Reise et al., 2010). Our study focuses on the stretch of mainland coast between Harlingen (53°10′46.2″N, 5°24′34.3″E) and Eemshaven (53°27′53.1″N 6°45′33.7″E), in the Netherlands (Figure 2a). This area is micro to meso-tidal (RWS, 2013). The mainland coast is protected against flooding by dikes of 8–10 m high and slope at an average gradient of ~1:4 at the seaward side (van Loon-Steensma et al., 2014). After the construction of the 'Afsluitdijk' (a dike closing off the Zuider Zee from the Wadden Sea) in the 1930s and the 'Lauwersmeerdijk' (a dike closing off Lauwerszee) in 1969, changes in the currents and bathymetry of the Dutch Wadden Sea led to the current distribution of tidal flats and marshes (De Jonge et al., 1993). Marshes are currently present in some areas along the dike as a result of accretion works aimed at land reclamation (Text S1).

2.2 | Tidal flat and marsh decadal development (GIS analysis)

Marsh development was investigated using contour lines at 1 m NAP (i.e. Dutch ordinance level, similar to mean sea level) extracted from two sets of intertidal elevation maps of the study area: for 2004 (5 m resolution) and 2012–2017 (2 m resolution) (Source: Rijkswaterstaat, The Dutch Ministry of Infrastructure and Water Management) with QGIS. Contour lines at 1 m NAP corresponded to the pioneer marsh edge (excluding pre-pioneer vegetation), which was contrasted with vegetation polygon maps from 2002 and 2014 obtained from Rijkswaterstaat, respectively. Contour lines, rather than polygon maps, were used for the analysis because it was a more objective representation of the marsh edge in addition to being related to the bathymetry of the area. Contour lines at 0.5 m NAP (hereafter called 'upper tidal flat') and 0 m NAP were obtained to visualize the location of the most elevated tidal flats in relation to the marsh presence. Changes in marsh width between the two sets of intertidal elevation maps (2004 and 2012/2017) were related to the changes in width and elevation of the upper tidal flat in front. Marsh width from the dike toe to the intersection with the 1 m NAP marsh contour was calculated for the two time steps (2004 and 2012/2017) drawing transects perpendicular to the dike with spacing of 500 m using the Digital Shoreline Analysis System from ArcGIS (Himmelstoss et al., 2018). Width change of the upper tidal flat in front of the marshes was obtained with the same procedure but from the marsh contour of 2004 to the contour lines at 0.5 m NAP of both time steps. Changes in elevation of the tidal flats fronting the marsh were obtained by subtracting the intertidal elevation maps from both time steps using the package 'raster calculator' from QGIS. The mean of the accretion/erosion values of the first 100 m of each transect perpendicular to the dike was used as a value of tidal flat elevation change.

2.3 | Wave run-up monitoring locations (field study)

Five locations, with different large grazers present, were selected along the Dutch Wadden Sea dikes to be monitored over 3 years (2018–2020), including the tidal flat of Eemshaven (53°27′53.1″N 6°45′33.7″E), the interface marsh-mudflat from Uithuizen (53°27′26.8″N 6°40′14.0″E), the marsh from Den Andel (53°25′36.1″N 6°30′53.7″E), the interface marsh-mudflat from Holwerd (53°23′18.9″N 5°56′05.9″E) and Zwarte Haan (53°18′44.8″N 5°37′34.0″E) (Figure 1b). Eemshaven, Uithuizen and Den Andel, the easternmost locations, have higher tidal ranges and higher mean high water levels compared to the western locations (i.e. Holwerd and Zwarte Haan) (RWS, 2013; Wang et al., 2018) (Figure 2a). All locations, except Zwarte Haan, were framed by brushwood groynes of ~0.5 m high. Field work was carried out under the permission from the Province of Friesland (01614250), It Fryske Gea (BIG/2018/6245), Staatsbosbeheer and Natuurmonumenten.

2.4 | Waves and water depth measurements

Transects of wave loggers were installed in all the locations to measure the water levels and wave heights (Figure 1b). To calculate the total wave attenuation of the foreshore for each transect, one wave logger (OSSI-10-003C) was deployed at 10 cm above the ground next to the dike and one at the marsh edge or equivalent distance on the mudflat transects (~300 m) (Figure 1c,d). The wave loggers were deployed from December 2018 in Eemshaven, Uithuizen and Den Andel, and from November 2019 in Holwerd and Zwarte Haan (Table 1; Table S1). Additional significant wave height data from

