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LETTERS

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Wave attenuation over coastal salt marshes under storm surge conditions

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Coastal communities around the world face an increasing risk from flooding as a result of rising sea level, increasing storminess and land subsidence[1,2]. Salt marshes can act as natural buffer zones, providing protection from waves during storms[3–7]. However, the effectiveness of marshes in protecting the coastline during extreme events when water levels are at a maximum and waves are highest is poorly understood[8,9]. Here we experimentally assess wave dissipation under storm surge conditions in a 300-metre-long wave flume tank that contains a transplanted section of natural salt marsh. We find that the presence of marsh vegetation causes considerable wave attenuation, even when water levels and waves are highest. From a comparison with experiments without vegetation, we estimate that up to 60% of observed wave reduction is attributed to vegetation. We also find that although waves progressively flatten and break vegetation stems and thereby reduce dissipation, the marsh substrate remained stable and resistant to surface erosion under all conditions. The effectiveness of storm wave dissipation and the resilience of tidal marshes even at extreme conditions suggest that salt marsh ecosystems can be a valuable component of coastal protection schemes.

Coastal margins are experiencing increased pressure from both physical environmental (sea-level rise, increased storminess[10]) and human use (increased population densities, resource requirements[11]) perspectives. This has resulted in a re-evaluation of coastal flood and erosion risk reduction methods[5]. Natural coastal landforms, including sand dunes, mudflats and salt marshes, are now widely recognized as potential barriers to wave and tidal flow or as wave/tidal energy buffers[7,11–13]. The inclusion of such natural features into quantitative flood risk assessments, however, has been hampered by a lack of: empirical evidence for their capacity to act as wave dissipaters under extreme water level and wave conditions (when their coastal protection service is most required); and a quantitative understanding of their ability to survive those types of conditions[8,14–16].

Previous studies have suggested that wave dissipation over submerged salt marsh canopies is dependent on water depth and incident wave energy, and that hydrodynamic conditions may exist beyond which marshes lose their wave dissipating effect[6,17,18]. The existence of such conditions makes intuitive sense, as the orbital wave motion that is affected by the submerged vegetation canopy decreases with increasing depth and decreasing incident wave energy. Existing empirical studies of wave reduction over vegetated canopies have, however, been limited to low water depths (<1 m) and low wave heights (<0.3 m; refs 18,19).

Salt marsh resistance to wave impact is intricately connected to wave dissipation over salt marsh surfaces[20]. Under high energy conditions, dissipation of wave energy may be achieved by wave shoaling/breaking as well as removal of material (both plant and soil) from the marsh edge/surface, rather than only by drag from the vegetation canopy[19]. Existing evidence points to the stabilizing effect of organic matter with respect to resistance of the marsh surface to erosion by waves from above (with contrasting evidence for roots increasing erosion on exposed marsh margins)[21]. Little is known, however, about the response of the marsh soil to extreme levels of wave impact, as might be experienced during a storm surge. The stability of the marsh surface under such conditions is critical to any assessment of its usefulness as part of coastal flood risk reduction schemes.

Here we present results of a unique large-scale flume experiment with three key aims: to explore the dissipation of waves over a vegetated marsh canopy under storm conditions; to quantify the effect of vegetation on wave attenuation compared with the effects of a mowed platform; and to quantify the response of marsh vegetation and soil surface to incident wave energy.

Waves were generated in a 300-m-long, 5-m-wide and 7-m-deep flume over a test section of almost 40 m length consisting of a coherent patchwork of marsh blocks (Fig. 1a). Blocks were characterized by a mixed canopy of *Elymus athericus*, *Puccinellia maritima*, and *Atriplex prostrata*, typical of mid to high southern North Sea marsh communities (Fig. 1b–d). Whereas incident wave heights on salt marsh margins are limited by shallow inshore water depths and thus are generally low (<0.3 m), above-marsh water depths are known to reach or exceed 2 m, accompanied by wave heights (H_s) in excess of 0.8 m, during storms[19]. Tests were thus conducted for regular and irregular non-breaking waves of heights up to 0.9 m in 2 m water depth above the vegetated bed. There was no statistical difference between flume and field soil bulk density, stem diameter and plant stem flexibility (Young's modulus; t-test; $p > 0.05$; see Table 1 and Supplementary Information for detail).

