

The contribution of salt marshes to wave attenuation during extreme storms

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This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Referee #1

(Remarks to the Author)

I enjoyed reading this contribution from Willemsen and others on Salt Marshes Globally Protect Against Extreme Storms. Wave attenuation is perhaps the least studied of the ecosystem services provided by tidal wetlands so their effort to extend previous physical models of vegetation-related contributions to wave attenuation strikes me as important. Their effort to estimate the contribution of vegetation to wave attenuation globally helps broaden the impact of the work.

Because most ecosystem science is performed at the scale of a few meters, a strength of the research is the large scale of this experimental manipulation. I was impressed by the effort required to extract 66 intact tidal marsh monoliths, each of which were fairly large at 2x2 m in area and 0.7 m deep. The quality of an experiment is not judged by its scale, but scientifically insightful efforts performed at this scale are relatively rare, so this aspect of the work needs acknowledgement. The wave heights and duration of the experiment are reasonably realistic for the conclusions they drew and the global extrapolation.

I agree with the major insights that the authors chose to highlight. The research places new bounds the capacity of aboveground vegetation to attenuate waves, and these bounds are different for low- and high-energy coastlines, and dependent on wave height. I consider these points to be meaningful because they add caveats to the broad, global claims we often make about tidal wetland ecosystem services and hopefully force us to be more nuanced and transparent about the benefits of protecting and restoring coastlines.

Major Comments

1. The focus of the authors on aboveground biomass and height is appropriate for the issue of wave attenuation which dominates most of the manuscript. However, an important part of the manuscript that appears in the abstract, results, and discussion is the stability of the marsh platform irrespective of vegetation. Missing is the fact that belowground plant tissue also contributes to platform stability by stabilizing soil structure. This is an important point that needs to be acknowledged and there is a robust literature to draw upon relating belowground biomass to erosion-relevant physical properties such as shear stress.

The implications of the absence of data and discussion on belowground biomass depends on how the effects of vegetation on marsh elevation were calculated. Based on L332-338 and L341-348 of the methods it appears that conclusions about plant effects on elevation are based only on measurements made on the marsh monoliths before and after the aboveground biomass was mowed. If so, the belowground biomass was largely intact after mowing and plant biomass was still stabilizing the soil against erosion.

Alternatively, if the authors are comparing changes in elevation in the marsh section of the flume to changes in elevation in the mudflat section of the flume, then conclusions about the absence of vegetation are reasonable as the mudflat did not plants, including their belowground biomass. This alternative approach does not seem to be the case, so the authors should modify their discussion to acknowledge the soil-stabilizing capacity of plant belowground biomass.

2. The authors acknowledge on L127 that wave attenuation depends on the stability of the marsh substrate. In the present

case the marsh substrate was 31-45% clay with properties like cohesion that contribute to the stability of the marsh platform. My sense is that the grain size distribution of the monoliths in this study transfer well to many coastal marshes. However, they also transfer poorly to many other coastal marshes in places like the Atlantic and Gulf coasts of North America where organic-rich soils and sediments are common. Importantly, I suspect that the global distribution of organic-rich soils co-varies with the distribution of low-energy coastlines, an important interaction that the authors do not recognize in the text of the paper.

To be clear, I am certainly not asking the authors to incorporate soil properties into their global model which would be difficult and beyond the capacity of their statistical model. The model they are using for a global extrapolation is appropriate for the data they have available from the flume study. Rather, I am asking them to discuss this matter in the section titled Global marsh vegetation reducing extremes.

3. I found the section on Global marsh vegetation reducing extremes to be a bit of a weak spot in the manuscript. While I appreciate text on the relevance of the work to topics like nature-based solutions, I think the text in this section would be better invested in advancing the field by discussing how to further refine the global model.

The authors make the point that their estimates are conservative because of the height and stiffness of the dominant plants in the marsh monoliths. I suggest they add discussion on the extent to which their conclusions would vary in marshes with more robust plants such as large areas of the world where invasive *Phragmites australis* or *Spartina alterniflora* are dominant or shrub-dominated marshes. I also suggest adding thoughts about how soil type would affect their estimates.

Minor Comments

L104. Please add some insights on the rooting structure of the two dominant species such as rooting depth and aspects of belowground morphology such as roots and rhizomes that may be relevant to marsh platform stability.

L141. The first paragraph lost me here when the authors report that the marsh platform elevation was fairly stable under extreme wave conditions irrespective of vegetation. Missing to this point is information about changes in the elevation in the absence of the aboveground vegetation, which occurred during the third repetition according to the methods section. Please edit the paragraph to support the claim that the platform was stable in the absence of vegetation.

L135. Change “coastal plane” to “coastal plain”

L139. Describing the stability of the marsh platform as a “survival mechanism” seems odd when discussing an ecosystem as opposed to an organism. I suggest editing this to “essential feature”.

L313. There seems to be an error in the dates since they state the monoliths were installed in the flume in Dec 2024 and the experimental runs occurred 10 months before in Feb 2024 (L319).

Referee #2

(Remarks to the Author)

Results, validity, originality, and significance:

It was a pleasure to read this manuscript. The primary contribution of this research is that it first investigates key physical processes related to wave forcing using an exceptionally large-scale flume experiment, and then extends this knowledge to enable modelling at the global scale. While the individual components are not particularly novel or groundbreaking, the study is significant when considered as a whole.

The study shows that salt marshes are effective in reducing erosion under highly energetic wave conditions (which have not been examined previously), but that wave attenuation itself is limited and occurs primarily under low-energy conditions. Essentially, the manuscript proposes an empirical relationship for estimating wave attenuation by vegetation as a function of storm exposure duration and incoming wave height.

The use of naturally occurring plants growing in their native soil in the experiments enhances the reliability of the results and their upscaling. However, it remains partly unclear whether it is appropriate to treat all salt marsh vegetation and sediment types equivalently (that is, whether vegetation and sediment properties should be included as predictors). On the other hand, the authors argue that their estimates are conservative, as they are based on plant species with relatively low breaking strength (i.e., “weak” species).

As a further note, the authors could have better stated the novelties themselves; presently it is partly left for the reader to interpret.

No flaws can be identified in the research, but the global representativeness of the experimental data (vegetation, sediment, etc) can be challenged.

No previous analyses exist at this large scale covering a broad range of wave conditions. The results are useful for critically evaluating NBS performance and directing their future developments.

Data and methodology:

The methods are clearly reported, allowing reproduction of similar experiments by others. However, the study relied much on conventional, laborious manual vegetation measurements. In addition to those, optical/photogrammetric, multispectral imaging, and other remote sensing methods could have been used to characterize vegetation (e.g. LAI, PAI). Such data would support validation across different scales and regions, while being useful as a reference for other researchers. As a further remark, the sample sizes of some biomass and vegetation height measurements appear small (see below detailed comment concerning N=6 for 20 cm x 20 cm quadrants and N=20 for random stems).

It remains unclear how representative the tested marsh soil is of other geographical and climatological conditions and what are the uncertainties in the global up-scaling based on one single soil sample. The erodibility of cohesive sediments such as the one tested are known to be uncertain to predict, because multiple factors such as the grain size, % clay fraction, % organic content, dry bulk density, and water content affect erodibility. If too much of the underlying sediment is eroded, vegetation is destroyed by uprooting (not necessarily by breaking). This mechanism facilitating/generating uprooting was apparently not considered in either the flume study (as erosion of the tested soil material was low) or the global up-scaling.

The methodology of obtaining the 1/100 and 1/1000 wave heights based on the storm surge observations is not clearly described.

It appears that statistical tests were rigorously completed, but in some cases number of data are limited: N=6 for biomass and N=20 for stem height. The rather low number of specimens likely explains why only few significant differences were observed (Table S2).

The manuscript does not specifically address the uncertainties related to the global up-scaling. The uncertainty could be addressed e.g. through different upscaling scenarios, in which the properties of vegetation or wave heights are varied. How much larger is the wave attenuation considering “less conservative” vegetation, e.g. stronger species or those with larger biomass/stem length (cf. Figure S1), or summer conditions with higher biomass and longer stems expected.

Conclusions:

The conclusions are supported by the data. However, some clarifications are needed:

- Row 231: 10% attenuation appears small to have any significant impact. Which attenuation level must be achieved for significant positive impacts?
- Can you elaborate on the uncertainty/sensitivity regarding the 10% wave attenuation, referring to the stated “conservative estimates based on using plant species with low breaking force (i.e., “weak”)”.
- R250-263: Improve the discussion by amending with management implications. Obviously salt marshes should be protected, but would some vegetation management/maintenance be useful and realistic in certain areas? Is this 10% reduction result cost-effective to support large-scale restorations? Can restoration activities be prioritized based on certain criteria?
- Fig 4: Africa and South America are not well represented on the map. It remains unclear, how biased the global analyses are.

Suggested improvements:

Improve logical flow, some explanations should appear earlier in the text:

- Short description of different salt marsh vegetation types/conditions globally
- Basis for 1 m wave height limit used?
- Wave action durations?

Suggestions and notes for clarification:

- Extended vegetation characterization would be helpful (cf. comment above). Optical, remote sensing, LAI, PAI -> global analyses of coastal vegetation change possible?
- How much time is needed for vegetation recovery after various storms?
- Comment on the representativeness of the tested vegetation in winter state (did the global up-scaling also consider hydrodynamics in winter?)
- From wave attenuation point of view, clarify how salt marsh vegetation differs from brackish water conditions (note e.g. Baltic Sea shown in map figures)
- Check that terminology is consistently used/defined: green-grey, NBS, ecosystem services
- Fig1: remove photos A and D as unnecessary (save space to enlarge B and C); WHM and scale bars are over-sized; could show waves instead of horizontal water surface;
- Fig1 option for more informative cross sectional and plan views: add conceptual descriptions of the key physical processes controlling erosion and wave attenuation
- R130-131: To allow easy comparisons, instead of absolute mm values, use time bound mm/h.
- Fig3 is not easy to follow as it does not directly follow the logic/naming of the cases of Table S1.
- FigS1: consider directly using references as subscripts in the Fig rather than abbreviations to the references, which makes reading the figure quite difficult
- Fig3C: clarify why the relationship is shown for stem length only, and not for biomass. Why was vegetation biomass not used in the regression model? Biomass appears to be a more direct proxy of the vegetation density than stem height. These two variables might complement each other in explaining bulk resistance to breaking and erosion (as found in the fluvial context).
- Extrapolation in Fig3D to durations larger than 15-20 h appears rather uncertain due to data scatter at lower durations. Consider removing the extrapolations since these are mostly not required in the upscaling.
- Justify the physical basis of considering wave attenuation by vegetation as relative share (%) of the total rather than as absolute value. Also clarify for the audience not so familiar with the topic why only wave height was considered, and not e.g. wave height in relation to water depth.
- Comment the role of day-to-day and other less extreme wave action in causing progressive vegetation damage and erosion of the substrate. How does the 7 mm of erosion in 21 hours in the experiment scale over storms of different frequencies occurring through decadal time-scales?
- The authors should consider the uncertainty arising from extrapolating the results obtained with the tested sediment to global sediment conditions. The comment applies overall but specifically referring to L233-235.

Further remarks:

Regarding the references, the manuscript appropriately incorporates previous literature on coastal environments but appears overly confined to this domain. It would benefit from engaging more extensively with research on fluvial and wetland environments, particularly recent advances in the parameterization of natural vegetation and in the characterization of drag and flow resistance associated with natural plants.

Overall, the abstract, introduction and conclusions are well written. However, see the comments/suggestions above for improvement. As a minor further detail in the abstract, the 1 m height limit is not explained/reasoned.

Please note that some of the statistical tests and interpretations fall outside the reviewer's core expertise.

Referee #3

(Remarks to the Author)

I co-reviewed this manuscript with one of the reviewers who provided the listed reports.

Referee #4

(Remarks to the Author)

Overall, this is quality research on an important topic, within a nuanced conclusion that I believe represents the truth about how the salt marsh surface versus vegetation provides protection. I like how the MS reveals something new, that we have all suspected but not yet proven. However, the title does not reflect the nuanced finding very well and it obscures this truth in a manner that perpetuates overly simple thinking. A better title that alludes to the conditional finding of the research would provide a more lasting, real-world value to its publication. Moreover, there could be a stronger emphasis throughout the beginning and ending of the text on the flume work versus the global analysis effort. The global analysis effort is a bit tacked onto the flume work.

The flume work is a serious, high quality study that likely required enormous effort. The fundamental contribution to the literature originates from the flume work, which is then extrapolated into the global analysis in a derivative manner. The finding that lower energy marshes provide quality vegetative-driven wave attenuation, whereas higher energy marshes do not, seems to be based on the flume study work. The relationships then play out at the global scale in that analysis. Thus, I'm not sure if there is anything emergent in the global analysis, and if there is, it should be better enunciated as to how that happened analytically.

The figures could be improved in quality. They are strong but could be better.

Line 84 - Should capitalize Gulf and East Coast

103 – what is Winter (?), as capitalized it seems strange. Do you mean the season? Why capitalize?

Fig. 1 – it would be helpful to see the width dimensions of the flume in the top view. I have questions about the wave reflection. I'm not going to drill you on it, but I don't fully like the pathway between the two surfaces. I'd rather see the center be the sampled area.

It would help to have a sentence about how you measured the vegetation in sections 145-154. When I look at Fig. 3, I wonder how did they get the dry biomass without destructive sampling (?). Perhaps this is in the Methods, but I'd like a sentence here.

200 - Not sure *E. athericus* is a conservative estimate, as compared with other species in global salt marshes. I would say it is pretty weak, low density, and low height compared with many other graminoids at least. This should be re-stated or made clear how.

Line 229. This is phrased strange, with emphasis on the 10% number, which is also used in line 226 but for high energy coasts. It just requires the reader to understand that you've switched the concept around. Suggest to reword.

305 - State how you picked up the mold. I imagine they were thousands of kg. With heavy machinery, and if so how did you avoid damage and where in marsh were these samples taken. I assume you are doing this by land and your marsh is a bit higher in elevation, ie you are not extracting using a boat. This would be valuable information for those of us that like to do this kind of stuff.

I can't (or can) imagine how fun and not fun this must have been to do this entire experiment. Having done these things, I am more strongly impressed by the flume work than the global analysis.

Please discuss wave reflection in Methods somewhere 319-338. How much observed? What about wave transformation in the width dimension across the pathway. Did you sample the whole section on either side? How did you avoid width dimensional effects?

I also wonder, did you see differential loss in the marsh vegetation in the length dimension, as the waves progressed in time? Like, was there an area where it was grinded away specifically where wave breaking occurred, or did it happen homogeneously, and how did it evolve. It would be good to have a sentence or two up in the main text on this.

349-366- I don't understand how you did destructive sampling for biomass, and yet produced Fig. 3. I guess the experiment only involved specific wave height/water depth combinations and did not evolve over time? ...thus did not require repeated sampling for a given treatment? I think this could be better clarified up in the main text.

405-414. Wave height is reasonable, but I'd think it would be just as easy to use wave power, like H and T_p , like H -squared times T , or some version. The period/wave length is very important, I think. But, I'm ok with it as first order guess.

Version 1:

Reviewer comments:

Referee #1

(Remarks to the Author)

I am quite satisfied with the responses to my comments. Below are a few suggested edits to improve the prose in my opinion that the authors can choose to make or not as they wish.

L114. Edit to "...without aboveground vegetation but with largely intact belowground biomass (see..."

L138. Edit to "...intact belowground biomass throughout all experimental runs..."

L140. Edit to "...irrespective of the short-term damage to aboveground biomass..."

L232. Create a new paragraph beginning with the sentence "Across multi-year..."

Referee #2

(Remarks to the Author)

The authors have worked rigorously to improve the manuscript and are thanked for the carefully prepared rebuttal letter. Most of the comments and criticisms raised in the previous review have been adequately addressed. There are still some issues needing attention, with details following below.

The abstract now clearly communicates the novelty of this research but the discussion section “Marsh vegetation reducing extremes” (L206-254) could be amended accordingly to highlight the key novelties. As a minor remark, use “approximately” and the number of decimals consistently (now approximately 2.00 m, 1.0 m, and 1 m).

R2R4: Please clarify why only few statistically significant differences were observed (Table S2), as this is not explicitly stated in text. Compare with L157-160: aboveground biomass and stem height did not change significantly across the experimental runs with different wave forcing, apart from biomass during the last experimental run with a significant wave height of 2.0 m (t-test for normal and Mann-Whitney U test for not normal distributed samples; Benjamini–Hochberg FDR p-value correction; $p > 0.05$; see SI Table S2).

R2R13: The potential of extended vegetation characterizations could be briefly mentioned in the discussion for both flume and global scales (see also R2R28 below).

R2R14: The response appears too optimistic, as the vegetation recovery in winter is likely very slow for a long period of time, resulting in reduced protection in case of consecutive storm events.

R2R16: The response is informative, but the brackish water condition is not specifically addressed in the MS text. Note also inconsistency with L228-232: “This is different for brackish and freshwater marshes, which are more prone to erosion due to shallower root zones and potentially low inorganic sediment content (Howes et al., 2010). Hence, our projection yields a conservative estimation regarding soil erodibility for salt marshes, but may overestimate the stability of organic-rich soils and brackish marshes.”

R2R25: Clarify how the relative values can be extrapolated to higher depths. What assumptions or scaling relationships support such extrapolation, and what are the associated uncertainties?

R2R28: The answer did not directly address the comment related to the advanced parameterizations of natural vegetation for hydrodynamic analyses. As stem height is used as a proxy for wave attenuation, how can it be efficiently monitored or estimated at different scales? In comparison, for floodplain flow analyses, LAI and PAI are useful, remotely sensed measures of vegetation quantity. Please elaborate on the potential of these and other comparable measures (e.g., canopy height models from LiDAR, SAR backscatter metrics, structure-from-motion photogrammetry, hyperspectral indices) that could be used as proxies to predict wave attenuation across scales, and discuss their feasibility and limitations for both flume and field/global applications.

Referee #3

(Remarks to the Author)

I co-reviewed this manuscript with one of the reviewers who provided the listed reports.

Referee #4

(Remarks to the Author)

Overall, a good revision. I don't have much more to say. I do think you should be citing Feagin et al. 2009, since it was one of the first wave erosion in salt marsh studies conducted and it has been omitted from the references. That work answers questions about extrapolation across soil types, which has implications for global applicability, as stated by one of the other reviewers. Also, the present study does not really address the below ground component, as pointed out by another reviewer, which is a critical piece of what wetland vegetation can and cannot do in terms of erosion reduction, and that citation differentiates between the two spheres above ground and below ground. In other words, that citation would help set the boundaries on the applicability of the present study, in that the present study is about the vegetation (only) and not the soil which is where you get global variance from the key finding.

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Rebuttal manuscript: How and where salt marshes protect against extreme storms

2026 – 04 - 28

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Referees' comments:

Referee #1 (Remarks to the Author):

R1Q0: I enjoyed reading this contribution from Willemsen and others on Salt Marshes Globally Protect Against Extreme Storms. Wave attenuation is perhaps the least studied of the ecosystem services provided by tidal wetlands so their effort to extend previous physical models of vegetation-related contributions to wave attenuation strikes me as important. Their effort to estimate the contribution of vegetation to wave attenuation globally helps broaden the impact of the work.

Because most ecosystem science is performed at the scale of a few meters, a strength of the research is the large scale of this experimental manipulation. I was impressed by the effort required to extract 66 intact tidal marsh monoliths, each of which were fairly large at 2x2 m in area and 0.7 m deep. The quality of an experiment is not judged by its scale, but scientifically insightful efforts performed at this scale are relatively rare, so this aspect of the work needs acknowledgement. The wave heights and duration of the experiment are reasonably realistic for the conclusions they drew and the global extrapolation.