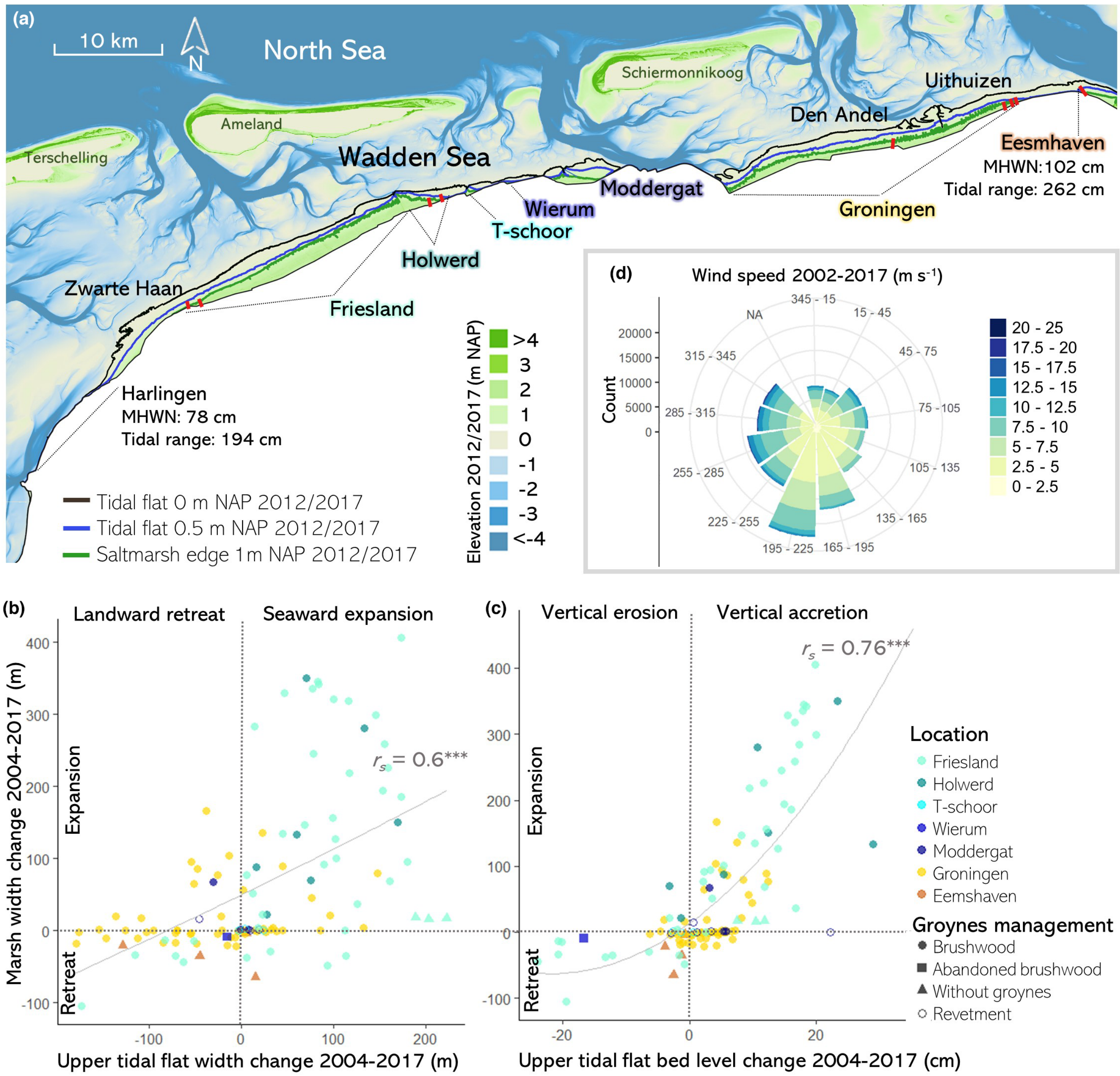


FIGURE 2 (a) Dutch Wadden Sea elevation map with contour lines at 0, 0.5 (upper tidal flat) and 1 (marsh edge) m NAP. Red lines indicate the transects with wave loggers, colours in the text relate to panels (b) and (c). (b) Relationship between marsh expansion and upper tidal flat seaward expansion/landward retreat. (c) Relationship between marsh expansion and change in vertical elevation of the upper tidal flat. Symbols indicate the type of groynes management present. Significant codes refer to $p < 0.001$ (***). (d) Wind speed and wind direction during 2002 until 2017.

more offshore were obtained from Rijkswaterstaat at six stations in the Wadden Sea (Figure S1). In this paper, we focused on a subset of 9 tides with high water that inundated all the sensors, most of them occurring during winter (December–February), but with some in spring (April) and autumn (September) (Table 1).

Mean water depth and significant wave height were calculated for each sensor as described in the script in Marin-Diaz, Fivash, et al. (2021). Values of significant wave height and mean water depth during the hour with higher water levels for each storm surge were averaged and used as reference values for the analysis. Wave attenuation by the foreshore was calculated as the percentage of significant wave height reduction between the sensor in the marsh edge or equivalent distance in the tidal flats and the sensor in front of the dike.

2.5 | Beach wrack levels and wave run-up monitoring

The wave-attenuating capacity of foreshores can be derived from measuring the maximum height where storm waves deposit

Date	Wind direction (degrees)	Wind speed (m/s)	Storm surge level (m NAP)	
			West	East
8 January 2019—tide 1	320	18	NA	3.0 ± 0.05
8 January 2019—tide 2	340	16	NA	2.2 ± 0.06
30 September 2019	300	13	NA	2.2 ± 0.03
9 December 2020	330	13	2.0 ± 0.06	2.2 ± 0.06
14 January 2020	210	14	2.0 ± 0.03	2.2 ± 0.06
11 February 2020	270	17	2.6 ± 0.02	2.8 ± 0.03
12 February 2020	270	15	2.0 ± 0.00	2.2 ± 0.02
20 November 2020	320	12	1.9 ± 0.03	2.0 ± 0.02
1 December 2020	10	12	1.8 ± 0.04	1.8 ± 0.03
5 April 2021	300	15	NA	NA

TABLE 1 Summary of the beach wrack measurement dates and the mean wind direction, hourly wind speed and mean storm surge levels, obtained from the deployed wave loggers and averaged for the East (Eemshaven, Uithuizen and Den Andel) and West (Holwerd and Zwarte Haan), during the highest water level. NA = no sensors deployed. In bold, the two biggest storms measured.

debris/beach wrack on a dike (Spencer et al., 2015; Zhu et al., 2020) (Figure 1a). Beach wrack lines on the dike were measured for 10 tides with an rtk-DGPS (Leica GS12) every ~30 m along 1–3 km in each location (Table 1). Beach wrack reached onto the dike behind the marsh zones only on 8 January 2019 and 11 February 2020. The actual wave run-up was calculated by subtracting the water level measured by the wave loggers at each location from the beach wrack level measured in the field.

2.6 | Monitoring of vegetation properties

Vegetation cover, height, biomass, density and structures (leaves and branches) from the most dominant vegetation along the wave logger transects (Figure 1c) were monitored in September and November 2019; February, March, August and December 2020 and February 2021. For each vegetation zone, the percentage of ground covered by vegetation was visually assessed and overall vegetation height was measured with a ruler in 6 replicates. For September and November 2019 and February and March 2020, stem density was counted from three 20 × 20 cm plots collected in each vegetation zone. For a subset of 10–20 stems per plot, the stem and diameter from the dominant species were measured in the laboratory. From a subset of 2–5 stems per plot, the structures (leaves or branches) were measured as in Bouma et al. (2005). Samples were then dried at 60 degrees until constant weight to obtain the dry biomass. In winter, vegetation measurements represent only the vegetation in the standing tussocks; therefore, the general ground cover should be taken into account.

2.7 | Foreshore elevation characterization and seasonal monitoring

Soil elevation profiles perpendicular to the dike with 2 m resolution and 100 m spacing along the dike were obtained from the newest intertidal elevation maps to date (2017–2019) (source: Rijkswaterstaat) using QGIS. From each of these profiles, (i) the elevation at 400 m from the dike was obtained as a measure of the 'offshore elevation' and (ii) the average elevation between 40 m (to avoid the ditches) until 100 m in front of the dike was obtained as a measure of the 'elevation in front of the dike'. These elevation values were used in the statistical analysis to relate to the correspondent beach wrack on the dike. In addition, seasonal elevation changes in the field were monitored with an rtk-DGPS (Leica GS12) every ~10 m along the wave logger transects to determine the stability of the marshes compared to the mudflats. Variability in elevation change was calculated as the standard deviation of the elevation for each transect.