Results show a clear dissipation pattern, remarkably consistent between regular and irregular waves. For regular waves, wave energy dissipation over the 40 m distance increased linearly from

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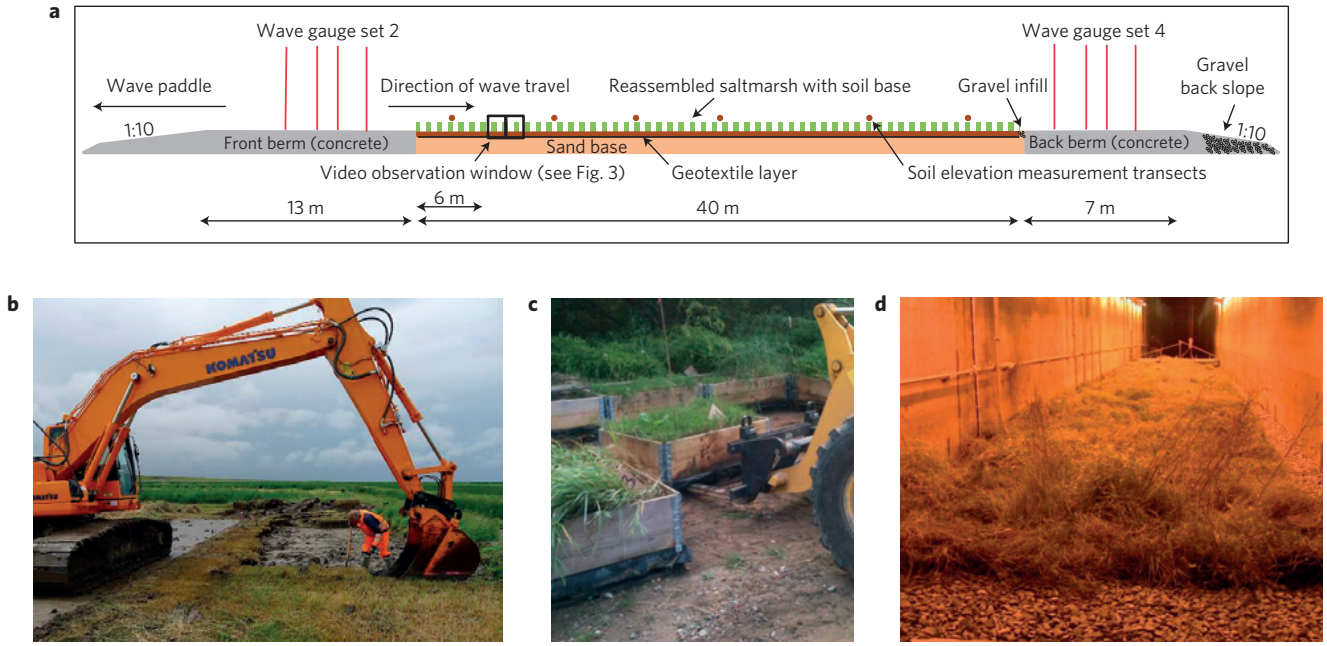

Figure 1 | Experimental set-up and photographs of excavation. a, General experimental set-up in the wave flume, with position of recording equipment relevant to reported results. **b**, Excavation of marsh blocks, northern German Wadden Sea (53° 42.754′ N, 7° 52.963′ E). **c**, Marsh blocks with *Elymus* vegetation cover before positioning in the flume test section. **d**, Reassembled salt marsh inside the 5-m-wide flume, looking towards the wave generator; lamps are mounted at about 3 m above the soil surface.

Table 1 | Plant stem flexibility (Young's modulus), height, density and diameter and soil bulk density at the field site where marsh blocks were extracted and in the flume immediately before the experimental runs (means ± one s.d.).