I agree with the major insights that the authors chose to highlight. The research places new bounds the capacity of aboveground vegetation to attenuate waves, and these bounds are different for low- and high-energy coastlines, and dependent on wave height. I consider these points to be meaningful because they add caveats to the broad, global claims we often make about tidal wetland ecosystem services and hopefully force us to be more nuanced and transparent about the benefits of protecting and restoring coastlines.

***R1R0:** Thank you for taking the time to review the manuscript and providing us with your valuable feedback. This is very much appreciated. We have improved the manuscript accordingly.*

Major Comments

R1Q1: 1. The focus of the authors on aboveground biomass and height is appropriate for the issue of wave attenuation which dominates most of the manuscript. However, an important part of the manuscript that appears in the abstract, results, and discussion is the stability of the marsh platform irrespective of vegetation. Missing is the fact that belowground plant tissue also contributes to platform stability by stabilizing soil structure. This is an important point that needs to be acknowledged and there is a robust literature to draw upon relating belowground biomass to erosion-relevant physical properties such as shear stress.

The implications of the absence of data and discussion on belowground biomass depends on how the effects of vegetation on marsh elevation were calculated. Based on L332-338 and L341-348 of the methods it appears that conclusions about plant effects on elevation are based only on measurements made on the marsh monoliths before and after the aboveground biomass was mowed. If so, the belowground biomass was largely intact after mowing and plant biomass was still stabilizing the soil against erosion.

Alternatively, if the authors are comparing changes in elevation in the marsh section of the flume to changes in elevation in the mudflat section of the flume, then conclusions about the

absence of vegetation are reasonable as the mudflat did not plants, including their belowground biomass. This alternative approach does not seem to be the case, so the authors should modify their discussion to acknowledge the soil-stabilizing capacity of plant belowground biomass.

R1R1: The manuscript has been improved according to the above comment in several ways:

- Erosion is indeed measured and discussed specifically for the salt marsh, and not for the bare tidal flat. The bare mudflat was not the focus of the study, hence it was a concrete construction that was not subject to change to enable a meaningful comparison of results from the salt marsh. Indeed the belowground biomass of the salt marsh was largely intact after mowing and belowground biomass stabilized the soil throughout the experiment. The text in the main body and Methods section has been changed for clarity:
 - (main body: lines 145 - 148) “Thus, with negligible surface erosion and largely intact vegetation belowground biomass and root structures throughout all experimental runs, our experiment suggests that marsh platforms are able to contribute to wave attenuation irrespective of the damage to aboveground biomass, as long as there is no lateral retreat due to seaward cliff initiation and erosion (Bouma et al., 2014; Mason et al., 2025)”.
 - (methods: lines 515 – 517) “The bare tidal flat was constructed using concrete to prevent bed level dynamics at the flat potentially affecting the incoming wave at the marsh edge, as the focus was on the dynamics of the vegetated salt marsh.”
 - (methods: lines 617 - 618) “The concrete bare tidal flat, seaward from the salt marsh in the flume, was not subject to change”.
- In general, root structures in salt marshes are found at a depth below the surface up to approximately 40 cm. As stated in review comment **R1Q1**, belowground biomass tissue contributes to soil strength, for example in marshes across Europe and North America (Brooks et al., 2021). A higher contribution to stability is expected for a salt marsh vegetation composition that has a higher plant diversity (e.g. Ford et al., 2016). Thus, we agree that it is important to address this clearly in the manuscript. In our experiment, *Elymus athericus* showed decreasing biomass of root material with depth with most dry belowground biomass (76% to 80%) in the top layer (5 cm depth) and only 2% to 7% of the total biomass at a depth of 20 cm, similar to marshes for example in the UK and US (Brooks et al., 2021). The roots of the dominant *Elymus athericus* species in our experiment were, despite the low plant diversity, able to stabilize the bed under the extreme conditions tested. These insights are added in the main body of text, Methods section and Extended Data. In the Methods, a section is now dedicated to belowground biomass (roots) and organic matter content (1.3. Organic matter content and root biomass of the substrate).
 - (main body of text: lines 133 – 137) “The presence of belowground biomass and roots in the marsh substrate is known to enhance soil stability Also, a clear root zone was present in our experiment, mainly in the top 10 cm of the substrate. Organic matter content in the marsh substrate was 4.7% ± 1.7% (see Methods and Extended Data table 2).”
 - (methods: lines 568 - 579) “Prior studies describe a rooting depth of vegetation species in salt marshes of 10 to 40 cm below the surface (Brooks et al., 2021). The *Elymus athericus* marsh cover has a web-like root structure (i.e. dichotomous branching), with long roots compared to other species, but an average to low central root and branch density (Bouma et al., 2001). Vegetation roots stabilize the soil, potentially with increasing stability if the

vegetation composition is more diverse (Ford et al., 2016). Root mass in our experiment was measured at 5, 10 and 20 cm depth, with n (sample size) = 4. Root samples were collected after the experimental wave runs at locations where the soil was undisturbed by placing bulk density rings (6 cm diameter and 4.05 cm depth), with the midpoint at the chosen depth. The rings with material were carefully dug out, roots were gently rinsed and dried in an oven at 60 °C for 48 hours, before weighing to obtain dry root mass (g) at each depth interval. Subsequently, root density was calculated. Belowground biomass was mainly present in the top layer in our experiment (5 cm; 78% of the total biomass; Extended Data table 1)."

- (Extended Data: lines 926 - 931) "Table 1. Root mass distribution"

R1Q2: 2. The authors acknowledge on L127 that wave attenuation depends on the stability of the marsh substrate. In the present case the marsh substrate was 31-45% clay with properties like cohesion that contribute to the stability of the marsh platform. My sense is that the grain size distribution of the monoliths in this study transfer well to many coastal marshes. However, they also transfer poorly to many other coastal marshes in places like the Atlantic and Gulf coasts of North America where organic-rich soils and sediments are common. Importantly, I suspect that the global distribution of organic-rich soils co-varies with the distribution of low-energy coastlines, an important interaction that the authors do not recognize in the text of the paper.

To be clear, I am certainly not asking the authors to incorporate soil properties into their global model which would be difficult and beyond the capacity of their statistical model. The model they are using for a global extrapolation is appropriate for the data they have available from the flume study. Rather, I am asking them to discuss this matter in the section titled Global marsh vegetation reducing extremes.

R1R2: *Thank you for emphasizing the importance of soil parameters globally. This has been acknowledged in the manuscript. Below we offer a mechanistic discussion, including a comparison with other studies/regions and explain how this is applied in the manuscript.*

- *The mean organic matter content of the marsh substrate used in the experiment was $4.7\% \pm 1.7\%$. This is added in main body of text and in the Methods section and described in more detail in the Extended Data. In the Methods, a subsection is now dedicated to belowground biomass (roots) and organic matter content (1.3. Organic matter content and root biomass of the substrate).*
 - *(main body of text: lines 135 – 137) "Organic matter content in the marsh substrate was $4.7\% \pm 1.7\%$ (see Methods and Extended Data Table 2)."*
 - *(methods: lines 559 - 561) "Mean organic matter content in the salt marsh substrate in our experiment was $4.7\% \pm 1.7\%$ and ranged between 2.3% and 7.6% (Extended Data Table 2). Organic matter content is determined using loss-on-ignition (LOI)."*
 - *(Extended Data: lines 929 - 936) "Table 2. Grain size characteristics and organic matter content"*
- *As mentioned in the reply to the previous comment (R1R1), information on root mass distribution over substrate depth is added in the main body of text, methods section and Extended Data. For completeness this is repeated below:*
 - *(main body of text: lines 133 – 137) "The presence of belowground biomass and roots in the marsh substrate is known to enhance soil stability Also, a clear root zone was present in our experiment, mainly in the top 10 cm of the*

substrate. Organic matter content in the marsh substrate was $4.7\% \pm 1.7\%$ (see Methods and Extended Data table 2)."

- (methods: lines 568 - 579) "Prior studies describe a rooting depth of vegetation species in salt marshes of 10 to 40 cm below the surface (Brooks et al., 2021). The *Elymus athericus* marsh cover has a web-like root structure (i.e. dichotomous branching), with long roots compared to other species, but an average to low central root and branch density (Bouma et al., 2001). Vegetation roots stabilize the soil, potentially with increasing stability if the vegetation composition is more diverse (Ford et al., 2016). Root mass in our experiment was measured at 5, 10 and 20 cm depth, with n (sample size) = 4. Root samples were collected after the experimental wave runs at locations where the soil was undisturbed by placing bulk density rings (6 cm diameter and 4.05 cm depth), with the midpoint at the chosen depth. The rings with material were carefully dug out, roots were gently rinsed and dried in an oven at 60 °C for 48 hours, before weighing to obtain dry root mass (g) at each depth interval. Subsequently, root density was calculated. Belowground biomass was mainly present in the top layer in our experiment (5 cm; 78% of the total biomass; Extended Data table 1)."
- (Extended Data: lines 923 - 928) "Table 1. Root mass distribution"
- Organic matter contents of the soil from our experiment can be compared with values from other salt marsh locations globally:
 - Our experiment, range: 2.3% – 7.6%, mean: 4.7%
 - Wadden Sea, Northwestern Europe, range: 1.3% – 8.8%, mean: 4.2% (Mittman-Goetsch et al., 2024)
 - East Coast US and Gulf of Mexico, range: 0% – 55% (Turner et al., 2005)
 - European regional seas, range: 0% - 76.7%, mean: 8.5% (Graversen et al., 2025)
 - Mediterranean Italy, range: 4% - 30% (Puppin et al., 2024)

The contribution of organic matter contents to shear strength of the soil is twofold: in general, organic content increases the erosion resistance of the soil, which is also the case for erosion on a grain-by-grain scale (Brooks et al., 2021; Evans et al., 2022; Marin-Diaz et al., 2022, 2025). However, there are important nuances, as organic-rich soils with a higher organic matter content and higher belowground root content are more compressible. So, in very organic-rich soils there can be a high void ratio and more open structure that results in instability (Brain et al., 2011; 2015). Marshes with these characteristics can be found on the East coast and Gulf of Mexico of the US (Brooks et al., 2021), but marshes with higher organic matter for example in Europe, appear to be stronger (Marin-Diaz et al., 2022; 2025). Compared to salt marshes, the erodibility of fresh and brackish marshes is larger due to shallower rooting and potentially low inorganic sediment content and high nutrient inputs. This is supported by preferential erosion of brackish marshes, whereas the salt marsh substrate remained largely unaffected during hurricanes Katrina and Rita in the Louisiana coastal plain (Howes et al., 2010). From this we conclude that the marsh substrate in our experiment is representative for marshes in general, but might overestimate the stability of more organic-rich soils found at the East coast of the US and Gulf of Mexico. So, our study yields a conservative estimator regarding soil erodibility for salt marshes in general, but might overestimate the stability of brackish marshes and marshes with organic-rich soils. Nevertheless, brackish and freshwater marshes are found more inland, and might experience less exposure than the saline marshes fronting the open sea. Organic matter content measured in the salt marsh in our experiment has been added to the main body of text. For comparison, data from

other locations globally has been added to the Methods section 1.3 (dedicated to the substrate). The implications discussed here are summarized in the last section of the main body of text.

- (main body of text: lines 135 – 137) “Organic matter content in the marsh substrate was $4.7\% \pm 1.7\%$ (see Methods and Extended Data Table 2).”
- (Extended Data: lines 929 - 936) “Table 2. **Grain size characteristics and organic matter content** of the top 30cm of the substrate at the two locations in the field site where the salt marsh blocks are collected.”
- (methods: lines 559 – 567) “Mean organic matter content in the salt marsh substrate in our experiment was $4.7\% \pm 1.7\%$ and ranged between 2.3% and 7.6% (Extended Data Table 2). Organic matter content is determined using loss-on-ignition (LOI). The organic matter content in the substrate in our experiment is similar to many other European salt marshes, which typically range between 0% and 76.7% (mean of 8.5%) (Graversen et al., 2025). More specifically, studies in the Wadden Sea, Northwestern Europe show a range between 1.3% and 8.8% (mean of 4.2%) (Mittmann-Goetsch et al., 2024)) and in the Mediterranean between 4% - 30% (Puppini et al., 2024). The organic matter content in our study is within the lower range when comparing to, for example, North American marshes, which are more organic-rich (range 0% - 55%) (Turner et al., 2000).”
- (main body of text: lines 253 - 266) “In general, our study implies that nature’s services to society (ecosystem services) depend on the stability of the salt marsh substrate, such as wave attenuation and carbon storage (Mason et al., 2023; Mcleod et al., 2011), and are unlikely to be affected by extreme storms via surface erosion, as the marsh substrate remains stable both at low- and high-energy coasts. Our flume experiment where this is based on contains two soil types (Extended Data table 2). The organic matter content of the soil is representative for European marshes, which corresponds to the lower range of the organic-rich soils at the East coast of the US and the Gulf of Mexico (see Methods) (Turner et al., 2000). Organic-rich soils can have a more open structure that might result in instability (Brooks et al., 2021), although this is not the case for higher organic matter content such as in European salt marshes (Marin-Diaz et al., 2022). This is different for brackish and freshwater marshes, which are more prone to erosion due to shallower root zones and potentially low inorganic sediment content (Howes et al., 2010). Hence, our projection yields a conservative estimation regarding soil erodibility for salt marshes, but may overestimate the stability of organic-rich soils and brackish marshes.”

R1Q3: 3. I found the section on Global marsh vegetation reducing extremes to be a bit of a weak spot in the manuscript. While I appreciate text on the relevance of the work to topics like nature-based solutions, I think the text in this section would be better invested in advancing the field by discussing how to further refine the global model.

The authors make the point that their estimates are conservative because of the height and stiffness of the dominant plants in the marsh monoliths. I suggest they add discussion on the extent to which their conclusions would vary in marshes with more robust plants such as large areas of the world where invasive *Phragmites australis* or *Spartina alterniflora* are

dominant or shrub-dominated marshes. I also suggest adding thoughts about how soil type would affect their estimates.

R1R3: The section “Marsh vegetation reducing extremes” is adjusted based on the comment above and comments from the other reviewers:

The discussion focusing on NbS in the section on “Marsh vegetation reducing extremes” is shortened (main body of text: lines 287 - 295).

Uncertainties related to global upscaling are now addressed twice, based on comments and suggestions of all reviewers. A wider comparison with literature is included and the effect of other (less conservative) marsh vegetation species is discussed and assessed in a scenario analysis testing the sensitivity of vegetation.

- Discussing the influence of vegetation species in salt marshes, brackish and freshwater wetlands as well as environments including seagrass meadows and riverine settings. This is implemented in the last section of the main body of text, in addition to Figure 1 in the Extended Data. For a more extensive discussion of substrate stability and erodibility please refer to the response to the previous comment (**R1R2**). In the methods section a new section has been written to put the vegetation used in our experiment in a wider perspective (methods Section 2.2. Stem height in salt marshes as proxy for wave attenuation).
 - (main body of text: lines 233 - 248) “Projecting results from the flume experiments to a global scale suggests that in general, salt marsh vegetation enhances the resistance of low-energy marsh coasts to extreme conditions. At almost all low-energy marsh coasts with waves up to 1 m, waves are attenuated by more than 10% for *Elymus athericus*, which can be considered a conservative wave attenuation estimator for salt marshes in general (Extended Data Figure 1). This wave attenuation functionality is also found in seagrass environments under low-energy conditions (Bradley & Houser, 2009), and may also apply in freshwater settings (Ren et al., 2021). Decreasing salinity induces an increase in species diversity, because species diversity increases with decreasing environmental stress (Więski et al., 2010). Also, it leads to a shift towards species with longer and less flexible stems compared to *Elymus athericus*, such as the common reed *Phragmites australis* (Zhu et al., 2019; Dijkema, 1990). Both higher species diversity and the shift to longer and less flexible stems enhance wave attenuation, even under higher vegetation damage. This corresponds with the result of our sensitivity analysis (Extended Data Figures 3-6).”
 - (main body of text: lines 253 - 266) “In general, our study implies that nature’s services to society (ecosystem services) depend on the stability of the salt marsh substrate, such as wave attenuation and carbon storage (Mason et al., 2023; Mcleod et al., 2011), and are unlikely to be affected by extreme storms via surface erosion, as the marsh substrate remains stable both at low- and high-energy coasts. Our flume experiment where this is based on contains two soil types (Extended Data table 2). The organic matter content of the soil is representative for European marshes, which corresponds to the lower range of the organic-rich soils at the East coast of the US and the Gulf of Mexico (see Methods) (Turner et al., 2000). Organic-rich soils can have a more open structure that might result in instability (Brooks et al., 2021), although this is not the case for higher organic matter content such as in European salt marshes (Marin-Diaz et al., 2022). This is different for brackish

and freshwater marshes, which are more prone to erosion due to shallower root zones and potentially low inorganic sediment content (Howes et al., 2010). Hence, our projection yields a conservative estimation regarding soil erodibility for salt marshes, but may overestimate the stability of organic-rich soils and brackish marshes.”

- (methods: lines 697 - 725) **“2.2. Stem height in salt marshes as proxy for wave attenuation**

Key for the functionality of the marsh is the presence of salt-tolerant vegetation (halophytes), such as herbs, grasses and shrubs, which typically depend on salinity and inundation gradients (Adam, 1993). The stem height of the vegetation is an important parameter, for wave attenuation. Stem height is used as a proxy for wave attenuation as penetration of the stem in the water column is considered a strong predictor of wave attenuation, especially under extreme wave heights and water levels (Vuik et al., 2018). As a result, damage to vegetation by a decreasing stem height will have a direct impact on wave attenuation. Stem height, as well as biomass of *E. athericus* is comparable with global marsh vegetation species that carry stems. Both values of damaged stem height and biomass at the end of our experiment, were smaller than values globally found for (other) salt marsh vegetation species (Extended Data Fig. 1), throughout the year.

Increasing wave attenuation with stem height can be expected both at low- and high-energy coasts, and is also found as a result of the flume experiment (Figure 3). Yet for high-energy conditions, the higher risk of damage may cancel this benefit. Comparing *Elymus* with *Spartina* spp., locally a species growing at a lower elevation and regionally a dominant species in e.g. North America (Pennings & Bertness, 2001; Bertness, 1991), wave-induced damage to *Spartina* spp. is lower due to a higher flexibility (Reents et al., 2022). Hence, attenuation can be expected to be higher as more stems and biomass persists (Fig. 3). Attenuation can also be expected to increase towards a lower salinity environment, since due to decreasing environmental stress, species diversity increases (Ren et al., 2021; Więski et al., 2010; Schulte Ostermann et al., 2024).

“70% of the salt marshes globally present are found in the temperate climate zone and therefore experience a winter season (Worthington et al., 2024). In general, the vegetation state at the end of the winter can be considered to yield a conservative estimate for vegetation stem height as vegetation outside the winter season, e.g. in the growing season, is more resistant (Reents et al., 2022). Furthermore, *E. athericus* in our experiment can be considered to yield a conservative estimate of wave attenuation, because its breaking force is relatively low (weak) compared to other salt marsh vegetation species (Zhu et al., 2019). Less vegetation damage leads to longer stems persisting and hence a higher wave attenuation capacity. In addition, we tested a single salt marsh zones, whereas salt marshes in general contain multiple zones that enhance the wave attenuation capacity (Schoutens et al., in preparation). Finally, only a small (70 m) part of the marsh was considered for wave attenuation.”