2.8 | Calculation of wind exposure and fetch

Wind direction and wind speed during the selected storms were obtained from the Royal Dutch Meteorological Institute (KNMI), recorded in the weather station of Lauwersoog (Figure 1b). In this study, fetch was considered as the distance over the intertidal area from a specific location of the dike to the system of Wadden barrier islands for a specific wind direction. Fetch for each beach wrack point and for every storm was calculated with the WAVER package from R (Marchand & Gill, 2018). The inputs used were the wind direction during the peak of each storm surge level, a shapefile with the locations along the dike where the beach wrack was measured and a shapefile with the foreshore and barrier islands obtained from the European Environment Agency. Relative exposure (RE) was calculated as the fetch multiplied by the wind speed.

2.9 | Statistical analysis

One-way ANOVA followed by Tukey HSD post-hoc test was used to test differences between transects in variability of soil elevation (measured in the field). Spearman correlations were used to analyse the relationships between mean water depth and significant wave heights. Pearson correlations were used to analyse the relationships between significant wave height and wave run-up. The relationship between run-up and beach wrack levels was determined with a multiple linear regression including the storm date as independent variable. Differences in beach wrack levels, run-up, storm surge water level and wave heights among each wave logger transect were tested with linear mixed models (LMM) with date as random factor followed by post-hoc Tukey HSD tests. Beach wrack levels could be compared including dates without wave loggers because water level from the wave sensors was not needed for the calculation, in contrast to the run-up calculation (Table 1). LMM with the date as random factor were used to investigate the effects of marsh width, foreshore elevation, offshore elevation, storm surge level, RE and fetch on the response variables beach wrack levels and run-up. Vegetation was represented by marsh width in the models. First, a simple model for each explanatory variable was run to obtain the effect of isolated variables. Secondly, collinearity between variables was tested with variance inflation factors (VIF) (Zuur et al., 2010). We dropped RE, which was correlated to Fetch (VIF > 3). Third, the most parsimonious model explaining run-up and beach wrack levels was selected based on stepwise regression and the lowest Akaike's information criterion. Interactions were not included because their relative importance (chi-square values) was small compared to the main effects (Table S2). Finally, we explored how these variables affected the water level and wave height, which were the underlying variables explaining most of the run-up and beach wrack levels, again using LMM with random date. Values with zero run-up were excluded from the analysis. Significance of the fixed effects was tested using the Type II Wald chi-square tests. Marginal and conditional R^2 of the LMM were obtained with the package SJSTATS from R. Normality and homogeneity were checked with residuals plots, and data were log transformed when necessary to comply with the assumptions. Statistical analyses were performed using R 3.5.0 (R Development Core Team, 2018).

3 | RESULTS

3.1 | Distribution and decadal development of marshes and tidal flats (GIS analysis)

Salt marshes were only present in areas with elevated tidal flats in front of the marsh (>0.5 m NAP), hereafter called 'upper tidal flats', and strongly related to human interventions (groynes/sedimentation fields) (Figure 2a; Figure S2). Salt marsh extension along the dike has remained stable over the past decade (Figure 2a; Figure S2). Most of the marsh landward erosion occurred in the western area (up to −100 m retreat in 13 years) which includes the location 'Zwarte Haan' (Figure 2b,c; Figure S2), also confirmed by field observations (Figure S3). Overall, marsh landward retreat was related to erosion or retreat of the upper tidal flats fronting the marsh (Figure 2b,c). Vice versa, offshore marsh expansion was related to the accretion and expansion of the upper tidal flats fronting the marsh. Expansion was up to 300–400 m in the western area including Holwerd (in 8 years) and Zwarte Haan (in 13 years) and up to 200 m in 10 years in Groningen (east).

3.2 | Seasonal variability of foreshore characteristics monitored in the field: Bathymetry and vegetation

The variability in elevation during the 3-year monitoring period was higher in the bare tidal flats than in the marshes, which remained mostly stable (the average standard deviation in tidal flat transects was 3.1 cm while in marsh transects was 1.5 cm) (ANOVA: $F_{8,90} = 7.5$, $p < 0.001$) (Figure S4). The pioneer marsh in this area was confirmed by vegetation dominated by *Spartina*, *Salicornia* and/or *Puccinellia*. The marsh plateau edge was considered as the limit of the dense pioneer vegetation (*Spartina* or dense *Salicornia* mixed with *Puccinellia*) (Figure 1c). The tallest vegetation (i.e. *Phragmites* and *Aster*) was found in Holwerd marsh throughout all the seasons, which was the only location not grazed by livestock, but where non-domesticated grazers like deer occur occasionally (Figures 1c and 3a). Zwarte Haan, Den Andel and Uithuizen marshes were grazed by cows, horses and sheep respectively and had shorter vegetation throughout the year (Figures 1c and 3a). Grazer footprints could be seen along the marsh plateau but were more abundant close to the dike. Uithuizen pioneer marsh was narrower than the other marsh transects, grazed by sheep and only composed of pioneer vegetation (Figure 1c). The vegetation height, ground cover and biomass declined during winter in all the locations (Figure 3). Shoot density declined in all species except for of *Atriplex* and *Spartina*, which lost the flowering stems but not the basal stems (Figure 3). Vegetation structures (leaves and branches) declined during winter, even when the total height had not significantly varied (e.g. in *Phragmites*) (Figure S5).

3.3 | Wave run-up, beach wrack levels and their relationship with water level and wave height

Wave run-up on the dikes was strongly correlated to measured beach wrack levels (MLR: $R^2 = 0.99$, $p < 0.001$). Therefore, locations with higher run-up also had higher beach wrack levels. However, for the same run-up values, eastern locations had ~20 cm higher beach wrack levels than western locations independently of the wind direction and speed. This could be attributed to the higher storm surge levels found in the east compared to the west (LMM: $X^2 = 192.03$, $p < 0.001$) (Table 1; Figure 5a). It should be noted that Lashley, Jonkman, et al. (2021) investigated the influence of non-linear wave interactions in the form of infragravity waves, also referred to as dynamic wave setup across the Dutch Wadden sea, and while there is some influence, it was found to be more prominent in the west than in the east.