	Stem flexibility Young's bending modulus (MPa)		Stem height (mm)	Stem diameter (mm)		Stem density (number per 20 x 20 cm quadrat)		Dry soil bulk density (g cm^{-3})	
	Mean	*N*	Mean	Mean	*N*	Mean	*N*	Mean	*N*
Puccinellia (Flume)	111.6 ± 66.3	17	220 ± 30	1.1 ± 0.3	17			0.6 ± 0.3	10
Puccinellia (Field)	284.5 ± 369.1	17		1.2 ± 0.2	17			0.7 ± 0.5	20
Elymus (Flume)	2,696.3 ± 1,963.8	18	700 ± 10	1.3 ± 0.3	18	49 ± 23	10	0.7 ± 1.0	20
Elymus (Field)	2,514.6 ± 2,977.1	18		1.7 ± 0.4	18	68 ± 8	10	0.8 ± 0.7	20

no dissipation in the case of waves with $H = 0.1$ m and $T = 1.5$ s to 19.5 % reduction for $H = 0.3$ m and $T = 3.6$ s (Fig. 2a). For irregular waves, dissipation between 11.9 and 17.9% occurred for $H_{rms,0}$ of 0.2–0.4 m (Fig. 2b). When incident wave heights increased beyond these levels, dissipation reduced to 13.8% for regular ($H = 0.6$ m, $T = 3.6$ s, Fig. 2a) and to 14.7% for irregular waves ($H_{rms,0} = 0.6$ m, $T_p = 4.0$ s, Fig. 2b), before increasing to 16.9% for the largest regular waves ($H = 0.7$ and 0.9 m; $T = 5.1$ and 4.1 s) and to 16.9% for the largest irregular waves ($H_{rms,0} = 0.7$ m, T_p 6.2 s).

Dissipation over the mowed surface was significantly lower in all regular wave tests (t-test, $p < 0.05$; Fig. 2a) and irregular wave tests (Fig. 2b). At (or just after) the point of maximum wave dissipation (H and $H_{rms,0} = 0.2$–0.4 m), wave height reduction over the mowed section was lower than over the section with intact vegetation by a factor of 0.4. Thus, it can be stated that the vegetation cover alone accounted for 60% of wave height reduction (Fig. 2a,b). However, when $H_{rms,0}$ increased towards 0.6 m, the vegetation cover accounted for only 40% of wave height dissipation (Fig. 2b).

Models of wave dissipation by vegetated beds commonly rely on knowledge of the drag coefficient C_D incorporated into a friction factor that takes account of vegetation stem density, height and diameter. The complex nature of salt marsh vegetation precludes the *a priori* determination of C_D from simple plant metrics. Nevertheless, an exponential decay relationship between the stem Reynolds number Re_V and C_D of the form $C_D = a + (b/Re_V)^c$ has been found to exist for other vegetation types[22–24]. Here, Re_V is a function of wave orbital velocity and the vegetation stem diameter. We initially used our vegetation metrics (Table 1) and the C_D–Re_V relationship developed for seagrasses to predict dissipation for our experimental conditions[22]. Figure 2a,b clearly shows that our observed dissipation exceeded that predicted by a factor of 1.5–2.2 for regular and 2.6–3.2 for irregular waves. We then calculated C_D for each experimental run from observed dissipation and plant metrics. C_D decreased with increasing Reynolds numbers Re_V, confirming the established exponential relationship between Re_V and C_D ($r^2 \geq 0.97$), but with coefficients a, b and c that differ from those of previous studies (Supplementary Information).

Analysis of video footage showed that the reduction in dissipation for regular waves exceeding 0.3 m in height was accompanied by a change in behaviour of the marsh vegetation. Under relatively low incident waves ($H < 0.3$ m; $T < 3.6$ s), the plants swayed and interacted with wave motion throughout the wave