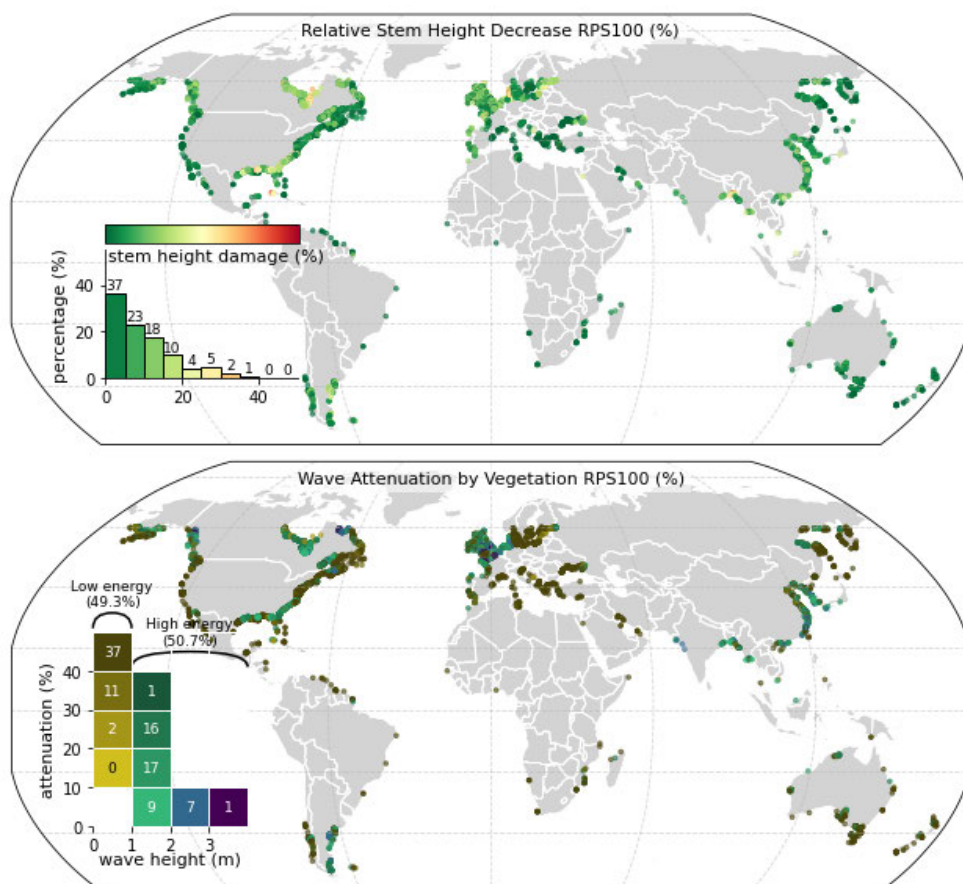
- Assessing the uncertainty for species that would yield less-conservative estimations by changing vegetation related parameters in the global upscaling. First, the vegetation height is doubled (100% increase) to resemble species with longer stems (e.g. *Phragmites australis*), while progressive damage remained the same (adapting relation in Fig. 3 panel B). Wave attenuation by vegetation for this adapted stem

height was calculated through the relations obtained in the experiment for *Elymus athericus* (Fig. 3 panel C). To finalize this assessment a new GLM was fitted to calculate wave attenuation by increased vegetation globally. With this first up-scaling scenario, additional damage by longer vegetation was not considered. Although *Elymus athericus* (used in our experiment) is considered a rather weak species (e.g. Reents et al., 2022), longer stems as *Phragmites australis* experience larger wave orbital velocities potentially leading to more damage. Hence, a second scenario is applied where exponential vegetation damage (Fig. 3 panel B) is increased by 100% (i.e. $y = a * e^{(b * x)}$ adapted to $y = a * e^{(2 * b * x)}$). These scenarios are applied to events with return periods of 100 and 1000 years, totaling four additional model runs.

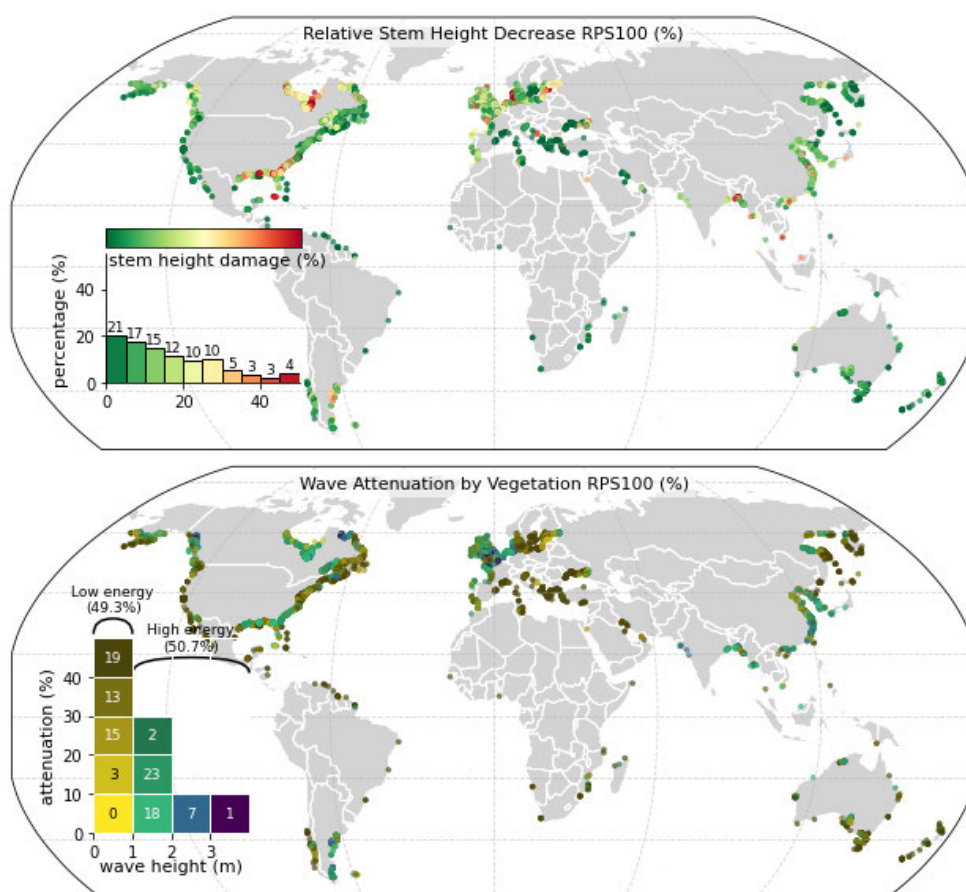
This scenario analysis for the sensitivity of vegetation properties (damage and height), emphasizes that longer species increase wave attenuation. Incoming wave heights between 0 and 1 m (low-energy waves) are attenuated generally by 30% or more, while incoming waves exceeding 1 m (high-energy waves) are attenuated less than 30% generally. When considering an increase in damage if vegetation is higher, a similar trend is observed, although the tipping point is now at 20%, which was at 10% in the initial scenarios. Incoming waves below 1 m are attenuated by more than 20%, while incoming waves exceeding 1 m are generally attenuated no more than 20% (see rebuttal Figure 1 and 2 for the results with a return period of 100 years; for a return period of 100 and 1000 years, Figures 3 - 6 are added in the Extended Data Figures 3 – 6). The scenario analysis therefore emphasizes that a less conservative estimate including longer vegetation leads to more attenuation, even when including increased damage. In addition, the trend regarding low-energy (< 1 m incoming wave height) and high-energy (>= 1 m incoming wave height) remains the same. Only the tipping point of wave attenuation switches between 10% (*Elymus athericus* model assessment), 20% (increased vegetation height with increased damage), and 30% (increased vegetation height only). These considerations are added in the last section of the main body of text and model results in the Extended Data.

- (main body of text: lines 245 - 248) “Both higher species diversity and the shift to longer and less flexible stems enhance wave attenuation, even under higher vegetation damage. This corresponds with the result of our sensitivity analysis (Extended Data Figures 3-6).”
- (Extended Data: lines 959 - 965) **“Figure 3. Storm events lead to decreasing wave attenuation due to vegetation damage, model results with increased vegetation height (return period of 100 years).** Water depth at the seaward salt marsh edge, and distribution of water depths over all transects (a), exposure duration for progressive vegetation damage and distribution (b), relative stem height decrease and distribution (c) and GLM-predicted attenuation by vegetation and distribution per wave attenuation percentage class and incoming wave height bin (d), calculated for a scenario where vegetation height is increased by 100%.”
- (Extended Data: lines 966 - 972) **“Figure 4. Storm events lead to decreasing wave attenuation due to vegetation damage, model results with increased vegetation height (return period of 1000 years).** Water depth at the seaward salt marsh edge, and distribution of water depths over all transects (a), exposure duration for progressive vegetation damage and distribution (b), relative stem height decrease and distribution (c) and GLM-predicted attenuation by vegetation and distribution per wave attenuation percentage class and incoming wave height bin (d), calculated for a scenario where vegetation height is increased by 100%.”

- (Extended Data: lines 973 - 979) “Figure 5. **Storm events lead to decreasing wave attenuation due to vegetation damage, model results with increased vegetation height and damage (return period of 100 years)**. Water depth at the seaward salt marsh edge, and distribution of water depths over all transects (a), exposure duration for progressive vegetation damage and distribution (b), relative stem height decrease and distribution (c) and GLM-predicted attenuation by vegetation and distribution per wave attenuation percentage class and incoming wave height bin (d), calculated for a scenario where vegetation height is increased by 100% and vegetation damage is also increased by 100%.”
- (Extended Data: lines 980 - 986) “Figure 6. **Storm events lead to decreasing wave attenuation due to vegetation damage, model results with increased vegetation height and damage (return period of 1000 years)**. Water depth at the seaward salt marsh edge, and distribution of water depths over all transects (a), exposure duration for progressive vegetation damage and distribution (b), relative stem height decrease and distribution (c) and GLM-predicted attenuation by vegetation and distribution per wave attenuation percentage class and incoming wave height bin (d), calculated for a scenario where vegetation height is increased by 100% and vegetation damage is also increased by 100%.”



Rebuttal figure 1. Relative stem height decrease and distribution (top panel) and GLM-predicted attenuation by vegetation and distribution per wave attenuation percentage class and incoming wave height bin (bottom panel) for a return period of 100 years calculated for a scenario where vegetation height is increased by 100%.



Rebuttal figure 2. Relative stem height decrease and distribution (top panel) and GLM-predicted attenuation by vegetation and distribution per wave attenuation percentage class and incoming wave height bin (bottom panel) for a return period of 100 years calculated for a scenario where vegetation height is increased by 100% and vegetation damage is also increased by 100%.

Minor Comments

R1Q4: L104. Please add some insights on the rooting structure of the two dominant species such as rooting depth and aspects of belowground morphology such as roots and rhizomes that may be relevant to marsh platform stability.

R1R4: In general, root structures are found at a depth below the surface up to approximately 10 to 40 cm. These root structures contribute to soil strength, e.g. in marshes across Europe and North America (Brooks et al., 2021). The salt marsh in our experiment was covered with *Elymus athericus*, with a web-like/branching root structure (i.e. dichotomous branching), with on average long roots compared to other species, but an average to low central root and branch density (Bouma et al., 2001). The substrate with *Elymus athericus* was able to remain at its position under the extreme conditions tested. Insights have been added regarding root structure for the dominant *Elymus athericus* vegetation species in our experiment.

The dominant species *Elymus athericus* in our experiment showed the same distribution of belowground biomass, as generally observed in marshes (Brooks et al., 2021), with most dry belowground biomass (76% to 80%) in the top layer (5 cm depth) and only 2% to 7% of the total biomass at a depth of 20 cm.

- (main body of text: lines 133 - 137) "The presence of belowground biomass and roots in the marsh substrate is known to enhance soil stability. Also, a clear root zone was present in our experiment, mainly in the top 10 cm of the substrate. Organic matter content in the marsh substrate was $4.7\% \pm 1.7\%$ (see Methods and Extended Data table 2).
- (methods: lines 568 - 579) "Prior studies describe a rooting depth of vegetation species in salt marshes of 10 to 40 cm below the surface (Brooks et al., 2021). The *Elymus athericus* marsh cover has a web-like root structure (i.e. dichotomous branching), with long roots compared to other species, but an average to low central root and branch density (Bouma et al., 2001). Vegetation roots stabilize the soil, potentially with increasing stability if the vegetation composition is more diverse (Ford et al., 2016). Root mass in our experiment was measured at 5, 10 and 20 cm depth, with n (sample size) = 4. Root samples were collected after the experimental wave runs at locations where the soil was undisturbed by placing bulk density rings (6 cm diameter and 4.05 cm depth), with the midpoint at the chosen depth. The rings with material were carefully dug out, roots were gently rinsed and dried in an oven at 60 °C for 48 hours, before weighing to obtain dry root mass (g) at each depth interval. Subsequently, root density was calculated. Belowground biomass was mainly present in the top layer in our experiment (5 cm; 78% of the total biomass; Extended Data table 1)."
- (Extended Data: lines 923 - 928) "Table 1. **Root mass distribution** mean and standard deviation at 5, 10 and 20 cm depth, with n (sample size) = 4. Root samples were collected after the experimental wave runs at locations where the soil was undisturbed by placing bulk density rings (6 cm diameter and 4.05 cm depth), with the midpoint at the chosen depth. The rings with material were carefully dug out, roots were gently rinsed and dried in an oven at 60 °C for 48 hours, before weighing to obtain dry root mass (g) at each depth interval. Subsequently, root density was calculated."

R1Q5: L141. The first paragraph lost me here when the authors report that the marsh platform elevation was fairly stable under extreme wave conditions irrespective of vegetation. Missing to this point is information about changes in the elevation in the absence of the aboveground vegetation, which occurred during the third repetition according to the methods section. Please edit the paragraph to support the claim that the platform was stable in the absence of vegetation.

R1R5: Thank you for noticing this. Erosion is reported for the flume experiments with wave-damaged aboveground vegetation being present. These erosion measurements show a resistant surface over the full span of the experiment. 7 mm erosion over 21 hours, a duration longer than the potential exposure duration for vegetation damage of storms with a return period of up to 1000 years (Dullaart et al., 2023).

Furthermore, vegetation damage in the field will not result in the same situation as our runs without aboveground vegetation, as stems will not break flush with the bed level surface (see manuscript figure 3B; Vuik et al., 2018). Hence, the experimental runs with fully cut aboveground vegetation are not considered realistic for the assessment of erosion, but solely used for comparison and calculating the individual contribution of aboveground vegetation. Nevertheless, further erosion was not observed during these tests without aboveground vegetation. The text has been revised for more clarity:

- (main body of text: lines 129 – 132): “Elevation measurements at 32 fixed locations at the salt marsh show, on average, a decreasing marsh surface over the total experimental time of 21 hours with damaged vegetation (7 mm; 0.33 mm/h), which is in the same order of magnitude as previous studies with smaller wave heights (4.4 mm surface lowering; 0.16 mm/h) (Moller et al., 2014; Spencer et al., 2016)”
- (main body of text: lines 145 – 148): “Thus, with negligible surface erosion and largely intact vegetation belowground biomass and root structures throughout all experimental runs, our experiment suggests that marsh platforms are able to contribute to wave attenuation irrespective of the damage to aboveground biomass, as long as there is no lateral retreat due to seaward cliff initiation and erosion (Bouma et al., 2016; Mason et al., 2025)”

R1Q6: L135. Change “coastal plane” to “coastal plain”

R1R6: Thanks, done.

- (main body of text: lines 139 - 140) “...in the Louisiana coastal plain.”

R1Q7: L139. Describing the stability of the marsh platform as a “survival mechanism” seems odd when discussing an ecosystem as opposed to an organism. I suggest editing this to “essential feature”.

R1R7: Changed.

- (main body of text: lines 140 - 144) The observed stability of the marsh substrate under extreme conditions is an essential feature for their existence in areas where regular wave attacks may be expected (Gijssman et al., 2021). Our experiment shows that this essential feature is also valid for extreme storms, which agrees with limited field and flume evidence (Spencer et al., 2016; Howes et al., 2010; Gijssman et al., 2021).

R1Q8: L313. There seems to be an error in the dates since they state the monoliths were installed in the flume in Dec 2024 and the experimental runs occurred 10 months before in Feb 2024 (L319).

R1R8: Indeed an error, changed now.

- (main body of text: line 553) “From December 2023 onwards”

Referee #2 (Remarks to the Author):

R2Q0: Results, validity, originality, and significance:

It was a pleasure to read this manuscript. The primary contribution of this research is that it first investigates key physical processes related to wave forcing using an exceptionally large-scale flume experiment, and then extends this knowledge to enable modelling at the global scale. While the individual components are not particularly novel or groundbreaking, the study is significant when considered as a whole.

The study shows that salt marshes are effective in reducing erosion under highly energetic wave conditions (which have not been examined previously), but that wave attenuation itself is limited and occurs primarily under low-energy conditions. Essentially, the manuscript proposes an empirical relationship for estimating wave attenuation by vegetation as a function of storm exposure duration and incoming wave height.

The use of naturally occurring plants growing in their native soil in the experiments enhances the reliability of the results and their upscaling. However, it remains partly unclear whether it is appropriate to treat all salt marsh vegetation and sediment types equivalently (that is, whether vegetation and sediment properties should be included as predictors). On the other hand, the authors argue that their estimates are conservative, as they are based on plant species with relatively low breaking strength (i.e., “weak” species).

As a further note, the authors could have better stated the novelties themselves; presently it is partly left for the reader to interpret.

No flaws can be identified in the research, but the global representativeness of the experimental data (vegetation, sediment, etc) can be challenged.

No previous analyses exist at this large scale covering a broad range of wave conditions. The results are useful for critically evaluating NBS performance and directing their future developments.

R2R0: *Thank you for taking the time to review the manuscript and providing us with your valuable feedback. This is very much appreciated. We improved the manuscript accordingly.*

- *The novelty has been clarified further and has been addressed in the abstract by explicitly explaining what knowledge and understanding is currently missing, and in the introduction by explicitly stating what knowledge is missing, to better guide the reader:*
 - *(abstract: lines 39 - 40) “However, a comprehensive, quantified understanding of salt marsh-wave interaction under extreme events is lacking.”*
 - *(main body of text: lines 92 - 95) “Quantified knowledge explaining progressive vegetation damage and potential substrate erosion under these conditions, and the efficacy of damaged marsh vegetation in wave attenuation during extreme wave events when waves exceed 1m is lacking.”*
 - *(main body of text: lines 96 - 105) “Based on flume experiments and projected storm simulations at a global scale, here we aim to quantify the persistence of the marsh substrate and address the progressive vegetation damage and*

associated reduced wave attenuation under extreme storm conditions, by assessing:

- I. The stability of salt marsh substrate under extreme wave events;*
- II. Progressive vegetation damage and associated wave attenuation under extreme events;*
- III. The global contribution of progressively damaged salt marsh vegetation to wave attenuation that proceeds from results of the flume experiments.”*

- *Further review points regarding the reliability of the results, global upscaling with respect to vegetation and soil are discussed in the detailed responses that follow hereafter, and in the previous responses in the comments of the referee #1. Please refer to:*
 - *Comment **R1Q1** and **R1Q4** and the response **R1R1** and **R1R4**, regarding the effect of roots and how the roots of salt marsh species used in our flume experiment (*Elymus athericus*) compare with the root zone from other salt marsh vegetation species.*
 - *Comment **R1Q2** and the response **R1R2**, regarding organic matter in the soil and similarities and differences, and the potential impact on erodibility when comparing the organic matter content from our salt marsh substrate to other regions worldwide.*
 - *Comment **R1Q3** and the response **R1R3**, regarding the representativeness of salt marsh vegetation species and the impact of translating the results to other species.*

Data and methodology:

R2Q1. The methods are clearly reported, allowing reproduction of similar experiments by others. However, the study relied much on conventional, laborious manual vegetation measurements. In addition to those, optical/photogrammetric, multispectral imaging, and other remote sensing methods could have been used to characterize vegetation (e.g. LAI, PAI). Such data would support validation across different scales and regions, while being useful as a reference for other researchers. As a further remark, the sample sizes of some biomass and vegetation height measurements appear small (see below detailed comment concerning N=6 for 20 cm x 20 cm quadrants and N=20 for random stems).