Given the differences in storms surge levels between western and eastern locations, beach wrack and run-up were always higher at dikes fronted directly by mudflats, compared to dikes fronted by marshes (LMM beach wrack: $X^2 = 397.12$, $p < 0.001$, run-up: $X^2 = 155.6$, $p < 0.001$) (Figure 4c,d). Wave run-up on the dike increased with higher waves measured at the dike toe (Figure 5a). Higher waves at the dike toe were observed with increasing water

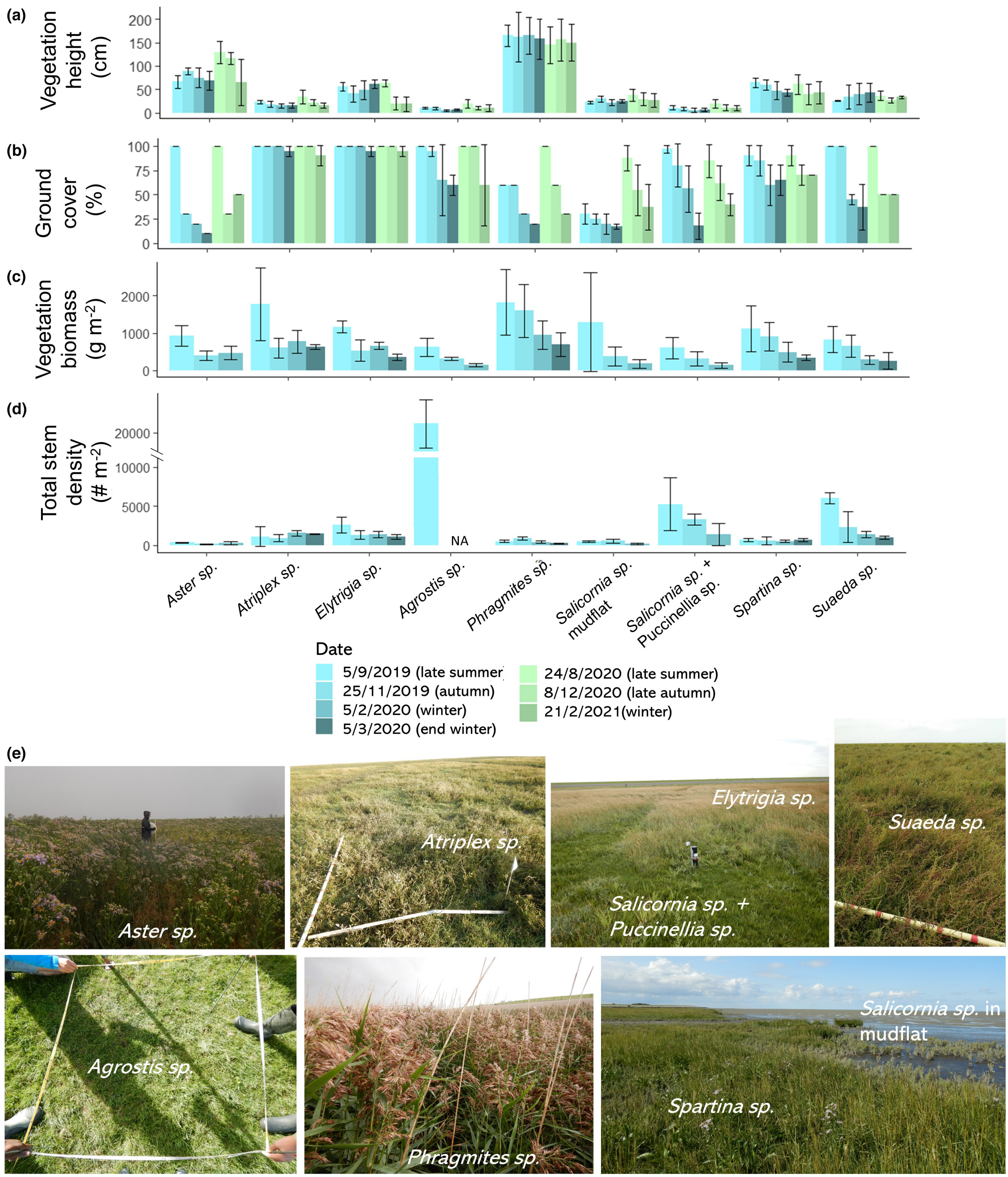


FIGURE 3 Seasonal changes in (a) vegetation height, (b) vegetation ground cover, (c) vegetation biomass and (d) total stem density; for the dominant vegetation species. Error bars represent standard deviations. Averages are not separated by location but by species. (e) Dominant vegetation species in summer state.