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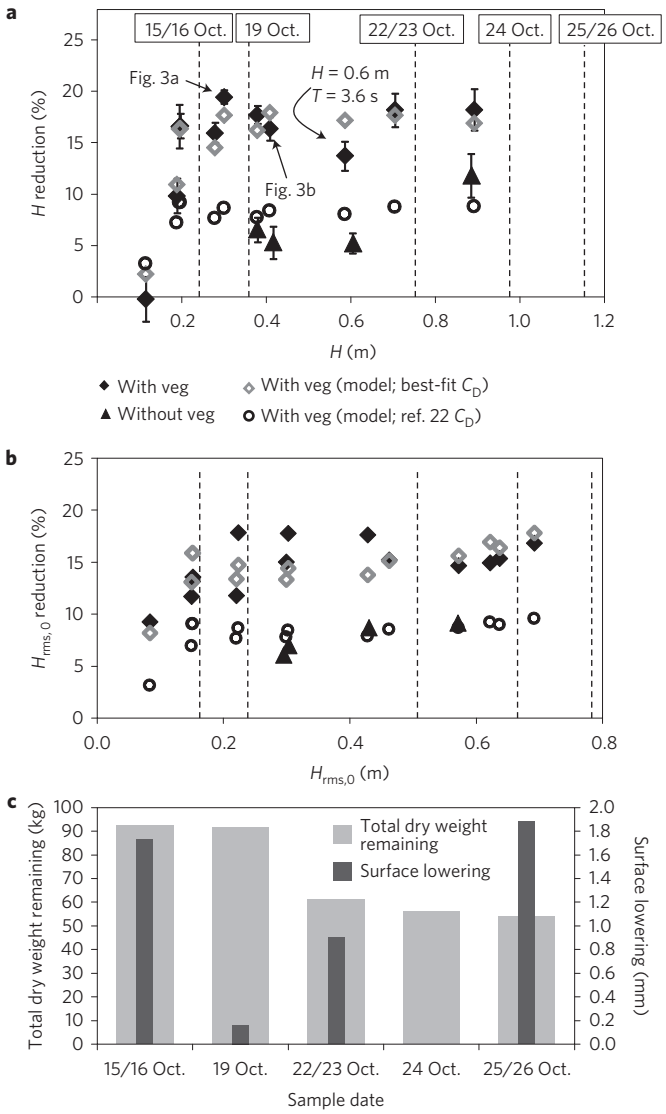

Figure 2 | Wave dissipation across 40 m of vegetated and mowed salt marsh. a,**b**, Percentage reduction for regular waves (**a**; *H*) and irregular waves (**b**; $H_{rms,0}$); error bars in **a** refer to the mean ±1 s.d.; filled diamonds/triangles refer to observed vegetated/mowed conditions, open diamonds and circles refer to modelled vegetated conditions using best-fit and ref. 22 C_D values respectively, vertical lines mark times of soil elevation and floating debris measurement (Fig. 2c). **c**, Plant biomass (light thick bars) remaining and mean surface elevation lowering (dark thin bars; standard error of ±10.4 mm not shown).

cycle (Figs 2a and 3a). For larger waves (stronger currents), however, stems bent over to angles >50° during the forward wave motion, allowing the flow for part of the wave cycle to skim over, rather than travel through the vegetation, thus retaining energy and reducing dissipation (Figs 2a and 3b).

Video observations confirmed that this flattening of the plants preceded the tendency for plant stems to fracture along lines of weakness that formed when stems folded over to high bending angles. Cumulatively, this breakage resulted in a loss of 31% (30 kg) of the total 98 kg of biomass after two days of runs under higher energy conditions (Fig. 2c). Such loss of plant material may then have contributed to the reduced dissipation (Fig. 2a,b). The soil surface remained remarkably stable, with an average lowering that was not significantly different from zero (4.4 ± 10.4 mm over the entire experiment). The trend for average surface lowering from one surface exposure to the next was greatest during the test runs with the largest waves, rather than during the test runs that resulted in the largest release of plant biomass (Fig. 2c).