R2R1. *Thank you for the comments, for a reply to the comments, we would like to refer to the more specific comments raised by referee #2:*

- *Regarding remote sensing data techniques, please see the response **R2R13** to detailed comment **R2Q13**.*
- *Regarding sample size, please see response **R2R4** to detailed comment **R2Q4**.*

R2Q2. It remains unclear how representative the tested marsh soil is of other geographical and climatological conditions and what are the uncertainties in the global up-scaling based on one single soil sample. The erodibility of cohesive sediments such as the one tested are known to be uncertain to predict, because multiple factors such as the grain size, % clay fraction, % organic content, dry bulk density, and water content affect erodibility. If too much of the underlying sediment is eroded, vegetation is destroyed by uprooting (not necessarily

by breaking). This mechanism facilitating/generating uprooting was apparently not considered in either the flume study (as erosion of the tested soil material was low) or the global up-scaling.

R2R2. *We agree that the representativeness of the soil was not clearly discussed in the initial draft of the manuscript. Please see:*

- *comment **R1Q1** and **R1Q4** and the responses **R1R1** and **R1R4**, regarding the effect of roots and how the roots of salt marsh species used in our flume experiment (*Elymus athericus*) compare with the root zone from other salt marsh vegetation species.*
- *comment **R1Q2** and the response **R1R2**, regarding organic matter in the soil and similarities and differences, and the potential impact on erodibility when comparing the organic matter content from our salt marsh substrate to other regions worldwide.*

The representativeness of the soil is extensively discussed in the rebuttal and clarified in the revised manuscript.

R2Q3. The methodology of obtaining the 1/100 and 1/1000 wave heights based on the storm surge observations is not clearly described.

R2R3. *Please see the response **R2R12** to the comment **R2Q12** “Wave action durations” below. The derivation of the hydrodynamic conditions when damage starts is now more clearly described in the methods section.*

- *(Methods: lines 755 - 760) “Since stem height damage in the Delta Flume experiment started already during the most tranquil hydrodynamic conditions ($h = 1.5$ m; $H_{m0} = 0.75$ m), initiation of stem height damage in the global model was set following previous controlled flume experiments (Rupprecht et al., 2017). In these previous experiments, starting at water depths of 1 m and wave heights of 0.1 m, first, significant stem damage was observed after water depths of 1 m and wave heights of 0.5 m on average (Rupprecht et al., 2017).”*

Subsequent derivation of exposure duration is now further described in the Methods section.

- *(methods: lines 760 - 766) “Using the local storm surge hydrographs, exposure duration for vegetation damage is calculated over the time window during which wave heights at the marsh exceed 0.5 m from the start of the storm until the point in time when the highest waves occur, i.e. at the peak of the storm surge hydrograph. The maximum incoming wave height at the marsh edge is calculated at the peak of the storm, with the most severe estimate for the wave height being 50% of the water depth (Van Zelst et al., 2021; Massel, 1996; Nelson et al., 1994). Finally, wave attenuation at the peak of the storm is calculated using the GLM, as the highest depth-limited waves potentially occur at this point.”*

R2Q4. It appears that statistical tests were rigorously completed, but in some cases number of data are limited: N=6 for biomass and N=20 for stem height. The rather low number of specimens likely explains why only few significant differences were observed (Table S2).

R2R4. *Indeed, dry biomass was collected at 6 locations in a 20 cm x 20 cm plot, (1) close to the seaward marsh edge, (2) at the center of the marsh and (3) at the landward marsh edge, distributed over the two transects. To obtain stem properties over time, 20 stems per measurement were collected from randomly distributed locations over the marsh. Per*

measurement, $20 \times 20 \text{ cm} \times 6 = 0.24 \text{ m}^2$ was removed. Including stem removal, this results in a total loss of less than 1% of the full marsh cover. While we agree that this resulted in a small sample size, this choice was made deliberately. Destructive measurements were minimized, to not damage the marsh too much which would prevent comparison between runs. A short explanation is provided in the main body of text. Further explanation is provided in the Methods section 1.4:

- (main body of text: lines 161 - 162) “Vegetation biomass and stem length were collected by destructive measurements, affecting a negligible marsh surface (see Methods).”
- (methods: lines 642 - 644) “The destructive measurements for biomass (vegetation measurement 2) and stem length (vegetation measurement 3) affected a marsh area smaller than 1% of the total salt marsh in the physical model.”

Although we agree that a larger sample size would have been beneficial, we ensured that our sample size was comparable with, or higher than, other peer-reviewed studies focusing on plant samples either in plots or in individual stems from a salt marsh, including:

- Zhu et al. (2020): $n = 10$ per species per location.
- Reents et al. (2022): $n = 5$ per species - treatment combination.
- van Veelen et al. (2020): $n = 5 - 15$ per species.
- Mason et al. (2025): $n = 8$.
- Paul et al. (2022): $n = 10$.

R2Q5. The manuscript does not specifically address the uncertainties related to the global up-scaling. The uncertainty could be addressed e.g. through different upscaling scenarios, in which the properties of vegetation or wave heights are varied. How much larger is the wave attenuation considering “less conservative” vegetation, e.g. stronger species or those with larger biomass/stem length (cf. Figure S1), or summer conditions with higher biomass and longer stems expected.

R2R5. Please see response **R1R3** to comment **R1Q3**.

Conclusions:

The conclusions are supported by the data. However, some clarifications are needed:

R2Q6. - Row 231: 10% attenuation appears small to have any significant impact. Which attenuation level must be achieved for significant positive impacts?

R2R6. We agree that the contribution of vegetation to wave attenuation seems rather small at some locations. However, the impact does not scale linearly with relative wave attenuation.

For incoming significant wave heights up to 1 m, the attenuation generally ranges between 10% and 40%, equaling a decrease of 0.1 to 0.4 m for a 1 m wave. For incoming waves exceeding 1 m, attenuation is approximately 0.1 to 0.5 m. Focusing on impact:

- 1) If coastal protection infrastructure is present landward of the salt marsh, overtopping discharge can substantially be reduced by marsh vegetation. Coastal protection costs by vegetation are sensitive to critical overtopping discharge, as the crest height scales non-linearly with the wave height in front of the coastal protection infrastructure (Pullen et al., 2007). Because of reduced overtopping rates, preventing a dike heightening of 1 m, saves approximately 7 million USD₂₀₀₅ PPP (Purchasing

Power Parity) per stretch of 1 km dike (Ward et al., 2017; Van Zelst et al., 2021). When interpolating this linearly, preventing 0.2 m of dike heightening saves 1.4 million USD. At present, depending on the economy, this can be multiplied by an average factor of more than two (<https://data.worldbank.org/indicator/NY.GDP.MKTP.PP.CD?end=2024&start=2005>). Thus, wave attenuation by marsh vegetation could yield considerable cost savings, even for relatively small reductions in wave height. In the absence of coastal protection infrastructure, small relative reductions in wave height can still make a meaningful impact in terms of shoreline stabilization, as the bed shear stress (erosional force) also scales non-linearly with the wave height.

- 2) The impact of wave attenuation by vegetation compared to the global average sea-level rise of 0.49 cm in the year 2100 (DeConto & Pollard, 2016), emphasizes that a small reduction of the incoming wave height might already offset a large part of the expected sea-level rise for the coming decades.

Both cost reduction and wave attenuation by vegetation potentially offsetting the impacts of sea level rise are discussed in the last section of the main body of text:

- (main body of text: lines 278 - 288) “Our results emphasize that restoration and conservation of salt marshes as a Nature-based Solution (NbS), supporting biodiversity, protect against extreme storms more effectively at low-energy coasts than at high-energy coasts. Hence, application at low-energy coasts should be prioritized, but even at high-energy coasts potential cost reduction is considerable as preventing 1 km dike heightening by 0.2 m, already saves 1.4 million USD2005 PPP (Purchasing Power Parity), because of reduced overtopping rates (van Zelst et al., 2021; Ward et al., 2017). In addition, reduction of the wave height by decimeters offsets predicted average sea level rise of 0.49 m in 2100 (RCP4.5) by decades (DeConto & Pollard, 2016). This cost reduction can motivate continuous support and maintenance that is required for salt marshes to prevent long-term erosion and guarantee their persistence at high-energy coasts.”

R2Q7. - Can you elaborate on the uncertainty/sensitivity regarding the 10% wave attenuation, referring to the stated “conservative estimates based on using plant species with low breaking force (i.e., “weak”)”.

R2R7. Please see the response **R1R3** to comment **R1Q3**.

R2Q8. - R250-263: Improve the discussion by amending with management implications. Obviously salt marshes should be protected, but would some vegetation management/maintenance be useful and realistic in certain areas? Is this 10% reduction result cost-effective to support large-scale restorations? Can restoration activities be prioritized based on certain criteria?

R2R8. Please see response **R2R6** to the above comment **R2Q6**. Low-energy coasts should be prioritized, but nevertheless potential cost reduction for dike heightening at high-energy coasts can be considerable. So, this can motivate restoration and management/maintenance efforts for marshes at high-energy coasts.

- (main body of text: lines 278 - 288) “Our results emphasize that restoration and conservation of salt marshes as a Nature-based Solution (NbS), supporting biodiversity, protect against extreme storms more effectively at low-energy coasts than at high-energy coasts. Hence, application at low-energy coasts should be

prioritized, but even at high-energy coasts potential cost reduction is considerable as preventing 1 km dike heightening by 0.2 m, already saves 1.4 million USD2005 PPP (Purchasing Power Parity), because of reduced overtopping rates (van Zelst et al., 2021; Ward et al., 2017). In addition, reduction of the wave height by decimeters offsets predicted average sea level rise of 0.49 m in 2100 (RCP4.5) by decades (DeConto & Pollard, 2016). This cost reduction can motivate continuous support and maintenance that is required for salt marshes to prevent long-term erosion and guarantee their persistence at high-energy coasts.”

R2Q9. - Fig 4: Africa and South America are not well represented on the map. It remains unclear, how biased the global analyses are.

R2R9. Africa and South America indeed represent a small proportion of global marsh area on the map. The global distribution of salt marshes, including Africa and South America, is captured in the data from Worthington et al. (2024) which we use in our global analysis. The data in Worthington et al. (2024) is represented in Marine ecoregions:

- South America is captured in Marine ecoregions:
 - o Temperate South America 3790 km² (7.2% of global total)
 - o Partly in Tropical Eastern Pacific: 80 km² (0.2% of global total)
 - o Partly in Tropical Atlantic 4810 km² (9.1% of global total)
- Africa
 - o Temperate Southern Africa 80 km² (0.2% of global total)
 - o Partly in Western Indo-Pacific 1920 km² (3.6% of global total)
 - o Partly in Tropical Atlantic 4810 km² (9.1% of global total)

This shows that only a very limited part of the world’s salt marshes is located in South America and Africa.

Further, to ensure that the lower area of marshes in Africa and South America did not lead to underrepresentation in our analysis, we checked the filtering of our data. After filtering the transects for the global analysis, as described in Methods subsection 2.3, exclusion of transects in South America and Africa is in the same order as for the other continents.

- o (methods: lines 730 - 741) “We incorporated several updates; (1) elevation data from DeltaDTM was used³² instead of MERIT⁷¹ and vegetation extent data was updated³³, (2) we filtered foreshores that are preceded by waterbodies with a minimal length of 1km using a global water mask⁷² to assure that foreshore data are derived at the right location, (3) salt marsh areas sheltered behind higher landscape features, such as dunes, were excluded by flagging vegetation presence false if the mean elevation in the vegetated zone is lower than the mean elevation of the preceding non-vegetated foreshore data points, and (4) false positives of vegetation presence in areas with steep transitions (e.g., steep coastal slopes or cliffs) were corrected by applying an Interquartile Range filter on elevation within vegetated areas with a multiplier of 1.5. In general, this filtering resulted in an equal reduction across continents.”

This notwithstanding, to address the concern and to increase the representation of Africa and South America in the maps (Figure 4 and Extended Data Figure 2, as well as new figures added to the Extended Data, 3 – 6), the projection has been changed to “Robinson” for a balance between visibility and equal area (see e.g. <https://pro.arcgis.com/en/pro-app/latest/help/mapping/properties/robinson.htm>) and figures are updated accordingly.

- (main body of text: lines 489 - 494) “Figure 4. **Storm events lead to decreasing wave attenuation due to vegetation damage**. Water depth at the seaward salt marsh edge, and distribution of water depths over all transects (a), exposure duration for progressive vegetation damage and distribution (b), relative stem height decrease and distribution (c) and GLM-predicted attenuation by vegetation and distribution per wave attenuation percentage class and incoming wave height bin (d) for a return period of 100 years.”
- (Extended Data: lines 952 - 957) “Figure 2. **Storm events lead to decreasing wave attenuation due to vegetation damage (return period of 1000 years)**. Water depth at the seaward salt marsh edge, and distribution of water depths over all transects (a), exposure duration for progressive vegetation damage and distribution (b), relative stem height decrease and distribution (c) and GLM-predicted attenuation by vegetation and distribution per wave attenuation percentage class and incoming wave height bin (d) for a return period of 1000 years.”

Suggested improvements:

Improve logical flow, some explanations should appear earlier in the text:

R2Q10- Short description of different salt marsh vegetation types/conditions globally

R2R10. This is now very shortly described in the introduction, because of limited available space. Further general information about the importance of vegetation and dependence on local physical conditions has been added in the methods section.

- (main body of text: lines 68 – 70) “Green-grey flood protection employs the natural capacity of ecosystems to buffer extreme wave events and consequently reduce flood risk. Specifically, salt marshes with unique salt-tolerant vegetation (Adam, 1993), often located in the temperate climate zone at muddy coasts, serve to: ...”
- (methods: lines 698 – 700) “Key for the functionality of the marsh is the presence of salt-tolerant vegetation (halophytes), such as herbs, grasses and shrubs, of which the distribution typically depends on salinity and inundation gradients (Adam, 1993).”

R2Q11. - Basis for 1 m wave height limit used?

R2R11. The 1 m wave height limit, that marks the distinction between low-energy and high-energy coasts, is a result of the experimental data and global assessment. The results from the flume experiment emphasize a higher wave attenuation capacity for lower incoming waves (Figure 3D). Subsequently, the 1 m wave height limit clearly appears in the global assessment (Figure 4D): marsh vegetation at locations that are relatively sheltered (with a wave height below 1 m; i.e. low-energy) have a large wave attenuating capacity (generally exceeding 10% wave attenuation), whereas relatively exposed locations where wave heights of 1 m are exceeded (i.e. high-energy conditions) contribute up to 10% of wave attenuation only. To address this comment and to better explain that this boundary proceeds from the analysis, the text is rephrased.

- (main body of text: lines 223 - 232) “The damaged stems, both as a result of exposure duration and from incoming waves during a storm, highlight a clear distinction in the wave attenuating capacity of the local marsh calculated using the GLM resulting from the flume experiment (Fig. 4D; Extended Data Fig. 2D): waves are effectively attenuated at lower energy salt marsh coasts with incoming waves up to 1 m. At these low-energy marsh coasts, wave attenuation by vegetation generally exceeds 10% (up

to 50%), covering up to half of the analyzed transects (46% - 34%, for return periods of 100 and 1000 years, respectively). In contrast, at high-energy marsh coasts, where incoming wave heights exceed 1 m, wave attenuation is limited to only 10%."

- (main body of text: lines 234 - 236) "projecting results from the flume experiments to a global scale suggests that in general, salt marsh vegetation enhances the resistance of low-energy marsh coasts to extreme conditions. At almost all low-energy marsh coast with waves up to 1 m, waves are attenuated by more than 10%"
- (abstract: lines 46 – 55) "Experimental results emphasize that vegetation was most effective in attenuating lower waves (up to approximately 1.0 m). The contribution of marsh vegetation to wave attenuation exceeds 10% (up to 50%) for low energetic marsh coasts (significant wave height, H_{m0} , at marsh edges <1 m). Vice versa attenuation at high-energy marsh coasts ($H_{m0}>1$ m) does not exceed 10%. This global assessment supports the differentiation between low- and high-energetic conditions resulting from the flume experiment."

R2Q12. - Wave action durations?

R2R12. The wave action duration is based on multiple processes and parameters:

- Regarding wave action for vegetation damage, in our experiment vegetation damage was observed already with the runs with lowest water depth and wave height combinations ($h = 1.5$ m and $H_{m0} = 0.75$ m). In previous controlled experiments lower wave heights and water levels were tested (Möller et al., 2014; Rupprecht et al., 2017). Starting at water depths of 1 m and wave heights of 0.1 m, the first significant stem damage was observed at water depths of 1 m and wave heights of on average 0.5 m. This is added very shortly in the main body of text and more extensively in the methods section.
 - (main body of text: lines 200 - 202) "Exposure duration, vegetation stem height damage and subsequent wave attenuation by vegetation was calculated at the storm surge peak for storms with a return period of 100 and 1000 years (see Methods)."
 - (methods: lines 749 - 753) "Globally observed peak water levels (exceeding 1 m water depth) at the globally derived salt marsh locations remain for the larger part (~90%) within the water level range applied in the wave flume. Globally observed exposure duration with water levels exceeding the threshold of 1.0 m (with H_{m0} of 0.5 m) did not exceed 1000 minutes (16.67 hours), which is within the duration of the flume experiment (21 hours)."
- Subsequently, based on global datasets the water depth and potential largest wave height above the marsh is determined. Using the local storm surge hydrographs, exposure duration (or wave action duration) is calculated over the time that wave heights at the marsh exceed 0.5 m from the start of the storm until the point in time the highest waves occur, i.e. at the peak of the storm surge hydrograph. This has been added in the methods section, where it is now more extensively discussed. Therefore, and to limit the length of the manuscript, the short explanation is removed from the main body of text.
 - (Methods: lines 755 - 766) "Since stem height damage in the Delta Flume experiment started already during the most tranquil hydrodynamic conditions ($h = 1.5$ m; $H_{m0} = 0.75$ m), initiation of stem height damage in the global model was set following previous controlled flume experiments (Rupprecht et al., 2017). In those previous experiments, starting at water depths of 1 m and wave heights of 0.1 m, first, significant stem damage was observed after

water depths of 1 m and wave heights of 0.5 m on average (Rupprecht et al., 2017). Using the local storm surge hydrographs, exposure duration for vegetation damage is calculated over the time window during which wave heights at the marsh exceed 0.5 m from the start of the storm until the point in time when the highest waves occur, i.e. at the peak of the storm surge hydrograph. The maximum incoming wave height at the marsh edge is calculated at the peak of the storm, with the most severe estimate for the wave height being 50% of the water depth (Van Zelst et al., 2021; Massel, 1996; Nelson et al., 1994). Finally, wave attenuation at the peak of the storm is calculated using the GLM, as the highest depth-limited waves potentially occur at this point.”