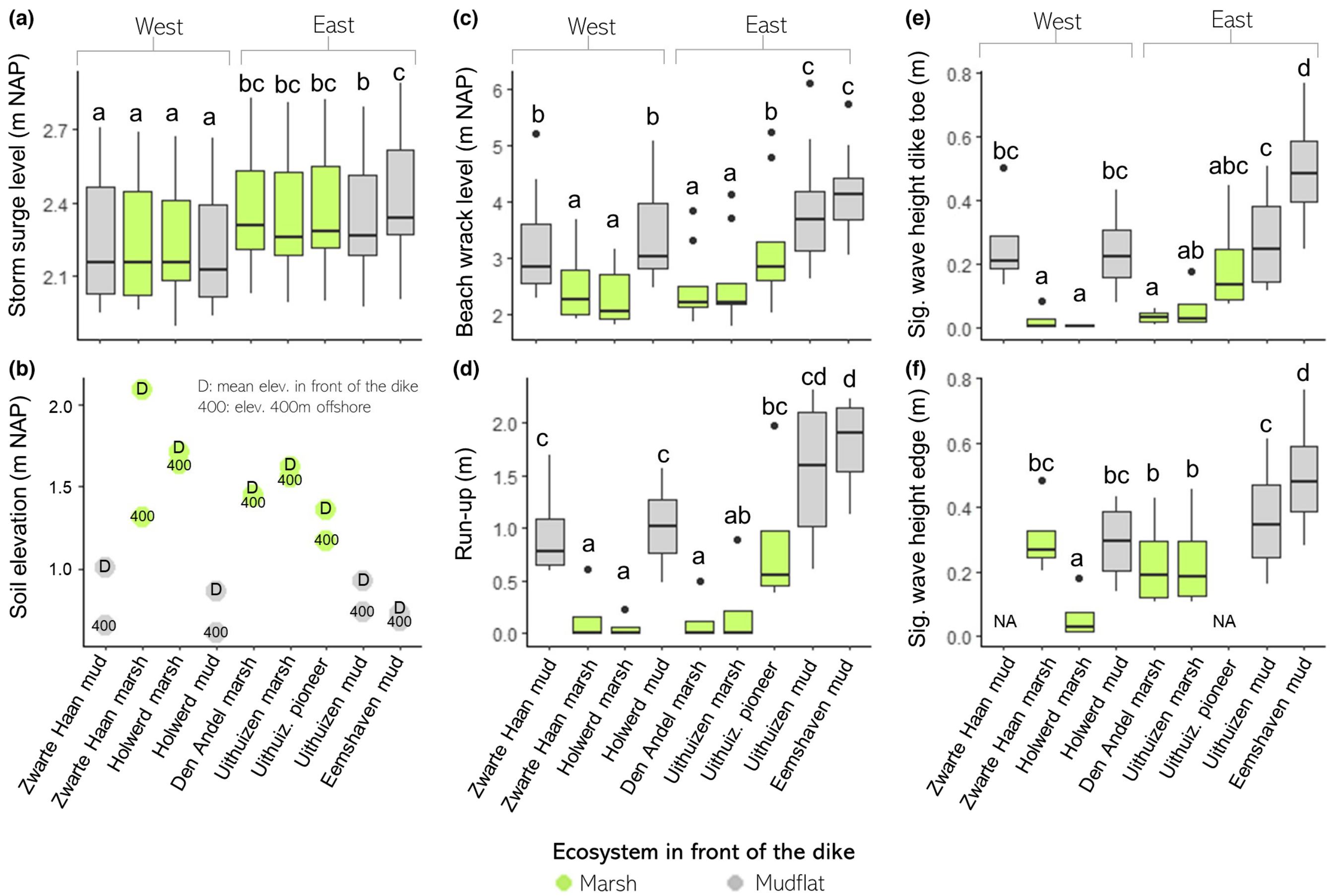


FIGURE 4 Differences among marsh (green) and mudflat (grey) transects with wave loggers for (a) storm surge water levels; (b) soil elevation in front of the dike and at 400 m from the dike; (c) beach wrack levels on the dike; (d) run-up on the dike; (e) significant wave height at the dike toe and (f) significant wave height at the marsh/mudflat edge (300 m offshore except for Den Andel at 400 m). Note that sensors were not present in the mudflat of Zwarte Haan edge and Uithuizen pioneer edge. Significant differences are indicated by letters (Tukey HSD, $p < 0.001$). Beach wrack levels could be compared including more storms dates because water level from the wave sensors was not needed for the calculation like in the run-up (Table 1).

depths (i.e. with high storm surge levels and in locations with lower elevations) (Figures 4b,e and 5b).

Waves from the more offshore Rijkswaterstaat stations were similar along the coast except for slightly higher waves occurring further offshore of Eemshaven, at Oude Westereems (Figure S1). Closer to the dike in Eemshaven, at Uithuizerwad, the waves were already comparable to the eastern stations (Figure S1). We argue that for the storms considered, the attenuation occurring over the foreshore played a larger role than the differences in the more offshore wave conditions. Differences of water level and wave heights between different storms were explained by astronomical tides and wind (Figure S6).

3.4 | Processes controlling spatial variability of wave run-up and beach wrack: Field measurements

Variability on beach wrack levels and run-up between locations was best explained by the bathymetric elevation in front of the dike, the marsh plateau width and the storm surge level, with the latter accounting for the differences of tidal range between locations in the west and east (Table S3; Figures 4 and 6; model: $mR^2=0.78$, $cR^2=0.9$ and $mR^2=0.66$, $cR^2=0.85$ respectively). Higher foreshore elevations combined with wider marshes were related to lower water depths and therefore lower wave heights (LMM: $X^2(1)=154$, $p<0.001$ and $X^2(1)=131$, $p<0.001$ respectively), which explains the lower run-up and beach wracks (Figure 5). Furthermore, run-up was near zero at the marshes during storms with water levels <2.5 m NAP (around 0.5 m water depth over the marsh soil), due to stronger wave attenuation related to the depth limitation (Figure 5). Surprisingly, neither wind exposure measured as fetch (m), nor RE related to the barrier islands could explain the observed differences in beach wrack and wave run-up between locations (Table S3). Although incoming waves with western wind directions, such as during the storm of 11 February 2020, were higher in Zwarte Haan and lower in Holwerd (which was sheltered by a harbour) (Figure S7), the determining effects of bathymetry and differences in storm surge levels overruled wind exposure effects.

Wave attenuation decreased with higher storm surge levels (Tables 1 and 2; Figure S7). Given the differences in incoming waves

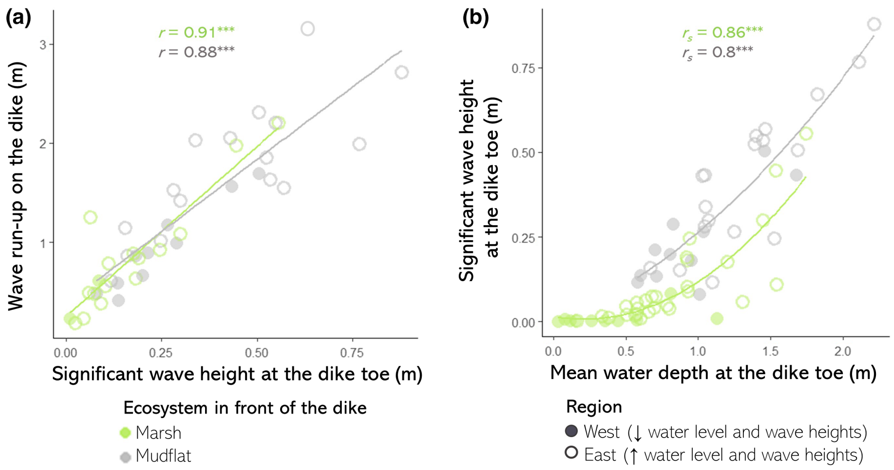


FIGURE 5 Relationships between (a) significant wave height and wave run-up on the dike, separated by salt marshes (green) and bare tidal flats (grey), excluding points with zero run-up, which occurred in cases where the waves where completely attenuated and (b) mean water depth and significant wave height including all the storm dates with wave run-up measured. Significant codes refer to $p < 0.001$ (***).