Wave attenuation of >80% has been reported in the literature for distances of about 160 m under low energy conditions[19]. The spatially nonlinear nature of wave dissipation means that a conversion of this figure to units of per cent per metre makes little sense[4], but the evidence presented here shows that non-breaking wave dissipation can still reach 20% over a 40 m distance even in water depths typically found during storm conditions. This contribution is generated not only by the marsh platform but also, and significantly, by the vegetation canopy. Moreover, we identify process transitions in wave dissipation across the submerged salt marsh surface, associated with specific incident wave energy levels. The spatio-temporal nonlinearity in wave dissipation over coastal wetlands has been linked to, amongst other factors, variability in the characteristics of the vegetation cover (for example, flexibility[25]). The established general nature of the relationship between Re_V and C_D seems robust, even for storm conditions, but the coefficients describing this relationship in our experiment differ markedly from those established for lower energy conditions and different vegetation types[22–24]. For regular waves of around 0.6 m height (Re_V of around 640), however, the model based on the empirical Re_V–C_D relationship leads to an over-prediction of dissipation (Fig. 2a) that warrants further investigation. We thus call for a re-evaluation of existing wave dissipation models and urge the scientific community to develop more appropriate methods for the *a priori* quantification of vegetation-induced drag for a broader range of plant species and wave conditions. Ideally, such methods should be able to quantify drag directly from plant metrics and knowledge of the incident flow field. Furthermore, the high bending angle and repeated bending of vegetation under energetic conditions lead to plant breakage along lines of weakness and a loss of biomass, a process that needs to be adequately represented in models of marsh canopy growth/recovery after storm incidence.

The higher than expected rates of storm wave dissipation and the fact that marsh surfaces are able to withstand larger wave forces without substantial erosion effects increase their reliability as part of coastal defence schemes and shifts debates about marsh stability and resilience to those locations where the marsh profile is exposed. In such settings, lateral retreat (for example, cliff undercutting/collapse on marsh fronts and channel widening)[26–28] may be enhanced by the presence of vegetation, for example, when roots become exposed to wave impact[21]. The long-term balance between vertical and lateral marsh dynamics thus becomes a key area for further study[8,9].

The evidence presented here can serve as a validation data set for a new and improved representation of drag and friction effects in numerical models of wave dissipation and vegetation movement under storm conditions. It also supports the incorporation of salt marshes into coastal protection schemes, such as the Dutch 'building with nature' approach[5,11,20]. Any such schemes must carefully consider incident wave heights and water depths, alongside wave dissipation requirements and the ecological conditions necessary for the maintenance of a healthy vegetation canopy.

Methods

Experimental set-up. Experiments were conducted in the Large Wave Flume (Grosser Wellenkanal, GWK) of Forschungszentrum Küste (FZK) in Hannover, Germany. The flume is the largest freely accessible wave tank in the world; it is 310 m long, 5 m wide and 7 m deep. The vegetated test section of 39.44 m length (about 180 m^2) consisted of vegetated marsh blocks of 1.2 m length, 0.8 m width and 0.3 m depth, cut from a natural marsh on the mainland coast in Eastern Frisia, German Wadden Sea. The vegetated section was positioned on a 1.2-m-high sand base covered in geotextile at a distance of 108 m from the wave paddle and illuminated to prevent plant deterioration when exposed. Adjacent to the front and rear end of the vegetated test section, a flat concrete surface and ramped concrete slope allowed waves to shoal (Fig. 1a).