Suggestions and notes for clarification:

R2Q13. - Extended vegetation characterization would be helpful (cf. comment above). Optical, remote sensing, LAI, PAI -> global analyses of coastal vegetation change possible?

***R2R13.** We agree that extended vegetation characterization would be helpful. In our current study we used the state-of-the-art global salt marsh distribution map from Worthington et al. (2024). So, in our global analysis the most recent global available salt marsh distribution is used. More detailed marsh distribution from remote sensing data, including vegetation species, is currently not available at a global scale. The spatially and temporally dynamic environment (tidal coverage of the intertidal zone, seasonal dynamics in water level and marsh development, as well as environmental/climate parameters including temperature salinity and precipitation) makes classification a complex process. Within the literature, studies exist that:*

- I. classified vegetation species at a national level (Hu et al., 2021)*
 - II. classified change between vegetated marsh and bare mudflat (Laenger et al., 2020)*
 - III. highlighted the importance of local ground truthing, which is a large effort on the global scale (Hu et al., 2021)*
 - IV. explored global marsh edge change between 2000 and 2019 (Campbell et al., 2022).*
- Each of those studies represents a large step forward in the field, but nonetheless data on species distribution at a global scale remains unavailable, and thus we could not incorporate this in our study. We therefore chose to work with the data of Worthington et al. (2024), which, critically, used the most recent data for the global distribution of marshes. All in all, these studies highlight that methods are being developed that might lead towards a global quantification of salt marsh species distribution, but they are not yet available, which explains our decision to use the most recent global salt marsh distribution combined with recent globally available DEMs in the coastal zone (Worthington et al., 2024; Pronk et al., 2024).*

R2Q14. - How much time is needed for vegetation recovery after various storms?

[REDACTION]

[REDACTION]

[REDACTION]

R2Q15. - Comment on the representativeness of the tested vegetation in winter state (did the global up-scaling also consider hydrodynamics in winter?)

R2R15. *Almost 70% of all worldwide salt marshes are located in the temperate climate zone (Worthington et al., 2024). Storm surges (i.e. extreme hydrodynamics) with a return period of 1/100 and 1/1000 years (Dullaart et al., 2023) were considered in the current study. In the northern hemisphere (75% of marshes including the Arctic) the storm waves occur in winter, whereas in the southern hemisphere the storm waves occur all year round (11.3% of the marshes) (Davies, 1980; Bosboom & Stive, 2015; Worthington et al., 2024). So, the largest proportion of the global marsh-relevant storms presented in Dullaart et al. (2023) occur during winter. For other locations, the (end of) Winter state of vegetation yields a conservative estimate of storm protection, as vegetation outside the winter season, e.g. in the growing season, is more resistant (Reents et al., 2022). To clarify this in the manuscript, this has been added to the methods subsection 2.2. “stem height in salt marshes as proxy for wave attenuation”. This methods subsection specifically discusses aboveground vegetation in a wider perspective (methods: lines 697 - 725):*

- *(methods: lines 716 - 725) “70% of the salt marshes globally present are found in the temperate climate zone and therefore experience a winter season (Worthington et al., 2024). In general, the vegetation state at the end of the winter can be considered to yield a conservative estimate for vegetation stem height as vegetation outside the winter season, e.g. in the growing season, is more resistant (Reents et al., 2022). Furthermore, E. athericus in our experiment can be considered to yield a conservative estimate of wave attenuation, because its breaking force is relatively low (weak) compared to other salt marsh vegetation species (Zhu et al., 2019). Less vegetation damage leads to longer stems persisting and hence a higher wave attenuation capacity. In addition, we tested a single salt marsh zones, whereas salt marshes in general contain multiple zones that enhance the wave attenuation capacity (Schoutens et al., in preparation). Finally, only a small (70 m) part of the marsh was considered for wave attenuation.”*

R2Q16. - From wave attenuation point of view, clarify how salt marsh vegetation differs from brackish water conditions (note e.g. Baltic Sea shown in map figures)

R2R16. *Marsh vegetation at a gradient from saline to brackish to fresh shows a tendency towards longer stems that can have a high flexural stiffness (Zhu et al., 2020; Dijkema 1990). These are important traits for contributing to wave attenuation, which is evident from our flume experiment and builds upon previous literature (e.g. Vuik et al., 2018). As a result, wave attenuation is likely to increase, although damage might also increase due to the larger presence of vegetation in the water column. This trade-off is assessed with a proxy by rerunning the model with a doubled (i.e. 200%) stem height and a doubled (i.e. 200%) stem height + doubled (i.e. 200%) progressive damage. Both scenarios result in an increased wave attenuating capacity of the marsh (Extended Data Figures 3-6). A more extensive discussion regarding this additional model analysis can be found in response **R1R3** to referee comment **R1Q3**. The results of the additional model analysis are discussed in the main body of text, section “Marsh vegetation reducing extremes”:*

- *(main body of text: lines 245 - 248) “Both higher species diversity and the shift to longer and less flexible stems enhance wave attenuation, even under higher vegetation damage. This agrees with the result of our sensitivity analysis (Extended Data Figures 3-6).”*

R2Q17. - Check that terminology is consistently used/defined: green-grey, NBS, ecosystem services

R2R17. *Consistent use of terminology is checked, and the terminology is now clearly defined:*

- (main body of text: lines (65 – 67) “Therefore, so-called green-grey flood protection – combining traditional grey-protection with green-ecosystems - is increasingly considered as a more sustainable strategy to keep coastal regions safe from coastal storm events with extreme waves (Borsje et al., 2011).”
- (main body of text: lines 278 - 280) “Our results emphasize that restoration and conservation of salt marshes as a Nature-based Solution (NbS), supporting biodiversity, protect against extreme storms more effectively at low-energy coasts than at high-energy coasts.”
- (main body of text: lines 253 - 254) “In general, our study implies that nature's services to society (ecosystem services) depend on the stability of the salt marsh substrate...”

R2Q18. Fig1: remove photos A and D as unnecessary (save space to enlarge B and C); WHM and scale bars are over-sized; could show waves instead of horizontal water surface;

R2R18. *To improve clarity, photos A and D are removed and photos B and C are enlarged. WHM and scale-bar size is decreased. To further improve the figure, schematic waves are added (lines 464 - 470).*

R2Q19. - Fig1 option for more informative cross sectional and plan views: add conceptual descriptions of the key physical processes controlling erosion and wave attenuation

R2R19. *Extending from response (R2R18) to the previous comment (R2Q18), (conceptual) information is added in figure 1 and the caption of figure 1. Conceptual waves and orbital velocities, that touch the vegetation to visualize the feedback between progressive vegetation damage and subsequent decreasing wave attenuation, are added. This is also described in the caption. In the top view (figure 1D), width dimensions (total and path) are now included.*

- (main body of text: lines 464 - 470) “Figure 1. Development of a large-scale salt marsh experiment. Obtaining the salt marsh blocks in the field at the Dutch mainland Wadden Sea coast (a); storing the blocks next to the Delta Flume at Deltares, Delft, the Netherlands (b); inundating the full physical model (c); schematic picture of the physical model with the salt marsh blocks from the field in the Delta Flume, , with the wave paddle at $X = 0$ m and a visualization of the wave forcing and attenuation by vegetation drag and roughness (d).”

R2Q20. - R130-131: To allow easy comparisons, instead of absolute mm values, use time bound mm/h.

R2R20. *Thank you for your suggestion. This has been added to the manuscript. In our experiment with significant wave heights between 0.75 and 2.00 m surface lowering was 7 mm (0.33 mm/h), which is in the same order of magnitude as previous studies with smaller wave heights (4.4 mm surface lowering; 0.16 mm/h) (Möller et al., 2014; Spencer et al., 2015).*

- (main body of text: lines 129 - 133) “Elevation measurements at 32 fixed locations at the salt marsh show, on average, a decreasing marsh surface over the total experimental time of 21 hours with damaged vegetation (7 mm; 0.33 mm/h), which is in the same order of magnitude as previous studies with smaller wave heights (4.4 mm surface lowering; 0.16 mm/h) (Möller et al., 2014; Spencer et al., 2015) ”

R2R21. - Fig3 is not easy to follow as it does not directly follow the logic/naming of the cases of Table S1.

R2Q21. Yes, thank you for highlighting this - we understand the previous lack of clarity. In Table S1 (Supplementary Information) a column is added emphasizing the vegetation measurements corresponding to Figure 3.

- (Supplementary Information: lines 26 - 32) “Table S1. **Experimental program for the Delta Flume tests at Deltares (Delft, the Netherlands)**”

R2Q22. - FigS1: consider directly using references as subscripts in the Fig rather than abbreviations to the references, which makes reading the figure quite difficult

R2R22. Figure 1 in the Extended Data and the caption of the figure (Extended Data) are adapted accordingly (i.e. references are directly numbered in the figure, and removed from the caption).

- (Extended Data: lines 939 – 948) “Figure 1. **Global salt marsh vegetation comparison.** Vegetation aboveground biomass (a) and vegetation stem length (b) measurements before the storm season between late August and November (“BS (Before Storm)”) and after the storm season in March and April (“AS (After Storm)”). *Elymus athericus* is measured during our experiment (“Ely DF”) at the start in the field and flume and at the end in the flume. For verification *Elymus athericus* is compared with other studies quantifying *Elymus* spp. and salt marsh vegetation species with stems, including *Spartina* spp. and *Phragmites* spp. Numbers indicate references to the studies where vegetation data is derived from.”

R2Q23. - Fig3C: clarify why the relationship is shown for stem length only, and not for biomass. Why was vegetation biomass not used in the regression model? Biomass appears to be a more direct proxy of the vegetation density than stem height. These two variables might complement each other in explaining bulk resistance to breaking and erosion (as found in the fluvial context).

R2R23. Stem length is used as a proxy for wave attenuation because penetration of the stem in the water column is considered an important predictor of wave attenuation, especially with extreme wave heights and water levels (Vuik et al., 2018). As a result, damage to vegetation by a decreasing stem height will have a direct impact on wave attenuation and thus was the preferred predictor for this analysis. When expanded across species, total biomass could include, for example, higher biomass species which are extremely flexible and exhibit a wave ‘avoidance’ strategy in which they lay down to avoid wave forcing, contributing minimally to wave attenuation (Bouma et al. 2010, Puijalon et al. 2011, Silinski et al. 2018). In such a case, biomass may be a poor predictor of wave attenuation capacity. In other words, the vertical distribution of biomass over the water column will impact the wave attenuation capacity more so than the biomass itself. To avoid this kind of overestimation of attenuation capacity, we preferred to use vegetation height. To

improve clarity regarding the use of stem height, in Methods section 2.1 (lines 482 - 492), biomass is removed and it is stated that stem length is used as predictor.

- (methods: lines 678 - 681) *~~"Biomass loss and Stem height decrease of E. athericus through exposure duration in this large scale experiment (Fig. 3) is used as a conservative estimator of wave attenuation by aboveground vegetation under the most severe conditions (water level to wave height ratio of 0.5)."~~*

Further explanation is provided in section 2.2 (dedicated to a wider perspective on aboveground vegetation, including why stem height is used).

- (methods: lines 700 - 704) *"Stem height is used as a proxy for wave attenuation as penetration of the stem in the water column is considered a strong predictor of wave attenuation, especially with extreme wave heights and water levels (Vuik et al., 2018). As a result, damage to vegetation by a decreasing stem height will have a direct impact on wave attenuation."*

R2Q24. - Extrapolation in Fig3D to durations larger than 15-20 h appears rather uncertain due to data scatter at lower durations. Consider removing the extrapolations since these are mostly not required in the upscaling.

R2R24. Thank you for noticing, Figure 3D (lines 480 - 486) is changed accordingly by limiting the setting the upper x-axis limit to 25 hours.

R2Q25. - Justify the physical basis of considering wave attenuation by vegetation as relative share (%) of the total rather than as absolute value. Also clarify for the audience not so familiar with the topic why only wave height was considered, and not e.g. wave height in relation to water depth.

R2R25. Wave attenuation is indeed considered as the relative share of the incoming wave height, and attenuation by vegetation is specifically assessed as this was uncertain until now. Absolute values can be calculated, but we prefer relative attenuation as (1) we would like to assess and compare the wave attenuating capacity by vegetation under a range of exposure scenarios in the Delta Flume and (2) relative values enable a comparison of attenuation at geographical locations in the global analysis, where the potential maximum incoming wave height is location specific. To improve the clarity of this choice to the audience, the use of wave height is clarified in Methods section 1.4.

- (methods: lines 668 – 669) *"Wave attenuation by vegetation was calculated as the relative share of the incoming wave to enable comparison of different experimental runs and global scenarios."*

R2Q26. - Comment the role of day-to-day and other less extreme wave action in causing progressive vegetation damage and erosion of the substrate. How does the 7 mm of erosion in 21 hours in the experiment scale over storms of different frequencies occurring through decadal time-scales?

R2R26. This is difficult to assess, as over decadal timescales processes of accretion and recovery are intertwined with potential erosion. Our current experiment, previous flume experiments of Möller et al. (2014), and data from field measurements after hurricanes Katrina and Rita (Howes et al., 2010), emphasize that storms with a location-dependent return period of a decadal to centennial time scale, already result in minimal surface erosion in salt marshes. Even if under extreme conditions surface erosion occurs, vegetation is found to regrow over the subsequent growing season (please see response **R2R14** to

reviewer comment **R2Q14**). As extreme conditions have already minor effect, it can be expected that daily conditions have a negligible effect on surface erosion.

Although surface erosion under day-to-day conditions is expected to be minor, other processes at longer time scales might affect the persistence of the salt marsh. These longer-term erosive processes in marshes are generally focusing on lateral (cliff) erosion and drowning (not keeping up with sea level rise). At the same time, the longer-term erosive processes can also be counteracted by salt marsh accretion during periodic tidal inundations which might be elevated during storms. Accretion up to several millimeters can be measured during a storm with a return period of approximately 5 years (e.g. Zhu et al., 2020). So, on the long-term time scale accretive and erosive processes play a role that might counteract each other, but might also result in net erosion, especially at high-energy coasts. The importance of counteracting long-term erosive processes when using salt marshes for wave attenuation is discussed in the main body of text. The discussion focusing on the long-term perspective of NbS regarding sediment trapping and growing with sea level rise has been omitted as suggested by referee 1 in comment **R1Q3** (also see the response to this comment **R1R3**).

- (main body of text: lines 286 – 288) *“This cost reduction might enable continuous support and maintenance required for the salt marsh to prevent long-term erosion and guarantee persistence at high-energy coasts.”*

R2Q27. - The authors should consider the uncertainty arising from extrapolating the results obtained with the tested sediment to global sediment conditions. The comment applies overall but specifically referring to L233-235.

R2R27. *We agree that the representativeness and uncertainty of the soil was not clearly discussed in the perspective of the global analysis in the manuscript. Please see:*

- *Comment **R1Q1** and **R1Q4** and the response **R1R1** and **R1R4**, regarding the effect of roots and how the roots of salt marsh species used in our flume experiment (*Elymus athericus*) compares with the root zone from other salt marsh vegetation species.*
- *Comment **R1Q2** and the response **R1R2**, regarding organic matter in the soil and similarities and differences, and the potential impact on erodibility when comparing the organic matter content from our salt marsh substrate to other regions worldwide.*

This topic is now extensively discussed in the rebuttal and clarified in the revised manuscript.

Further remarks:

R2Q28. Regarding the references, the manuscript appropriately incorporates previous literature on coastal environments but appears overly confined to this domain. It would benefit from engaging more extensively with research on fluvial and wetland environments, particularly recent advances in the parameterization of natural vegetation and in the characterization of drag and flow resistance associated with natural plants.

R2R28. *Thank you for raising this. Other environments, including seagrass meadows, brackish and freshwater marshes, as well as riverine settings and the (potential) contribution to wave attenuation are now discussed in the last section of the main body of text. In addition, a comparison is made with the key messages from these environments and our findings.*

- (main body of text: lines 236 - 248) “At almost all low-energy marsh coast with waves up to 1 m, waves are attenuated by more than 10% for *Elymus athericus*, which can be considered a conservative wave attenuation estimator for salt marshes in general (SI Figure S1). This wave attenuation functionality is also found in seagrass environments under low-energy conditions (Bradley & Houser, 2009), and may also apply in freshwater settings (Ren et al., 2021). Decreasing salinity induces an increase in species diversity, because species diversity increases with decreasing environmental stress (Więski et al., 2010). Also, it leads to a shift towards species with longer and less flexible stems compared to *Elymus athericus*, such as the common reed *Phragmites australis* (Zhu et al., 2019; Dijkema et al., 1990). Both higher species diversity and the shift to longer and less flexible stems enhance wave attenuation, even under higher vegetation damage. This corresponds with the result of our sensitivity analysis (Extended Data Figures 3-6).”

R2Q29. Overall, the abstract, introduction and conclusions are well written. However, see the comments/suggestions above for improvement. As a minor further detail in the abstract, the 1 m height limit is not explained/reasoned.

R2R29. *The manuscript has been updated to reflect the comments/suggestions above. Regarding the 1 m wave height limit, please see response R2R11 to comment R2Q11 “Basis for 1 m wave height limit used?”.*

R2Q30. Please note that some of the statistical tests and interpretations fall outside the reviewer’s core expertise.

R2R30. *Thank you for noting, the statistics have been checked thoroughly once again. Additions have been made, for example inclusion of sample size in figures and statistical analyses. In the Supplementary Information, table S2, information is added regarding tests, variance, distribution and U values of statistical tests.*

- (Supplementary Information: lines 34 - 39) **“Table S2. Overview of statistical significance between measurements in between experimental runs for vegetation stem height and biomass, with a Student’s t-test for normal distributed samples with equal variance and a Welch t-test for normal distributed samples assumed without equal variance and Mann-Whitney U test for not normal distributed samples. A Benjamini–Hochberg FDR p-value correction is applied. With a corrected p-value<0.05 for significant differences. ”**

Referee #3 (Remarks to the Author):

R3Q0. I co-reviewed this manuscript with one of the reviewers who provided the listed reports.

R3R0. *Thank you.*

Referee #4 (Remarks to the Author):

R4Q0. Overall, this is quality research on an important topic, within a nuanced conclusion that I believe represents the truth about how the salt marsh surface versus vegetation provides protection. I like how the MS reveals something new, that we have all suspected but not yet proven. However, the title does not reflect the nuanced finding very well and it obscures this truth in a manner that perpetuates overly simple thinking. A better title that alludes to the conditional finding of the research would provide a more lasting, real-world value to its publication. Moreover, there could be a stronger emphasis throughout the beginning and ending of the text on the flume work versus the global analysis effort. The global analysis effort is a bit tacked onto the flume work.

The flume work is a serious, high quality study that likely required enormous effort. The fundamental contribution to the literature originates from the flume work, which is then extrapolated into the global analysis in a derivative manner. The finding that lower energy marshes provide quality vegetative-driven wave attenuation, whereas higher energy marshes do not, seems to be based on the flume study work. The relationships then play out at the global scale in that analysis. Thus, I'm not sure if there is anything emergent in the global analysis, and if there is, it should be better enunciated as to how that happened analytically.

R4R0. *Thank you for taking the time to review the manuscript and providing valuable feedback. We appreciate and very much agree with the acknowledgement of the importance of the nuanced conclusion regarding salt marsh functioning for coastal protection. The points raised are processed and, in our opinion, have improved the manuscript .*

To emphasize the results from the flume experiment relative to the global analysis, "globally" is removed from the title. The title (line 1) is now "How and where salt marshes protect against extreme storms". By this we aim to include nuances of wave attenuation related to dependency of the incoming wave height, i.e. lower or higher (where), and the mechanisms that play a role, i.e. related to damage of vegetation and stability of soil (how).