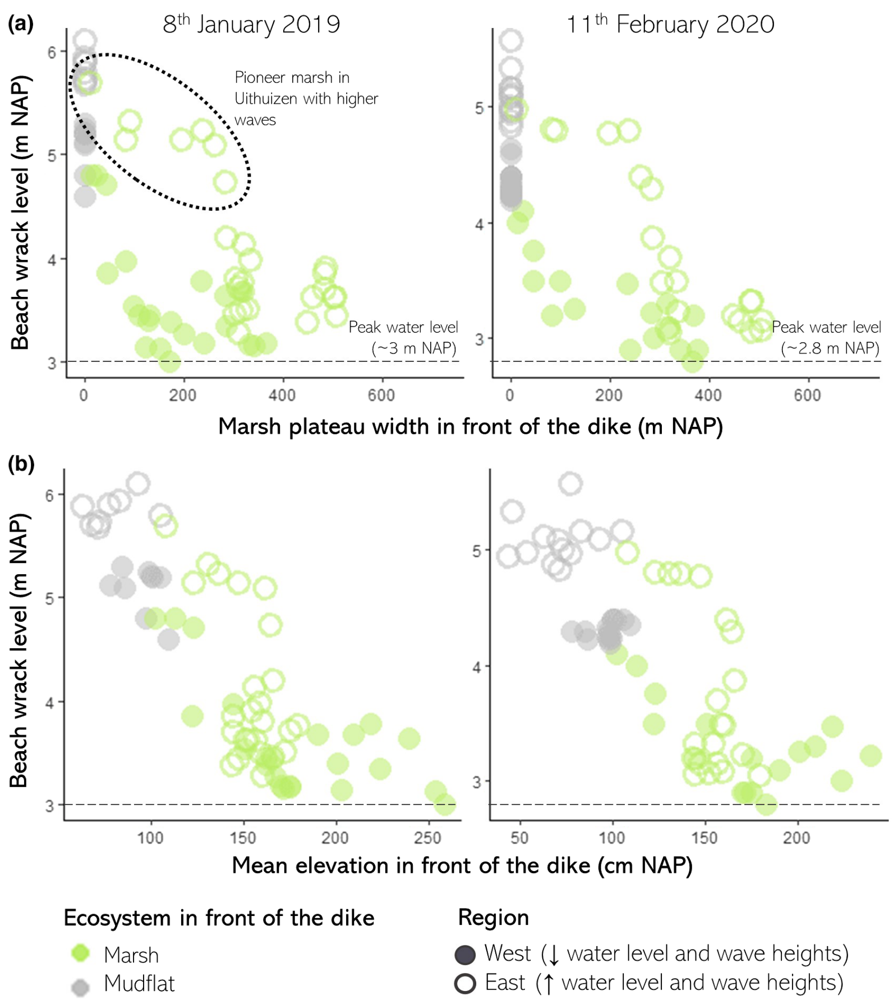


FIGURE 6 Relationships between beach wrack levels during the two biggest storms measured and (a) soil elevation in front of the dike and (b) marsh plateau width. Run-up is not shown because wave loggers were missing in the west during in January, and therefore could not be calculated. However, beach wrack and run-up were closely correlated (MLR: $R^2 = 0.99$, $p < 0.001$). Peak water level refers to the east region and was ~20 cm lower in the west.

between locations (Figure 4f) and storm surge levels, mudflats attenuated the waves to a lesser extent when compared to marshes, even if the marshes had short vegetation due to seasonality or grazing (Table 2; Figure 4e; Figure S7). Within marshes, greater wave attenuation in Den Andel could be attributed to the wider marsh while in Zwarte Haan to the higher elevation and lower storm surge levels compared to Uithuizen (Table 2; Figures 1c and 4a; Figure S7). In the marsh of Holwerd, the waves were always completely attenuated, related to smaller incoming waves due to higher fronting tidal flats and lower storm surge levels (Table 2; Figure 4b,f; Figure S7). The higher run-up in the pioneer marsh of Uithuizen, compared to other locations with the same marsh width, were attributed to higher waves reaching the dike due to a lower foreshore both offshore and at the dike toe (Figures 1c and 4b).

TABLE 2 Wave attenuation during the 2 biggest storms and average wave attenuation for all 9 storms measured. Elevation in front of the dike and surge levels for the 2 storms are shown as a reference of the inundation level at each location.

		Wave attenuation (%)		
Location	Elevation in front of the dike (m NAP)	Storm on 8 January 2019—tide 1 (storm surge level ~3 m NAP)	Storm on 11 February 2020 (storm surge level ~2.6 west—2.8 east m NAP)	Average from all storms measured (±SD)
Eeemshaven mudflat	0.6	−0.4	−0.5	−0.05 ± 8.13 (n = 9)
Uithuizen mudflat	0.9	15.1	17.24	22.7 ± 8.8 (n = 9)
Uithuizen marsh	1.5	50.0	61.41	77.4 ± 13.7 (n = 9)
Den Andel marsh	1.4	80.6	86.1	84.9 ± 3.2 (n = 9)
Holwerd mudflat	0.8	NA	0.2	16.8 ± 17.1 (n = 6)
Holwerd marsh	1.7	NA	94.66	87.3 ± 8.2 (n = 6)
Zwarte Haan marsh	2.1	NA	82.79	95.6 ± 7.2 (n = 6)

In summary, a marsh of ~300 m width and more than 1.5 m elevation, effectively mitigated against wave run-up during the measured medium-intensity storms—with little to no wave run-up observed in some cases (Figure S8), where the beach wrack level was approximately the same as the storm-surge water level. At marshes with higher elevations (i.e. Zwarte Haan, >2 m NAP), or with lower incoming waves as a result of the presence of wider elevated tidal flats in front of the marsh (i.e. Holwerd), even a narrow width of ~100 m attenuated the run-up. On the other hand, the combination of narrow pioneer marshes (<300 m) with low elevation (<1.5 m NAP) and high incoming waves (i.e. Uithuizen pioneer marsh) was not as effective.