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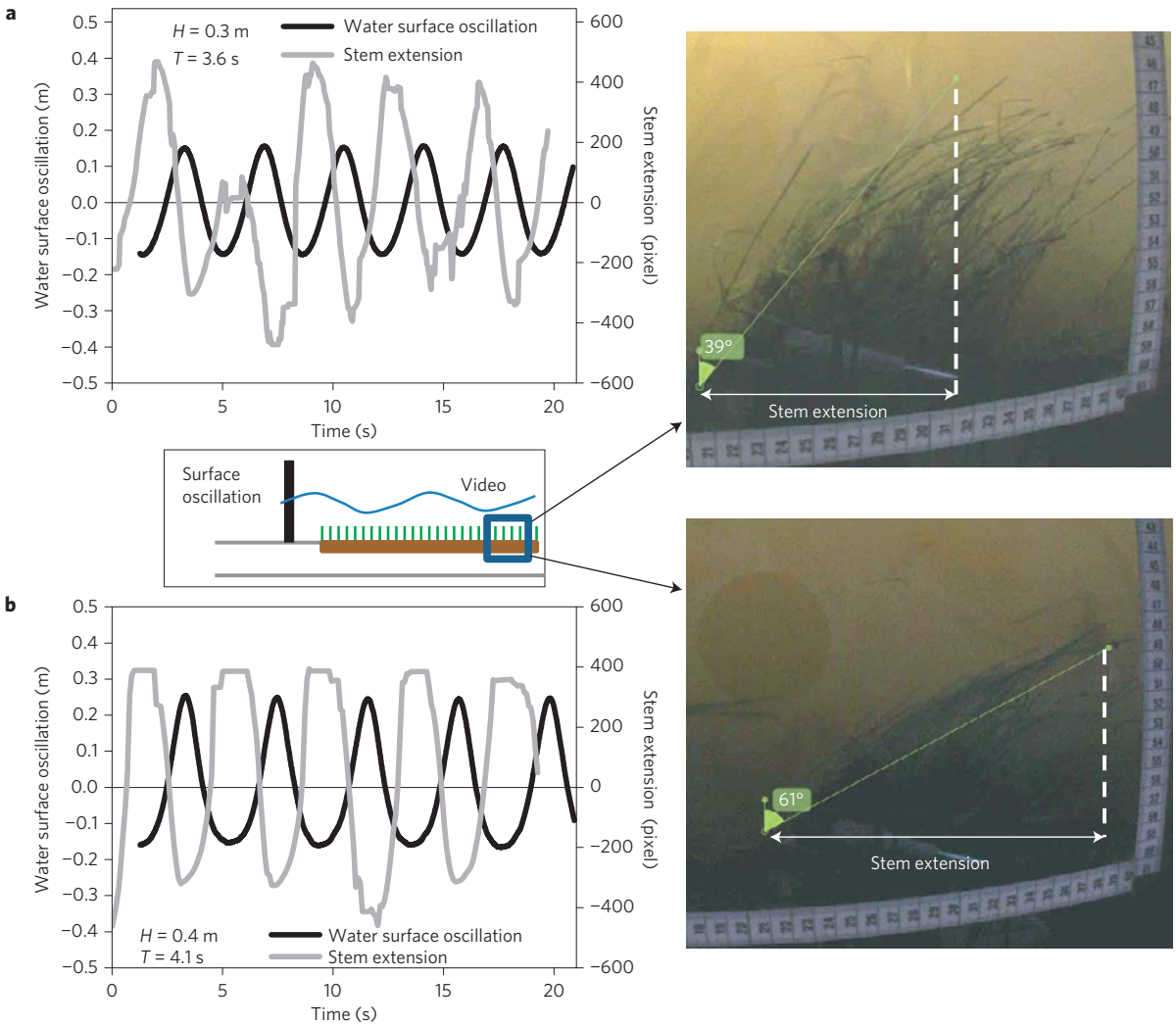

Figure 3 | *Puccinellia* plant canopy movement during wave motion. a,**b**, Water level excursion (*y* axis) and time trace of horizontal stem extension (video pixel units; positive values in the direction of wave motion (white arrow in photographs)) under waves experiencing maximum dissipation (Fig. 2a) (**a**) and waves of greater height and period but experiencing lower dissipation (Fig. 2a) (**b**). A phase shift results from water level measurement occurring approximately 10 m forward of video observations (see also experimental set-up in Fig. 1a). Lack of visibility in highly turbid water precluded analysis of conditions at $H = 0.6$ m, $T = 3.6$ s (Fig. 2a).

Wave conditions and inundation schedule. The flume was filled with fresh water to 2.0 m water depth above the vegetated soil surface and seven wave heights (H_0: 0.1, 0.2, 0.3, 0.4, 0.6, 0.7 and 0.9 m) were simulated. Irregular waves ($N \geq 1{,}000$) were generated using a JONSWAP spectrum with a peak enhancement factor of 3.3, followed by a regular wave run ($N \geq 100$). After each two days of tests, the flume was drained and exposed for at least 12 h to allow plants to acquire oxygen. Tests were conducted with initially intact and then mowed vegetation to determine the effect of the vegetation as opposed to the topographic effect of the soil base.

Wave measurements. Sixteen wire wave gauges were deployed in sets of four (to enable reflection analysis at each location). Here we report analysed wave parameters from sets 2 and 4 that relate to the changes in wave characteristics over the full 40 m of the vegetated section (Fig. 1a,d). Wave gauges within each set were separated in the direction of wave travel by 2.07 m (front two gauges), 1.55 m (middle two), and 1.58 m (back two).