In the abstract, the text is changed to emphasize that the results show that the highest efficacy of wave attenuation by vegetation is valid for lower waves. The global analysis uses and builds upon these results.

- *(abstract: lines 46 - 47) "Experimental results emphasize that vegetation was most effective in attenuating lower waves (up to approximately 1.0 m)."*

- (abstract: lines 53 – 55) “This global assessment supports the differentiation between low- and high-energetic conditions resulting from the flume experiment”

Globally is removed from the aim and mentioned as an extension to the flume study.

- (main body of text: lines 96 - 105) “Based on flume experiments and projected storm simulations at a global scale, here, we aim to ~~globally~~ quantify the persistence of the marsh substrate and address the progressive vegetation damage and associated reduced wave attenuation under extreme storm conditions, by assessing:
 - I. The stability of salt marsh substrate under extreme wave events;
 - II. Progressive vegetation damage and associated wave attenuation under extreme events;
 - III. The global contribution of progressively damaged salt marsh vegetation to wave attenuation that proceeds from results of the flume experiments.”

When describing the results of the global analysis, it is mentioned that this is extending on the experimental results and that results emphasizing low incoming wave - large attenuation versus high incoming wave - low attenuation follow from the flume experiment. This is also done in the discussion in the last section of the main text.

- (main body of text: lines 196 - 197) “To analyze the contribution of vegetation to wave attenuation under extreme wave conditions, extending the experimental results to a global scale, ...”
- (main body of text: lines 223 – 227) “The damaged stems, both as a result of exposure duration and from incoming waves during a storm, highlight a clear distinction in the wave attenuating capacity of the local marsh calculated using the GLM resulting from the flume experiment (Fig. 4D; SI Fig. S2D): waves are effectively attenuated at lower energy salt marsh coasts with incoming waves up to 1 m.”
- (main body of text including subheading: lines 233 - 236) “**Global Marsh vegetation reducing extremes**
Projecting results from the flume experiments to a global scale suggests that in general, salt marsh vegetation enhances the resistance of low-energy marsh coasts to extreme conditions.”

Further review points are discussed below.

R4Q1. The figures could be improved in quality. They are strong but could be better.

R4R1. Thank you for the suggestion. Also based on other referee comments, the following improvements are implemented:

- Figure 1 (lines 464 - 470): unnecessary pictures have been removed and the remaining pictures (panels A – C) are increased in size; information has been added in the cross-section and top-view and elements have been resized.
- Figure 3 (lines 480 - 486) In panel D x axis limits are reduced to better fit the data range. The upper x-axis limit is now 25 hours instead of 40, to prevent extrapolation outside the range of observed data.
- Figure 4 (lines 489 - 494) and figure 2 in Extended Data (lines 952 – 958) and figures 3 – 6 in Extended Data (lines 959 - 986): projection is changed to have a better balance between visualization and the size of Africa and South America; a mistake in panel B regarding plotting the markers at the world map is improved, now showing the proper results. Markers are made smaller and transparent to better visualize differences.

- *Figure 1 (in Extended Data; lines 939 - 948): former extensive way of referencing in figure and caption has been improved.*

Furthermore, all figures are resized to have consistent figures and fit with the Nature requirements for figure formatting.

R4Q2. Line 84 - Should capitalize Gulf and East Coast

R4R2. *Done.*

- *(main body of text: line 91) “, and the Gulf and East coast of the United States”*

R4Q3. 103 – what is Winter (?), as capitalized it seems strange. Do you mean the season? Why capitalize?

R4R3. *Changed to lowercase.*

- *(main body of text: line 109 - 110) “A salt marsh in winter state was transplanted to two cross-shore transects using the first 200 m of the flume (Fig. 1).”*

R4Q4. Fig. 1 – it would be helpful to see the width dimensions of the flume in the top view. I have questions about the wave reflection. I’m not going to drill you on it, but I don’t fully like the pathway between the two surfaces. I’d rather see the center be the sampled area.

R4R4. *Thank you for this observation. Below our answers:*

- *The width dimensions of the physical model are now included in Figure 1, panel D (line 130) The width of the flume is 5 m and the width of the pathway is approximately 30 cm. The pathway is around 5 cm deeper compared to the vegetation surfaces, enabling the marsh to drain. This height difference is comparable to the variations in the vegetated surfaces related to variations in the clay height as well as the vegetation heights. Since the variations are similar in magnitude, we do not expect that the pathway results in any significant variations across the width. To address your comment and make this clearer to the reader, this information is added in the manuscript*
 - o *(methods: lines 503 – 507) “In between the two rows a path was constructed 5 cm below the surface of the marsh, to drain both marsh profiles and enabling access, maintenance and (manual) measurements. The height difference between the path and marsh surface was comparable to the variations in the vegetated marsh, i.e. the clay heights and the vegetation height.”*
- *We agree that a pathway in between the two transects might not be ideal for all measurements. From a practical point of view, we choose to use this setup to allow two transects with different substrates in terms of grain size characteristics (Extended Data Table 2: lines 929 - 936). For deploying sensors (not interfering with vegetation), maintenance and measurements, this was the most effective way. This was necessary to prevent having two pathways at the walls and to allow measurements to be taken without needing to get down with the crane (which would have been too time-consuming and limited the possible measurements).*
- *Wave reflection is being discussed in response **R4R10** to referee comment **R4Q10**.*

R4Q5. It would help to have a sentence about how you measured the vegetation in sections 145-154. When I look at Fig. 3, I wonder how did they get the dry biomass without destructive sampling (?). Perhaps this is in the Methods, but I'd like a sentence here.

R4R5. *We agree that this should be clarified in the main body of text. Destructive measurements were done (bi-)daily to collect dry biomass and stem length. Dry biomass was collected at 6 locations in a 20 cm x 20 cm plot, (1) close to the seaward marsh edge, (2) at the center of the marsh and (3) at the landward marsh edge distributed over the two transects. To obtain stem properties over time, 20 stems per measurement were collected from randomly distributed locations over the marsh. This data is presented in figure 3.*

*To enable comparison between runs, destructive measurements were minimized, to prevent substantial damage to the marsh. Per measurement, $20 \times 20 \text{ cm} \times 6 = 0.24 \text{ m}^2$ vegetation was removed. Including stem removal, this resulted in a total loss of less than 1% of the full marsh cover. A short explanation has been added to the main body of text. Further explanation has been provided in the Methods section. Please also see response **R2R4** to referee comment **R2Q4**.*

- *main body of text: lines 161 - 162) "Vegetation biomass and stem length were collected by destructive measurements, affecting a negligible marsh surface (see Methods)."*
- *(methods: lines 642 - 644) "The destructive measurements for biomass (vegetation measurement 2) and stem length (vegetation measurement 3) affected a marsh area smaller than 1% of the total salt marsh in the physical model."*

R4Q6. 200 - Not sure *E. athericus* is a conservative estimate, as compared with other species in global salt marshes. I would say it is pretty weak, low density, and low height compared with many other graminoids at least. This should be re-stated or made clear how.

R4R6. *Indeed, we agree that *E. athericus* is a rather "weak species" when considering biomass, individual stem height and strength of the stem and comparing with other graminoids. Therefore the physical contribution of this vegetation species to wave attenuation is expected to be in the lower range of wave attenuation by salt marsh vegetation. Stiffer, denser and taller species (see for example the comparison in Extended Data Figure 1) have been shown to contribute more to wave attenuation (Mendez & Losada, 2004; van Veelen et al., 2020; Zhang et al, 2022). Hence, *E. athericus* is assumed to be a conservative estimate, as more attenuation is expected with other vegetation species (c.f. Zhang et al., 2022). Please see response **R1R3** to comment **R1Q3**, in which your feedback is also addressed, for an extensive elaboration on this topic and how this is handled in the manuscript and Extended Data.*

R4Q7. Line 229. This is phrased strange, with emphasis on the 10% number, which is also used in line 226 but for high energy coasts. It just requires the reader to understand that you've switched the concept around. Suggest to reword.

R4R7. *We meant to state that wave attenuation generally exceeds 10% at low-energy marsh coast, but is limited to 10% at high-energy marsh coasts. In response to your comment and to improve the clarity in the text, the phrasing is adapted.*

- *(methods: lines 227 - 232) "At these low-energy marsh coasts, wave attenuation by vegetation generally exceeds 10% (up to 50%), covering up to half of the analyzed transects (46% - 34%, for return periods of 100 and 1000 years, respectively). In*

contrast, at high-energy marsh coasts, where incoming wave heights exceed 1 m, wave attenuation is limited to only 10%."

R4Q8. 305 - State how you picked up the mold. I imagine they were thousands of kg. With heavy machinery, and if so how did you avoid damage and where in marsh were these samples taken. I assume you are doing this by land and your marsh is a bit higher in elevation, ie you are not extracting using a boat. This would be valuable information for those of us that like to do this kind of stuff.

R4R8. *We agree that this should be clearer in the text, and so this information is added in the Methods section.*

- (methods: lines 539 - 549) *"The salt marsh blocks were harvested by pushing a mold of 2.0 x 2.0 m² (depth of 0.7 m) or 2.2 x 2.2 m² (depth of 0.4 m) into the ground. The area around the mold was dug out using a 35 to 50 tons excavator. Subsequently, a steel bottom plate was slid under the mold to prevent disturbance of vegetation and the marsh substrate within the mold as much as possible. Subsequently, the 3000 to 6000 kg marsh blocks were lifted, deployed on a closed truck to prevent wind damage and then transported to the Delta Flume. The harvest location was elevated above spring tide to assure safe access over land. To work safely and minimize disturbances to the ecosystem, the harvest was executed after the breeding season and before the storm season, during daylight, in the shortest period possible. Temporary steel road plates were used to distribute the weight of the excavator and trucks, which minimized damage to the marsh"*

The mold was picked up by sliding a forklift, attached to a 35 to 50 tons excavator, under the steel bottom plate. Subsequently, the marsh block including mold was lifted and deployed on a closed truck. The salt marsh blocks including molds had a weight of approximately 3000 to 6000 kg. The excavator and trucks drove over temporary steel road plates to better distribute their weight over the marsh and minimize disturbance.

The marsh blocks were collected at the high marsh, elevated above spring tide to enable access for a period of multiple weeks. Collection took place after breeding season and before storm season, to minimize disturbance and chances of inundation by water level setup due to storms. Further disturbance was minimized by executing the work in the shortest period possible, by working only during daylight.

R4Q9. I can't (or can) imagine how fun and not fun this must have been to do this entire experiment. Having done these things, I am more strongly impressed by the flume work than the global analysis.

R4R9. *Thank you, your understanding is very much appreciated. Indeed it was complex and intense, but a lot of fun at the same time! The main message of the manuscript is now better emphasized as a result from the flume experiment, please see the response **R4R0** to point one of this review **R4Q0**.*

R4Q10. Please discuss wave reflection in Methods somewhere 319-338. How much observed? What about wave transformation in the width dimension across the pathway. Did you sample the whole section on either side? How did you avoid width dimensional effects?

R4R10. *We agree that it is necessary to further elaborate on here.*

First regarding reflection, the reflection coefficient in deep water varied between 0.2 (low waves and 4% wave steepness; experimental run SM-01 in Table S1 in Supplementary Information) and 0.35 (high waves and 2% wave steepness; experimental run SM-14 in Table S1 Supplementary Information)

- (methods: lines 609 – 613) “The motion of the wave paddle, compensates for reflected waves to avoid reflection back into the physical model. The reflection coefficient in deep water varies between 0,2 (low waves and 4% wave steepness; experimental run SM-01 in Table S1 in Supplementary Information) and 0.35 (high waves and 2% wave steepness; experimental run SM-14 in Table S1 in Supplementary Information).”

The wave height meters (WHM) were located on one side of the flume wall, so we do not have information on the variation in width. However, no variations in the width direction were discernible during experimental runs. As is the case in general for flumes, we assume no variations in width (as width (5 m) $\ll$ length (300 m)) (e.g. Van Gent, 2001). Wave flumes are used for studies uniform in width, whereas wave basins (width $\approx$ length) are used for 3D effects specifically. In the Delta Flume waves are created uniformly in the width direction and will stay uniformly in the width direction as long as there is no significant variation in the width direction in the physical model set-up. Since the model set-up is symmetrical in the width direction and the variations in height due to the pathway are similar to the variations in the vegetation surfaces, we do not expect any wave transformation in the width dimension. This information has been added to the methods section (also see response **R4R4** to previous comment **R4Q4**, regarding suggestions for improving the sketch of the setup in figure 1).

- (methods: lines 654 – 659) “Wave characteristics were measured using fixed resistance type wave gauges present in the Delta Flume at the left wall of the flume (looking from the wave paddle to the end of the flume) with a measurement accuracy smaller than 1 cm (Van Gent, 2001). No variations in the width direction were discernible during experimental runs, because the setup was symmetrical in the width direction. We assume no variations in width, as is the case in general for flumes (as width, 5 m $\ll$ length, 300 m) (Van Gent, 2001).”

The wave paddle is equipped with ARC (Active Reflection Compensation) that measures the water elevation in front of the wave generator. This water level elevation consists of the waves that are being generated at the wave generator and also the waves that are being reflected off the physical model. The motions of the wave paddle are then compensated for these waves in such a way that the waves are not being re-reflected back towards the physical model. The result is a wave field almost without model effects caused by re-reflection. This additional information has been added to the methods section.

- (methods: lines 607 – 610) “Waves were forced with a wave paddle equipped with an ARC (Active Reflection Compensation). The water level elevation in front of the wave paddle was continuously measured to observe the wave field including reflected waves. The motion of the wave paddle, compensates for reflected waves to avoid reflection back into the physical model.”

R4Q11. I also wonder, did you see differential loss in the marsh vegetation in the length dimension, as the waves progressed in time? Like, was there an area where it was grinded away specifically where wave breaking occurred, or did it happen homogeneously, and how did it evolve. It would be good to have a sentence or two up in the main text on this.

R4R11. Thank you. For stem characteristics quantifications, 20 stems were selected spatially random every measurement. Therefore, there is no specific location dedicated to stem length. Visually we observed slightly more vegetation damage closer to the seaward edge, which can be considered the breaking zone. This has been added to the main body of text.

- (main body of text: lines 171 – 172) “Throughout the experimental runs, visual inspection showed the largest vegetation damage close the seaward vegetation edge.”

R4Q12. 349-366- I don't understand how you did destructive sampling for biomass, and yet produced Fig. 3. I guess the experiment only involved specific wave height/water depth combinations and did not evolve over time? ...thus did not require repeated sampling for a given treatment? I think this could be better clarified up in the main text.

R4R12. Following your previous comment **R4Q4** we further clarified the destructive measurements.

- main body of text: lines 161 - 162) “Vegetation biomass and stem length were collected by destructive measurements, affecting a negligible marsh surface (see Methods).”
- (methods: lines 642 - 644) “The destructive measurements for biomass (vegetation measurement 2) and stem length (vegetation measurement 3) affected a marsh area smaller than 1% of the total salt marsh in the physical model.”

Please also see response **R2R4** to referee comment **R2Q4**.

Regarding experimental settings for wave height / water level combinations (full experimental program in Supplementary Information table S1), we aimed at collecting wave measurements for the same wave height / water level combinations with increasing vegetation damage. Repetition of the same wave height / water level combinations was impossible due to the inherent vegetation damage by wave impact. Therefore a set of wave height / water level combinations was repeated three times. This has been added to the main body of text and methods.

- (main body of text: lines 152 - 155) “The experimental runs are clustered into three distinct groups of repeating wave height and water depth combinations with increasing aboveground vegetation damage inherent to continuous wave impact in the first two groups and no aboveground vegetation in the last group (see SI Table S1 and Methods).”
- (methods: lines 595 - 602) “This sequence was executed three times to study marsh stability and wave attenuation under potentially increasing vegetation damage: 1) light vegetation damage; 2) substantial vegetation damage; and 3) removed aboveground vegetation (see SI Table S1). This allowed us to explicitly quantify wave attenuation by vegetation as a result of progressive damage of the aboveground biomass, by subtracting wave attenuation by the marsh elevation in experimental runs without aboveground biomass (percentage decrease of H_{m0}) from wave attenuation in runs with full and damaged vegetation.”

Furthermore, Supplementary Information, table S1 has been improved by consequently naming vegetation damage according to the repetition of the wave height / water level combination.

R4Q13. 405-414. Wave height is reasonable, but I'd think it would be just as easy to use wave power, like H and T_p , like $H^2 T_p$, or some version. The period/wave length is very important, I think. But, I'm ok with it as first order guess.

***R4R13.** We agree that other more in-depth indicators can be used to represent wave impact. Since the relations with wave height and wave height attenuation are a good predictor already (e.g. Figure 3D), we prefer to keep this relation. In addition, wave height and wave height attenuation by vegetation are the most tangible indicators for a reader, since they directly show what (damaged) vegetation contributes, i.e. a decrease in wave height. Wave height is more tangible than wave power for the audience that is less knowledgeable and experienced with wave mechanics/theory and/or works in a different field of research, for whom this manuscript is also written.*

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Rebuttal manuscript: How and where salt marshes protect against extreme storms

2026 – 04 - 28

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Referees' comments:

Referee #1 (Remarks to the Author):

R1Q0: I enjoyed reading this contribution from Willemsen and others on Salt Marshes Globally Protect Against Extreme Storms. Wave attenuation is perhaps the least studied of the ecosystem services provided by tidal wetlands so their effort to extend previous physical models of vegetation-related contributions to wave attenuation strikes me as important. Their effort to estimate the contribution of vegetation to wave attenuation globally helps broaden the impact of the work.

Because most ecosystem science is performed at the scale of a few meters, a strength of the research is the large scale of this experimental manipulation. I was impressed by the effort required to extract 66 intact tidal marsh monoliths, each of which were fairly large at 2x2 m in area and 0.7 m deep. The quality of an experiment is not judged by its scale, but scientifically insightful efforts performed at this scale are relatively rare, so this aspect of the work needs acknowledgement. The wave heights and duration of the experiment are reasonably realistic for the conclusions they drew and the global extrapolation.

I agree with the major insights that the authors chose to highlight. The research places new bounds the capacity of aboveground vegetation to attenuate waves, and these bounds are different for low- and high-energy coastlines, and dependent on wave height. I consider these points to be meaningful because they add caveats to the broad, global claims we often make about tidal wetland ecosystem services and hopefully force us to be more nuanced and transparent about the benefits of protecting and restoring coastlines.

R1R0: Thank you for taking the time to review the manuscript and providing us with your valuable feedback. This is very much appreciated. We have improved the manuscript accordingly.

Major Comments

R1Q1: 1. The focus of the authors on aboveground biomass and height is appropriate for the issue of wave attenuation which dominates most of the manuscript. However, an important part of the manuscript that appears in the abstract, results, and discussion is the stability of the marsh platform irrespective of vegetation. Missing is the fact that belowground plant tissue also contributes to platform stability by stabilizing soil structure. This is an important point that needs to be acknowledged and there is a robust literature to draw upon relating belowground biomass to erosion-relevant physical properties such as shear stress.

The implications of the absence of data and discussion on belowground biomass depends on how the effects of vegetation on marsh elevation were calculated. Based on L332-338 and L341-348 of the methods it appears that conclusions about plant effects on elevation are based only on measurements made on the marsh monoliths before and after the aboveground biomass was mowed. If so, the belowground biomass was largely intact after mowing and plant biomass was still stabilizing the soil against erosion.