4 | DISCUSSION

This study shows that salt marshes can protect the dikes independently of the vegetation species, the seasonal state of the vegetation, grazing management and wind exposure. This could simplify the considerations needed to include salt marshes and adjacent tidal flats into nature-based coastal protection schemes. Furthermore, the presence and expansion of a marsh was found to be related to the presence of elevated and accreting tidal flats, highlighting the importance of the management of ecosystems fronting the marshes for coastal protection. Including these ecosystems would not only benefit coastal protection, but it would provide other ecosystem services such as carbon sequestration, fisheries support and water purification (Barbier et al., 2011; Duarte et al., 2013; Temmink et al., 2022).

4.1 | Salt marsh development related to sediment dynamics

Our study shows that marsh presence along the Wadden Sea dikes is related to areas with elevated tidal flats (above 0.5 m NAP) which depends on where sediment is transported and deposited by the tides, waves and currents (Schuerch et al., 2014; Wang et al., 2018). Furthermore, the results show a relationship between the fronting tidal flat accretion both vertically and in width, and the marsh offshore expansion. While higher tidal flats will attenuate more waves reaching the marsh edge, promoting marsh expansion; lower and narrower tidal flats can lead to higher wave exposure of the marsh edge and therefore to more marsh erosion (Callaghan et al., 2010; Hu et al., 2015; Leonardi et al., 2018). Higher exposure on the marsh edge can also lead to a reduction in seedling establishment opportunities due to increased sediment dynamics (Bouma et al., 2016; Willemsen et al., 2017). This may be the case of the eroding marshes of Zwarte Haan (west area, Figure S2), which had the largest incoming waves from all the marsh locations measured (Figure 4f), likely as a result of low-lying fronting tidal flats. Furthermore, Zwarte Haan area has been exposed to the most predominant wind direction and intensities in the study area in the last 2 decades (Figure 2d), which could have also promoted the sediment erosion of the marsh edges (cf Leonardi et al., 2018).

4.2 | Wave run-up differences are driven mainly by the marsh presence

This study provides field evidence that salt marshes effectively protect the dikes across locations by reducing the beach wrack levels (by up to ~3 m in the storms measured in this study) and the corresponding wave run-up, mainly due to forming higher and more stable soils (Figure 1c; Figure S4) which reduced wave heights (Table 2). In some cases during moderate storms, run-up was completely attenuated as a consequence of the elevated marsh foreshore which led to depth-limited waves (Zhu et al., 2019). As the tidal range varies across the Dutch Wadden Sea, areas to the East with higher water levels experienced higher beach wrack and wave run-up.

Higher marshes (e.g. above 2 m NAP), even being narrow (~100 m width), will provide more protection than lower marshes. Although our study shows that a marsh width of 300 m and a marsh elevation of ~1.5 m was effective, even wider marshes would guarantee wave attenuation during more severe storms (Zhu et al., 2020). Nevertheless, because the highest percentage of attenuation often occurs in the first part of a marsh plateau (Möller & Spencer, 2002; Ysebaert et al., 2011), a narrow marsh may still have some protective value to the dike. Wave attenuation may be less during stronger storms (1/1000 year storms, or worse) than we encountered during our monitoring period. However, flume experiments (Möller et al., 2014) and models (e.g. Vuik et al., 2016; Willemsen et al., 2020) report that marshes also then remain effective in wave dampening, although the effect is reduced due to higher water levels (Keimer et al., 2021).

Although bathymetry explained most of the run-up attenuation across sites, part of this attenuation may be due to the vegetation friction (Keimer et al., 2021; Vuik et al., 2016; Willemsen et al., 2020). The contribution of the vegetation was not tested in our analyses because the high variability of vegetation parameters in time and space made it impossible to create a single vegetation variable to fit the statistics. For example, ungrazed locations with taller and stiffer vegetation like Holwerd may have had a somewhat greater wave attenuating effect due to the higher biomass, higher ratio of vegetation to water depth and higher drag forces (Bouma et al., 2010; Maza et al., 2022; Ysebaert et al., 2011). Conversely, livestock grazing in Uithuizen, Den Andel and Zwarte Haan, which kept the overall vegetation shorter, could have been attributed to a lower wave attenuation compared to non-grazed vegetation. Similarly, seasonality may play a role as vegetation properties, such as biomass and height, will be lower in the winter than in the summer. Although grazed marshes attenuated run-up, low-intensity grazing will be recommended over high-intensity grazing to avoid soil over-compaction, excessive decrease in vegetation height and decrease in biodiversity, while still increasing soil erosion resistance and preventing the dominance of high marsh species with low root density (Davidson et al., 2017; Kosmalla et al., 2022; Marin-Diaz, Govers, et al., 2021; Pagés et al., 2018). Finally, wind fetch to the islands did not explain differences in wave run-up. On the other hand, Holwerd was sheltered by the harbour with western winds, and this could have further reduced the beach wracks in this location.

4.3 | Are the marshes 'where we need them most'? A catch-22 situation

Marshes effectively reduced the run-up on the dikes during medium-intensity storms (Figure 7a). However, locations currently more vulnerable to run-up (i.e. locations with lower bathymetry, therefore deeper water levels and higher waves) are also the locations where the marshes will not naturally occur (Figure 7b). In this sense, marshes can be in exposed locations ('where we need them most') if sediment is deposited with sufficient elevation thus reducing wave loadings and providing adequate windows of opportunities for marsh establishment (Bouma et al., 2016; Hu et al., 2015, 2021). Large-scale sediment dynamics determining the presence of higher tidal flats may be affected by wave exposure, currents,