Wave analysis. For the regular wave tests, the first 11 fully developed waves were found to be entirely unaffected by reflection from the flume end and were used to determine average wave height (H, from min–max water surface elevations) and period (T, from zero-upcrossing points). For irregular wave tests, the root-mean-square wave height in front of ($H_{\mathrm{rms},0}$) and behind ($H_{\mathrm{rms},1}$) the vegetated section was calculated after reflection analysis, as described in the Supplementary Information. Dissipation was analysed by comparing values at the last gauge of set 2 (3.02 m in front of the vegetated section) and the first of set 4 (2.2 m behind the vegetated section) and expressed as a positive percentage of the wave height at the start of the section. If present, error bars indicate the standard deviation of the difference between the wave heights.

Wave dissipation model. Dalrymple *et al.*'s[29] model was used to compute the dissipation of regular waves and Mendez and Losadas'[30] model was applied to irregular waves over the 40-m-long vegetated section x with H_0 ($H_{\mathrm{rms},0}$) incident wave height and H_1 ($H_{\mathrm{rms},1}$) damped wave height behind the section:

$$\frac{H_0 - H_1}{H_0} = \frac{\alpha x}{1 + \alpha x} \text{ (reg. waves)}$$

$$\frac{H_{\mathrm{rms},0} - H_{\mathrm{rms},1}}{H_{\mathrm{rms},0}} = \frac{\alpha x}{1 + \alpha x} \text{ (irreg. waves)}$$

in which

$$\alpha = A \frac{S_{\mathrm{D}}}{S_{\mathrm{S}}^2} C_{\mathrm{D}} k \left[\frac{\sinh^3 kS_{\mathrm{H}} + 3 \sinh kS_{\mathrm{H}}}{\sinh kh (\sinh 2kh + 2kh)} \right]$$

where $A = 4/(9\pi)H_0$ for regular waves and $A = 2/(3\sqrt{\pi})H_{\mathrm{rms},0}$ for irregular waves, $k = 2\pi/L$ (L is the wave length of peak period T_{p}), h is the water depth, S_{D} is the stem diameter, S_{S} is the stem spacing, S_{H} is the stem height as measured on the test section for *Elymus*, the dominant species ($h = 2$ m, $S_{\mathrm{D}} = 1.3$ mm, $S_{\mathrm{S}} = 28.6$ mm, $S_{\mathrm{H}} = 700$ mm; Table 1).

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The drag coefficient C_D was determined as a function of the vegetation Reynolds Number Re_v (ref. 22):

$$C_D = -0.046 + \left(\frac{305.5}{Re_v}\right)^{0.977} \quad \text{(regular waves; } r^2 = 0.97\text{)}$$

$$C_D = 0.159 + \left(\frac{227.3}{Re_v}\right)^{1.615} \quad \text{(irregular waves; } r^2 = 0.99\text{)}$$

with

$$Re_v = U_{max}\frac{S_D}{\nu_k}$$

where ν_k is the kinematic viscosity (1×10^{-6} m^2 s^{-1}) and $U_{max} = f(H_0$ or $H_{rms,0}$ resp. and $T_p)$ the orbital velocity at the bottom in front of the vegetated section based on linear wave theory.

For further details on field site, test section construction, wave analysis and methods used to analyse vegetation behaviour and damage as well as soil elevation change, refer to the Supplementary Information.

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Author contributions

I.M., B.K.v.W., G.W., T.S., T.J.B., S.S., M.K., M.M-L., M.P. and K.J. designed the experiment. I.M., F.R., M.K., M.M-L., M.P., T.S., G.W. and S.S. participated in the construction and running of the experiment. I.M. and M.K. conducted the wave data analysis with F.R. processing biomass and video information. I.M. processed the soil elevation data and wrote the initial manuscript. All authors contributed to and approved the final manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to I.M.

Competing financial interests

The authors declare no competing financial interests.

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ADDENDUM

Wave attenuation over coastal salt marshes under storm surge conditions

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