Alternatively, if the authors are comparing changes in elevation in the marsh section of the flume to changes in elevation in the mudflat section of the flume, then conclusions about the

absence of vegetation are reasonable as the mudflat did not plants, including their belowground biomass. This alternative approach does not seem to be the case, so the authors should modify their discussion to acknowledge the soil-stabilizing capacity of plant belowground biomass.

R1R1: The manuscript has been improved according to the above comment in several ways:

- Erosion is indeed measured and discussed specifically for the salt marsh, and not for the bare tidal flat. The bare mudflat was not the focus of the study, hence it was a concrete construction that was not subject to change to enable a meaningful comparison of results from the salt marsh. Indeed the belowground biomass of the salt marsh was largely intact after mowing and belowground biomass stabilized the soil throughout the experiment. The text in the main body and Methods section has been changed for clarity:
 - (main body: lines 145 - 148) “Thus, with negligible surface erosion and largely intact vegetation belowground biomass and root structures throughout all experimental runs, our experiment suggests that marsh platforms are able to contribute to wave attenuation irrespective of the damage to aboveground biomass, as long as there is no lateral retreat due to seaward cliff initiation and erosion (Bouma et al., 2014; Mason et al., 2025)”.
 - (methods: lines 515 – 517) “The bare tidal flat was constructed using concrete to prevent bed level dynamics at the flat potentially affecting the incoming wave at the marsh edge, as the focus was on the dynamics of the vegetated salt marsh.”
 - (methods: lines 617 - 618) “The concrete bare tidal flat, seaward from the salt marsh in the flume, was not subject to change”.
- In general, root structures in salt marshes are found at a depth below the surface up to approximately 40 cm. As stated in review comment **R1Q1**, belowground biomass tissue contributes to soil strength, for example in marshes across Europe and North America (Brooks et al., 2021). A higher contribution to stability is expected for a salt marsh vegetation composition that has a higher plant diversity (e.g. Ford et al., 2016). Thus, we agree that it is important to address this clearly in the manuscript. In our experiment, *Elymus athericus* showed decreasing biomass of root material with depth with most dry belowground biomass (76% to 80%) in the top layer (5 cm depth) and only 2% to 7% of the total biomass at a depth of 20 cm, similar to marshes for example in the UK and US (Brooks et al., 2021). The roots of the dominant *Elymus athericus* species in our experiment were, despite the low plant diversity, able to stabilize the bed under the extreme conditions tested. These insights are added in the main body of text, Methods section and Extended Data. In the Methods, a section is now dedicated to belowground biomass (roots) and organic matter content (1.3. Organic matter content and root biomass of the substrate).
 - (main body of text: lines 133 – 137) “The presence of belowground biomass and roots in the marsh substrate is known to enhance soil stability Also, a clear root zone was present in our experiment, mainly in the top 10 cm of the substrate. Organic matter content in the marsh substrate was 4.7% ± 1.7% (see Methods and Extended Data table 2).”
 - (methods: lines 568 - 579) “Prior studies describe a rooting depth of vegetation species in salt marshes of 10 to 40 cm below the surface (Brooks et al., 2021). The *Elymus athericus* marsh cover has a web-like root structure (i.e. dichotomous branching), with long roots compared to other species, but an average to low central root and branch density (Bouma et al., 2001). Vegetation roots stabilize the soil, potentially with increasing stability if the

vegetation composition is more diverse (Ford et al., 2016). Root mass in our experiment was measured at 5, 10 and 20 cm depth, with n (sample size) = 4. Root samples were collected after the experimental wave runs at locations where the soil was undisturbed by placing bulk density rings (6 cm diameter and 4.05 cm depth), with the midpoint at the chosen depth. The rings with material were carefully dug out, roots were gently rinsed and dried in an oven at 60 °C for 48 hours, before weighing to obtain dry root mass (g) at each depth interval. Subsequently, root density was calculated. Belowground biomass was mainly present in the top layer in our experiment (5 cm; 78% of the total biomass; Extended Data table 1)."

- (Extended Data: lines 926 - 931) "Table 1. Root mass distribution"

R1Q2: 2. The authors acknowledge on L127 that wave attenuation depends on the stability of the marsh substrate. In the present case the marsh substrate was 31-45% clay with properties like cohesion that contribute to the stability of the marsh platform. My sense is that the grain size distribution of the monoliths in this study transfer well to many coastal marshes. However, they also transfer poorly to many other coastal marshes in places like the Atlantic and Gulf coasts of North America where organic-rich soils and sediments are common. Importantly, I suspect that the global distribution of organic-rich soils co-varies with the distribution of low-energy coastlines, an important interaction that the authors do not recognize in the text of the paper.

To be clear, I am certainly not asking the authors to incorporate soil properties into their global model which would be difficult and beyond the capacity of their statistical model. The model they are using for a global extrapolation is appropriate for the data they have available from the flume study. Rather, I am asking them to discuss this matter in the section titled Global marsh vegetation reducing extremes.

R1R2: *Thank you for emphasizing the importance of soil parameters globally. This has been acknowledged in the manuscript. Below we offer a mechanistic discussion, including a comparison with other studies/regions and explain how this is applied in the manuscript.*

- *The mean organic matter content of the marsh substrate used in the experiment was $4.7\% \pm 1.7\%$. This is added in main body of text and in the Methods section and described in more detail in the Extended Data. In the Methods, a subsection is now dedicated to belowground biomass (roots) and organic matter content (1.3. Organic matter content and root biomass of the substrate).*
 - *(main body of text: lines 135 – 137) "Organic matter content in the marsh substrate was $4.7\% \pm 1.7\%$ (see Methods and Extended Data Table 2)."*
 - *(methods: lines 559 - 561) "Mean organic matter content in the salt marsh substrate in our experiment was $4.7\% \pm 1.7\%$ and ranged between 2.3% and 7.6% (Extended Data Table 2). Organic matter content is determined using loss-on-ignition (LOI)."*
 - *(Extended Data: lines 929 - 936) "Table 2. Grain size characteristics and organic matter content"*
- *As mentioned in the reply to the previous comment (R1R1), information on root mass distribution over substrate depth is added in the main body of text, methods section and Extended Data. For completeness this is repeated below:*
 - *(main body of text: lines 133 – 137) "The presence of belowground biomass and roots in the marsh substrate is known to enhance soil stability Also, a clear root zone was present in our experiment, mainly in the top 10 cm of the*

substrate. Organic matter content in the marsh substrate was $4.7\% \pm 1.7\%$ (see Methods and Extended Data table 2)."

- (methods: lines 568 - 579) "Prior studies describe a rooting depth of vegetation species in salt marshes of 10 to 40 cm below the surface (Brooks et al., 2021). The *Elymus athericus* marsh cover has a web-like root structure (i.e. dichotomous branching), with long roots compared to other species, but an average to low central root and branch density (Bouma et al., 2001). Vegetation roots stabilize the soil, potentially with increasing stability if the vegetation composition is more diverse (Ford et al., 2016). Root mass in our experiment was measured at 5, 10 and 20 cm depth, with n (sample size) = 4. Root samples were collected after the experimental wave runs at locations where the soil was undisturbed by placing bulk density rings (6 cm diameter and 4.05 cm depth), with the midpoint at the chosen depth. The rings with material were carefully dug out, roots were gently rinsed and dried in an oven at 60°C for 48 hours, before weighing to obtain dry root mass (g) at each depth interval. Subsequently, root density was calculated. Belowground biomass was mainly present in the top layer in our experiment (5 cm; 78% of the total biomass; Extended Data table 1)."
- (Extended Data: lines 923 - 928) "Table 1. Root mass distribution"
- Organic matter contents of the soil from our experiment can be compared with values from other salt marsh locations globally:
 - Our experiment, range: 2.3% – 7.6%, mean: 4.7%
 - Wadden Sea, Northwestern Europe, range: 1.3% – 8.8%, mean: 4.2% (Mittman-Goetsch et al., 2024)
 - East Coast US and Gulf of Mexico, range: 0% – 55% (Turner et al., 2005)
 - European regional seas, range: 0% - 76.7%, mean: 8.5% (Graversen et al., 2025)
 - Mediterranean Italy, range: 4% - 30% (Puppin et al., 2024)

The contribution of organic matter contents to shear strength of the soil is twofold: in general, organic content increases the erosion resistance of the soil, which is also the case for erosion on a grain-by-grain scale (Brooks et al., 2021; Evans et al., 2022; Marin-Diaz et al., 2022, 2025). However, there are important nuances, as organic-rich soils with a higher organic matter content and higher belowground root content are more compressible. So, in very organic-rich soils there can be a high void ratio and more open structure that results in instability (Brain et al., 2011; 2015). Marshes with these characteristics can be found on the East coast and Gulf of Mexico of the US (Brooks et al., 2021), but marshes with higher organic matter for example in Europe, appear to be stronger (Marin-Diaz et al., 2022; 2025). Compared to salt marshes, the erodibility of fresh and brackish marshes is larger due to shallower rooting and potentially low inorganic sediment content and high nutrient inputs. This is supported by preferential erosion of brackish marshes, whereas the salt marsh substrate remained largely unaffected during hurricanes Katrina and Rita in the Louisiana coastal plain (Howes et al., 2010). From this we conclude that the marsh substrate in our experiment is representative for marshes in general, but might overestimate the stability of more organic-rich soils found at the East coast of the US and Gulf of Mexico. So, our study yields a conservative estimator regarding soil erodibility for salt marshes in general, but might overestimate the stability of brackish marshes and marshes with organic-rich soils. Nevertheless, brackish and freshwater marshes are found more inland, and might experience less exposure than the saline marshes fronting the open sea. Organic matter content measured in the salt marsh in our experiment has been added to the main body of text. For comparison, data from

other locations globally has been added to the Methods section 1.3 (dedicated to the substrate). The implications discussed here are summarized in the last section of the main body of text.

- (main body of text: lines 135 – 137) “Organic matter content in the marsh substrate was $4.7\% \pm 1.7\%$ (see Methods and Extended Data Table 2).”
- (Extended Data: lines 929 - 936) “Table 2. **Grain size characteristics and organic matter content** of the top 30cm of the substrate at the two locations in the field site where the salt marsh blocks are collected.”
- (methods: lines 559 – 567) “Mean organic matter content in the salt marsh substrate in our experiment was $4.7\% \pm 1.7\%$ and ranged between 2.3% and 7.6% (Extended Data Table 2). Organic matter content is determined using loss-on-ignition (LOI). The organic matter content in the substrate in our experiment is similar to many other European salt marshes, which typically range between 0% and 76.7% (mean of 8.5%) (Graversen et al., 2025). More specifically, studies in the Wadden Sea, Northwestern Europe show a range between 1.3% and 8.8% (mean of 4.2%) (Mittmann-Goetsch et al., 2024)) and in the Mediterranean between 4% - 30% (Puppini et al., 2024). The organic matter content in our study is within the lower range when comparing to, for example, North American marshes, which are more organic-rich (range 0% - 55%) (Turner et al., 2000).”
- (main body of text: lines 253 - 266) “In general, our study implies that nature’s services to society (ecosystem services) depend on the stability of the salt marsh substrate, such as wave attenuation and carbon storage (Mason et al., 2023; Mcleod et al., 2011), and are unlikely to be affected by extreme storms via surface erosion, as the marsh substrate remains stable both at low- and high-energy coasts. Our flume experiment where this is based on contains two soil types (Extended Data table 2). The organic matter content of the soil is representative for European marshes, which corresponds to the lower range of the organic-rich soils at the East coast of the US and the Gulf of Mexico (see Methods) (Turner et al., 2000). Organic-rich soils can have a more open structure that might result in instability (Brooks et al., 2021), although this is not the case for higher organic matter content such as in European salt marshes (Marin-Diaz et al., 2022). This is different for brackish and freshwater marshes, which are more prone to erosion due to shallower root zones and potentially low inorganic sediment content (Howes et al., 2010). Hence, our projection yields a conservative estimation regarding soil erodibility for salt marshes, but may overestimate the stability of organic-rich soils and brackish marshes.”

R1Q3: 3. I found the section on Global marsh vegetation reducing extremes to be a bit of a weak spot in the manuscript. While I appreciate text on the relevance of the work to topics like nature-based solutions, I think the text in this section would be better invested in advancing the field by discussing how to further refine the global model.

The authors make the point that their estimates are conservative because of the height and stiffness of the dominant plants in the marsh monoliths. I suggest they add discussion on the extent to which their conclusions would vary in marshes with more robust plants such as large areas of the world where invasive *Phragmites australis* or *Spartina alterniflora* are

dominant or shrub-dominated marshes. I also suggest adding thoughts about how soil type would affect their estimates.

R1R3: The section “Marsh vegetation reducing extremes” is adjusted based on the comment above and comments from the other reviewers:

The discussion focusing on NbS in the section on “Marsh vegetation reducing extremes” is shortened (main body of text: lines 287 - 295).

Uncertainties related to global upscaling are now addressed twice, based on comments and suggestions of all reviewers. A wider comparison with literature is included and the effect of other (less conservative) marsh vegetation species is discussed and assessed in a scenario analysis testing the sensitivity of vegetation.

- Discussing the influence of vegetation species in salt marshes, brackish and freshwater wetlands as well as environments including seagrass meadows and riverine settings. This is implemented in the last section of the main body of text, in addition to Figure 1 in the Extended Data. For a more extensive discussion of substrate stability and erodibility please refer to the response to the previous comment (**R1R2**). In the methods section a new section has been written to put the vegetation used in our experiment in a wider perspective (methods Section 2.2. Stem height in salt marshes as proxy for wave attenuation).
 - (main body of text: lines 233 - 248) “Projecting results from the flume experiments to a global scale suggests that in general, salt marsh vegetation enhances the resistance of low-energy marsh coasts to extreme conditions. At almost all low-energy marsh coasts with waves up to 1 m, waves are attenuated by more than 10% for *Elymus athericus*, which can be considered a conservative wave attenuation estimator for salt marshes in general (Extended Data Figure 1). This wave attenuation functionality is also found in seagrass environments under low-energy conditions (Bradley & Houser, 2009), and may also apply in freshwater settings (Ren et al., 2021). Decreasing salinity induces an increase in species diversity, because species diversity increases with decreasing environmental stress (Więski et al., 2010). Also, it leads to a shift towards species with longer and less flexible stems compared to *Elymus athericus*, such as the common reed *Phragmites australis* (Zhu et al., 2019; Dijkema, 1990). Both higher species diversity and the shift to longer and less flexible stems enhance wave attenuation, even under higher vegetation damage. This corresponds with the result of our sensitivity analysis (Extended Data Figures 3-6).”
 - (main body of text: lines 253 - 266) “In general, our study implies that nature’s services to society (ecosystem services) depend on the stability of the salt marsh substrate, such as wave attenuation and carbon storage (Mason et al., 2023; Mcleod et al., 2011), and are unlikely to be affected by extreme storms via surface erosion, as the marsh substrate remains stable both at low- and high-energy coasts. Our flume experiment where this is based on contains two soil types (Extended Data table 2). The organic matter content of the soil is representative for European marshes, which corresponds to the lower range of the organic-rich soils at the East coast of the US and the Gulf of Mexico (see Methods) (Turner et al., 2000). Organic-rich soils can have a more open structure that might result in instability (Brooks et al., 2021), although this is not the case for higher organic matter content such as in European salt marshes (Marin-Diaz et al., 2022). This is different for brackish

and freshwater marshes, which are more prone to erosion due to shallower root zones and potentially low inorganic sediment content (Howes et al., 2010). Hence, our projection yields a conservative estimation regarding soil erodibility for salt marshes, but may overestimate the stability of organic-rich soils and brackish marshes.”

- (methods: lines 697 - 725) **“2.2. Stem height in salt marshes as proxy for wave attenuation**

Key for the functionality of the marsh is the presence of salt-tolerant vegetation (halophytes), such as herbs, grasses and shrubs, which typically depend on salinity and inundation gradients (Adam, 1993). The stem height of the vegetation is an important parameter, for wave attenuation. Stem height is used as a proxy for wave attenuation as penetration of the stem in the water column is considered a strong predictor of wave attenuation, especially under extreme wave heights and water levels (Vuik et al., 2018). As a result, damage to vegetation by a decreasing stem height will have a direct impact on wave attenuation. Stem height, as well as biomass of *E. athericus* is comparable with global marsh vegetation species that carry stems. Both values of damaged stem height and biomass at the end of our experiment, were smaller than values globally found for (other) salt marsh vegetation species (Extended Data Fig. 1), throughout the year.

Increasing wave attenuation with stem height can be expected both at low- and high-energy coasts, and is also found as a result of the flume experiment (Figure 3). Yet for high-energy conditions, the higher risk of damage may cancel this benefit. Comparing *Elymus* with *Spartina* spp., locally a species growing at a lower elevation and regionally a dominant species in e.g. North America (Pennings & Bertness, 2001; Bertness, 1991), wave-induced damage to *Spartina* spp. is lower due to a higher flexibility (Reents et al., 2022). Hence, attenuation can be expected to be higher as more stems and biomass persists (Fig. 3). Attenuation can also be expected to increase towards a lower salinity environment, since due to decreasing environmental stress, species diversity increases (Ren et al., 2021; Więski et al., 2010; Schulte Ostermann et al., 2024).

“70% of the salt marshes globally present are found in the temperate climate zone and therefore experience a winter season (Worthington et al., 2024). In general, the vegetation state at the end of the winter can be considered to yield a conservative estimate for vegetation stem height as vegetation outside the winter season, e.g. in the growing season, is more resistant (Reents et al., 2022). Furthermore, *E. athericus* in our experiment can be considered to yield a conservative estimate of wave attenuation, because its breaking force is relatively low (weak) compared to other salt marsh vegetation species (Zhu et al., 2019). Less vegetation damage leads to longer stems persisting and hence a higher wave attenuation capacity. In addition, we tested a single salt marsh zones, whereas salt marshes in general contain multiple zones that enhance the wave attenuation capacity (Schoutens et al., in preparation). Finally, only a small (70 m) part of the marsh was considered for wave attenuation.”