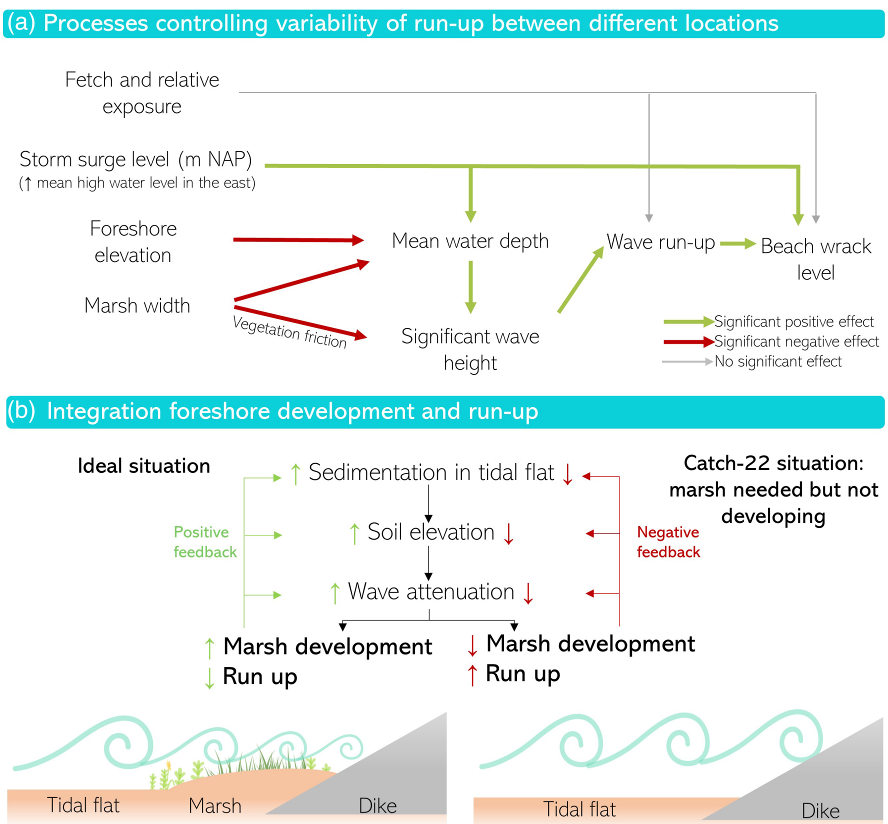


FIGURE 7 (a) Mechanisms of the effect from the bathymetry, storm surge levels and vegetation investigated with LMM. Wind exposure was not further investigated because it was not related to the run-up and beach wrack levels. Green arrows indicate significant positive effect ($p < 0.001$), red arrows indicate significant negative effect ($p < 0.001$) and grey arrows indicate not significant effect ($p > 0.05$). (b) Schematic diagram of catch-22 situation between the foreshore elevation, marsh formation and wave run-up attenuation.

storms surges, sediment supply, dredging activities as well as biotic factors (e.g. Ladd et al., 2021; Mariotti & Fagherazzi, 2013; Schuerch et al., 2014), although this was not covered in this study.

Management of the local conditions on the tidal flats (e.g. sediment supply, sediment accretion and hydrodynamics) is key for marsh expansion (Hu et al., 2021; Ladd et al., 2019; Mariotti & Fagherazzi, 2013). Enough sediment supply is especially important to keep up with sea-level rise and in situations where the ecosystems are not able to migrate inland due to human constructions like sea dikes (Doody, 2013; Hu et al., 2021). Foreshore management may also require actions in the land watershed such as opening upstream dams or reduce river dredging (Mariotti & Fagherazzi, 2013). If this is not possible, sediment nourishments may be an option (Baptist et al., 2019; Hu et al., 2021). In areas where sediment accretion is possible but marshes are not occurring naturally (e.g. Zwarte Haan and Eemshaven), creating windows of opportunity for marsh establishment by reducing hydrodynamics may be an option (i.e. wave-breaking brushwood groynes or large woody debris) (Bouma et al., 2016; Dijkema et al., 2011; Falkenrich et al., 2021; Hu et al., 2015, 2021). A more ecologically valuable alternative may be to restore adjacent ecosystems such as seagrass or shellfish reefs (Chowdhury et al., 2019; Walles et al., 2015). However, the success of using ecosystem restoration will depend on factors such as the hydrodynamic forcing of the location and if there is enough space to develop (Marin-Diaz, Fivash, et al., 2021; Morris et al., 2019; Schoonees et al., 2019). Finally, in the most exposed locations with insufficient tidal flat accretion, where marsh development may not be possible even with human intervention, hard engineered solutions to protect from floods may be the only option (e.g. dike heightening) (Schoonees et al., 2019).

In summary, marshes effectively reduce run-up during the measured medium-intensity storms but are not necessarily developing 'where we currently need them most'. This problem means that engineering measures will always be needed in vulnerable locations: *either* to stimulate tidal flat accretion to induce marsh development at those exposed places where marshes cannot develop without our help *or* to strengthen exposed dikes where nature-based solutions are too costly, not achievable, or going at the expense of other ecological values, such as causing the loss of mudflats that are important for migratory birds (Boere & Piersma, 2012).

AUTHOR CONTRIBUTIONS

Beatriz Marin-Diaz, Laura L. Govers, Daphne van der Wal, Christopher H. Lashley, Tjeerd J. Bouma and Han Olff conceived the ideas and designed the methodology; Kornelis de Jong and Jan-Willem Nieuwenhuis contributed importantly to the experimental design by selecting specific contrasting locations that were relevant to compare from the perspective on dike constructions by the regional water authorities. Beatriz Marin-Diaz, Leon Kaptein and Pol Martinez-Garcia collected the data; Beatriz Marin-Diaz analysed the data; Han Olff, Daphne van der Wal, Leon Kaptein and Tjeerd J. Bouma contributed to the data analysis; Beatriz Marin-Diaz led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

All authors declare no conflict of interests.

DATA AVAILABILITY STATEMENT

Data available via the 4TU.Research Data Repository https://doi.org/10.4121/872ad544-c7c7-41c2-8307-3e353c9befd2 (Marin-Diaz et al., 2023).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Text S1: Summary of the history of the accretion works for marsh creation in the Dutch Wadden Sea.

Table S1: Recording settings utilized for the wave loggers.

Table S2: Output models explaining flotsam with interactions and without interactions.

Table S3: Set of linear mixed models explaining the relationships of bathymetry, storm surge level and wind with the beach wrack level and run-up, with the storm date as random.

Figure S1: Significant wave height obtained from publicly available water time series data collected by Rijkswaterstaat.

Figure S2: Intertidal elevation change with the marsh edge at 1 m NAP and the upper mudflat edge (0 and 0.5 m NAP) for 2004 and 2012/2017.

Figure S3: Erosion observed at the marsh edge of Zwarte Haan, The Netherlands.

Figure S4: Variability in elevation change along the transects with wave loggers.

Figure S5: Changes over the season of (a) vegetation diameters, (b) number of structures (leaves or branches) per stem, and (c) height at which structures were attached per stem.

Figure S6: Relationships between wind speed and (a) water level in front of the dike and (b) significant wave height in front of the dike.

Figure S7: Effect of different foreshore types on wave attenuation.

Figure S8: Correlations between run-up and beach wrack levels on the dike with marsh elevation and marsh width for all the measured dates.

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