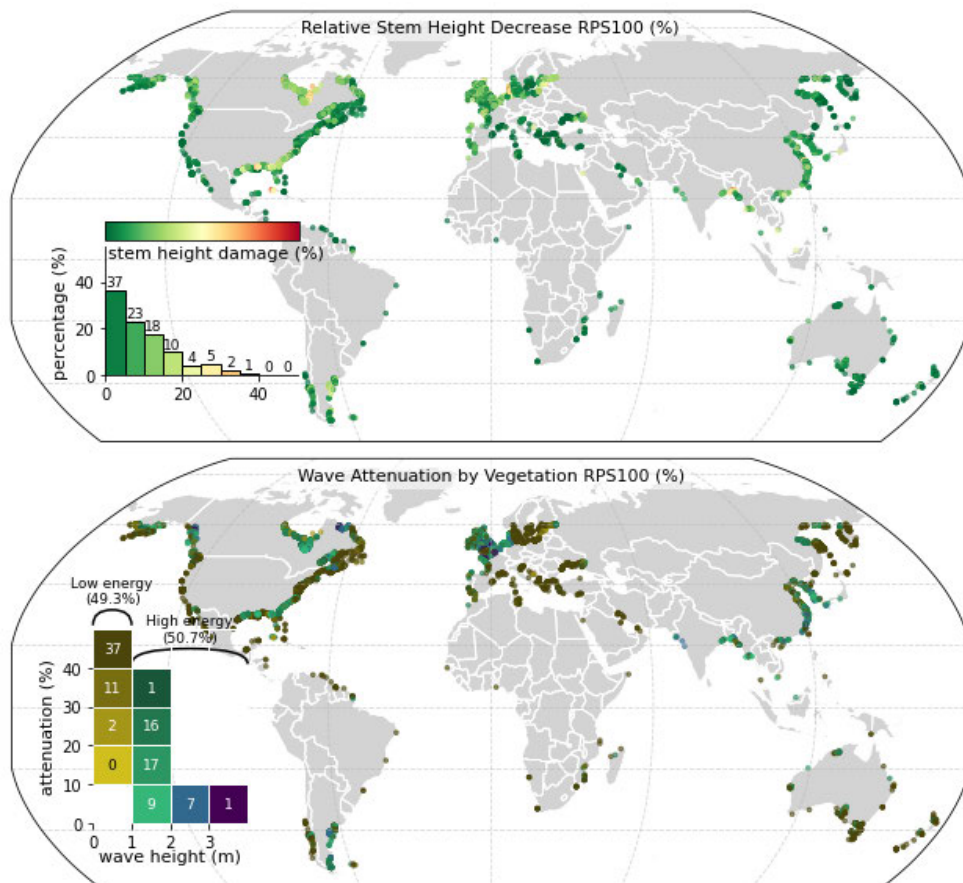
- Assessing the uncertainty for species that would yield less-conservative estimations by changing vegetation related parameters in the global upscaling. First, the vegetation height is doubled (100% increase) to resemble species with longer stems (e.g. *Phragmites australis*), while progressive damage remained the same (adapting relation in Fig. 3 panel B). Wave attenuation by vegetation for this adapted stem

height was calculated through the relations obtained in the experiment for *Elymus athericus* (Fig. 3 panel C). To finalize this assessment a new GLM was fitted to calculate wave attenuation by increased vegetation globally. With this first up-scaling scenario, additional damage by longer vegetation was not considered. Although *Elymus athericus* (used in our experiment) is considered a rather weak species (e.g. Reents et al., 2022), longer stems as *Phragmites australis* experience larger wave orbital velocities potentially leading to more damage. Hence, a second scenario is applied where exponential vegetation damage (Fig. 3 panel B) is increased by 100% (i.e. $y = a * e^{(b * x)}$ adapted to $y = a * e^{(2 * b * x)}$). These scenarios are applied to events with return periods of 100 and 1000 years, totaling four additional model runs.

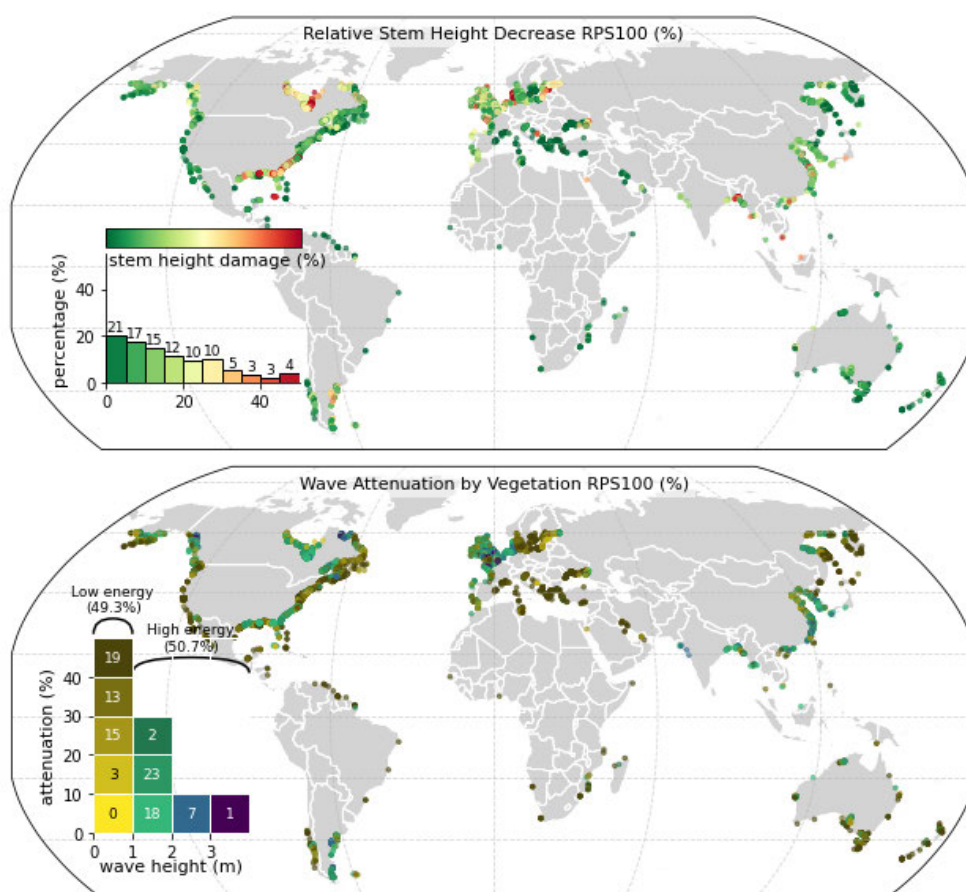
This scenario analysis for the sensitivity of vegetation properties (damage and height), emphasizes that longer species increase wave attenuation. Incoming wave heights between 0 and 1 m (low-energy waves) are attenuated generally by 30% or more, while incoming waves exceeding 1 m (high-energy waves) are attenuated less than 30% generally. When considering an increase in damage if vegetation is higher, a similar trend is observed, although the tipping point is now at 20%, which was at 10% in the initial scenarios. Incoming waves below 1 m are attenuated by more than 20%, while incoming waves exceeding 1 m are generally attenuated no more than 20% (see rebuttal Figure 1 and 2 for the results with a return period of 100 years; for a return period of 100 and 1000 years, Figures 3 - 6 are added in the Extended Data Figures 3 – 6). The scenario analysis therefore emphasizes that a less conservative estimate including longer vegetation leads to more attenuation, even when including increased damage. In addition, the trend regarding low-energy (< 1 m incoming wave height) and high-energy (>= 1 m incoming wave height) remains the same. Only the tipping point of wave attenuation switches between 10% (*Elymus athericus* model assessment), 20% (increased vegetation height with increased damage), and 30% (increased vegetation height only). These considerations are added in the last section of the main body of text and model results in the Extended Data.

- (main body of text: lines 245 - 248) “Both higher species diversity and the shift to longer and less flexible stems enhance wave attenuation, even under higher vegetation damage. This corresponds with the result of our sensitivity analysis (Extended Data Figures 3-6).”
- (Extended Data: lines 959 - 965) **“Figure 3. Storm events lead to decreasing wave attenuation due to vegetation damage, model results with increased vegetation height (return period of 100 years).** Water depth at the seaward salt marsh edge, and distribution of water depths over all transects (a), exposure duration for progressive vegetation damage and distribution (b), relative stem height decrease and distribution (c) and GLM-predicted attenuation by vegetation and distribution per wave attenuation percentage class and incoming wave height bin (d), calculated for a scenario where vegetation height is increased by 100%.”
- (Extended Data: lines 966 - 972) **“Figure 4. Storm events lead to decreasing wave attenuation due to vegetation damage, model results with increased vegetation height (return period of 1000 years).** Water depth at the seaward salt marsh edge, and distribution of water depths over all transects (a), exposure duration for progressive vegetation damage and distribution (b), relative stem height decrease and distribution (c) and GLM-predicted attenuation by vegetation and distribution per wave attenuation percentage class and incoming wave height bin (d), calculated for a scenario where vegetation height is increased by 100%.”

- (Extended Data: lines 973 - 979) “Figure 5. **Storm events lead to decreasing wave attenuation due to vegetation damage, model results with increased vegetation height and damage (return period of 100 years)**. Water depth at the seaward salt marsh edge, and distribution of water depths over all transects (a), exposure duration for progressive vegetation damage and distribution (b), relative stem height decrease and distribution (c) and GLM-predicted attenuation by vegetation and distribution per wave attenuation percentage class and incoming wave height bin (d), calculated for a scenario where vegetation height is increased by 100% and vegetation damage is also increased by 100%.”
- (Extended Data: lines 980 - 986) “Figure 6. **Storm events lead to decreasing wave attenuation due to vegetation damage, model results with increased vegetation height and damage (return period of 1000 years)**. Water depth at the seaward salt marsh edge, and distribution of water depths over all transects (a), exposure duration for progressive vegetation damage and distribution (b), relative stem height decrease and distribution (c) and GLM-predicted attenuation by vegetation and distribution per wave attenuation percentage class and incoming wave height bin (d), calculated for a scenario where vegetation height is increased by 100% and vegetation damage is also increased by 100%.”



Rebuttal figure 1. Relative stem height decrease and distribution (top panel) and GLM-predicted attenuation by vegetation and distribution per wave attenuation percentage class and incoming wave height bin (bottom panel) for a return period of 100 years calculated for a scenario where vegetation height is increased by 100%.



Rebuttal figure 2. Relative stem height decrease and distribution (top panel) and GLM-predicted attenuation by vegetation and distribution per wave attenuation percentage class and incoming wave height bin (bottom panel) for a return period of 100 years calculated for a scenario where vegetation height is increased by 100% and vegetation damage is also increased by 100%.

Minor Comments

R1Q4: L104. Please add some insights on the rooting structure of the two dominant species such as rooting depth and aspects of belowground morphology such as roots and rhizomes that may be relevant to marsh platform stability.

R1R4: In general, root structures are found at a depth below the surface up to approximately 10 to 40 cm. These root structures contribute to soil strength, e.g. in marshes across Europe and North America (Brooks et al., 2021). The salt marsh in our experiment was covered with *Elymus athericus*, with a web-like/branching root structure (i.e. dichotomous branching), with on average long roots compared to other species, but an average to low central root and branch density (Bouma et al., 2001). The substrate with *Elymus athericus* was able to remain at its position under the extreme conditions tested. Insights have been added regarding root structure for the dominant *Elymus athericus* vegetation species in our experiment.

The dominant species *Elymus athericus* in our experiment showed the same distribution of belowground biomass, as generally observed in marshes (Brooks et al., 2021), with most dry belowground biomass (76% to 80%) in the top layer (5 cm depth) and only 2% to 7% of the total biomass at a depth of 20 cm.

- (main body of text: lines 133 - 137) "The presence of belowground biomass and roots in the marsh substrate is known to enhance soil stability. Also, a clear root zone was present in our experiment, mainly in the top 10 cm of the substrate. Organic matter content in the marsh substrate was $4.7\% \pm 1.7\%$ (see Methods and Extended Data table 2).
- (methods: lines 568 - 579) "Prior studies describe a rooting depth of vegetation species in salt marshes of 10 to 40 cm below the surface (Brooks et al., 2021). The *Elymus athericus* marsh cover has a web-like root structure (i.e. dichotomous branching), with long roots compared to other species, but an average to low central root and branch density (Bouma et al., 2001). Vegetation roots stabilize the soil, potentially with increasing stability if the vegetation composition is more diverse (Ford et al., 2016). Root mass in our experiment was measured at 5, 10 and 20 cm depth, with n (sample size) = 4. Root samples were collected after the experimental wave runs at locations where the soil was undisturbed by placing bulk density rings (6 cm diameter and 4.05 cm depth), with the midpoint at the chosen depth. The rings with material were carefully dug out, roots were gently rinsed and dried in an oven at 60 °C for 48 hours, before weighing to obtain dry root mass (g) at each depth interval. Subsequently, root density was calculated. Belowground biomass was mainly present in the top layer in our experiment (5 cm; 78% of the total biomass; Extended Data table 1)."
- (Extended Data: lines 923 - 928) "Table 1. **Root mass distribution** mean and standard deviation at 5, 10 and 20 cm depth, with n (sample size) = 4. Root samples were collected after the experimental wave runs at locations where the soil was undisturbed by placing bulk density rings (6 cm diameter and 4.05 cm depth), with the midpoint at the chosen depth. The rings with material were carefully dug out, roots were gently rinsed and dried in an oven at 60 °C for 48 hours, before weighing to obtain dry root mass (g) at each depth interval. Subsequently, root density was calculated."

R1Q5: L141. The first paragraph lost me here when the authors report that the marsh platform elevation was fairly stable under extreme wave conditions irrespective of vegetation. Missing to this point is information about changes in the elevation in the absence of the aboveground vegetation, which occurred during the third repetition according to the methods section. Please edit the paragraph to support the claim that the platform was stable in the absence of vegetation.

R1R5: Thank you for noticing this. Erosion is reported for the flume experiments with wave-damaged aboveground vegetation being present. These erosion measurements show a resistant surface over the full span of the experiment. 7 mm erosion over 21 hours, a duration longer than the potential exposure duration for vegetation damage of storms with a return period of up to 1000 years (Dullaart et al., 2023).

Furthermore, vegetation damage in the field will not result in the same situation as our runs without aboveground vegetation, as stems will not break flush with the bed level surface (see manuscript figure 3B; Vuik et al., 2018). Hence, the experimental runs with fully cut aboveground vegetation are not considered realistic for the assessment of erosion, but solely used for comparison and calculating the individual contribution of aboveground vegetation. Nevertheless, further erosion was not observed during these tests without aboveground vegetation. The text has been revised for more clarity:

- (main body of text: lines 129 – 132): “Elevation measurements at 32 fixed locations at the salt marsh show, on average, a decreasing marsh surface over the total experimental time of 21 hours with damaged vegetation (7 mm; 0.33 mm/h), which is in the same order of magnitude as previous studies with smaller wave heights (4.4 mm surface lowering; 0.16 mm/h) (Moller et al., 2014; Spencer et al., 2016)”
- (main body of text: lines 145 – 148): “Thus, with negligible surface erosion and largely intact vegetation belowground biomass and root structures throughout all experimental runs, our experiment suggests that marsh platforms are able to contribute to wave attenuation irrespective of the damage to aboveground biomass, as long as there is no lateral retreat due to seaward cliff initiation and erosion (Bouma et al., 2016; Mason et al., 2025)”

R1Q6: L135. Change “coastal plane” to “coastal plain”

R1R6: Thanks, done.

- (main body of text: lines 139 - 140) “...in the Louisiana coastal plain.”

R1Q7: L139. Describing the stability of the marsh platform as a “survival mechanism” seems odd when discussing an ecosystem as opposed to an organism. I suggest editing this to “essential feature”.

R1R7: Changed.

- (main body of text: lines 140 - 144) The observed stability of the marsh substrate under extreme conditions is an essential feature for their existence in areas where regular wave attacks may be expected (Gijssman et al., 2021). Our experiment shows that this essential feature is also valid for extreme storms, which agrees with limited field and flume evidence (Spencer et al., 2016; Howes et al., 2010; Gijssman et al., 2021).

R1Q8: L313. There seems to be an error in the dates since they state the monoliths were installed in the flume in Dec 2024 and the experimental runs occurred 10 months before in Feb 2024 (L319).

R1R8: Indeed an error, changed now.

- (main body of text: line 553) “From December 2023 onwards”

Referee #2 (Remarks to the Author):

R2Q0: Results, validity, originality, and significance:

It was a pleasure to read this manuscript. The primary contribution of this research is that it first investigates key physical processes related to wave forcing using an exceptionally large-scale flume experiment, and then extends this knowledge to enable modelling at the global scale. While the individual components are not particularly novel or groundbreaking, the study is significant when considered as a whole.

The study shows that salt marshes are effective in reducing erosion under highly energetic wave conditions (which have not been examined previously), but that wave attenuation itself is limited and occurs primarily under low-energy conditions. Essentially, the manuscript proposes an empirical relationship for estimating wave attenuation by vegetation as a function of storm exposure duration and incoming wave height.

The use of naturally occurring plants growing in their native soil in the experiments enhances the reliability of the results and their upscaling. However, it remains partly unclear whether it is appropriate to treat all salt marsh vegetation and sediment types equivalently (that is, whether vegetation and sediment properties should be included as predictors). On the other hand, the authors argue that their estimates are conservative, as they are based on plant species with relatively low breaking strength (i.e., “weak” species).

As a further note, the authors could have better stated the novelties themselves; presently it is partly left for the reader to interpret.

No flaws can be identified in the research, but the global representativeness of the experimental data (vegetation, sediment, etc) can be challenged.

No previous analyses exist at this large scale covering a broad range of wave conditions. The results are useful for critically evaluating NBS performance and directing their future developments.

R2R0: *Thank you for taking the time to review the manuscript and providing us with your valuable feedback. This is very much appreciated. We improved the manuscript accordingly.*

- *The novelty has been clarified further and has been addressed in the abstract by explicitly explaining what knowledge and understanding is currently missing, and in the introduction by explicitly stating what knowledge is missing, to better guide the reader:*
 - *(abstract: lines 39 - 40) “However, a comprehensive, quantified understanding of salt marsh-wave interaction under extreme events is lacking.”*
 - *(main body of text: lines 92 - 95) “Quantified knowledge explaining progressive vegetation damage and potential substrate erosion under these conditions, and the efficacy of damaged marsh vegetation in wave attenuation during extreme wave events when waves exceed 1m is lacking.”*
 - *(main body of text: lines 96 - 105) “Based on flume experiments and projected storm simulations at a global scale, here we aim to quantify the persistence of the marsh substrate and address the progressive vegetation damage and*

associated reduced wave attenuation under extreme storm conditions, by assessing:

- I. The stability of salt marsh substrate under extreme wave events;*
- II. Progressive vegetation damage and associated wave attenuation under extreme events;*
- III. The global contribution of progressively damaged salt marsh vegetation to wave attenuation that proceeds from results of the flume experiments.”*

- *Further review points regarding the reliability of the results, global upscaling with respect to vegetation and soil are discussed in the detailed responses that follow hereafter, and in the previous responses in the comments of the referee #1. Please refer to:*
 - *Comment **R1Q1** and **R1Q4** and the response **R1R1** and **R1R4**, regarding the effect of roots and how the roots of salt marsh species used in our flume experiment (*Elymus athericus*) compare with the root zone from other salt marsh vegetation species.*
 - *Comment **R1Q2** and the response **R1R2**, regarding organic matter in the soil and similarities and differences, and the potential impact on erodibility when comparing the organic matter content from our salt marsh substrate to other regions worldwide.*
 - *Comment **R1Q3** and the response **R1R3**, regarding the representativeness of salt marsh vegetation species and the impact of translating the results to other species.*

Data and methodology:

R2Q1. The methods are clearly reported, allowing reproduction of similar experiments by others. However, the study relied much on conventional, laborious manual vegetation measurements. In addition to those, optical/photogrammetric, multispectral imaging, and other remote sensing methods could have been used to characterize vegetation (e.g. LAI, PAI). Such data would support validation across different scales and regions, while being useful as a reference for other researchers. As a further remark, the sample sizes of some biomass and vegetation height measurements appear small (see below detailed comment concerning N=6 for 20 cm x 20 cm quadrants and N=20 for random stems).

R2R1. *Thank you for the comments, for a reply to the comments, we would like to refer to the more specific comments raised by referee #2:*

- *Regarding remote sensing data techniques, please see the response **R2R13** to detailed comment **R2Q13**.*
- *Regarding sample size, please see response **R2R4** to detailed comment **R2Q4**.*

R2Q2. It remains unclear how representative the tested marsh soil is of other geographical and climatological conditions and what are the uncertainties in the global up-scaling based on one single soil sample. The erodibility of cohesive sediments such as the one tested are known to be uncertain to predict, because multiple factors such as the grain size, % clay fraction, % organic content, dry bulk density, and water content affect erodibility. If too much of the underlying sediment is eroded, vegetation is destroyed by uprooting (not necessarily

by breaking). This mechanism facilitating/generating uprooting was apparently not considered in either the flume study (as erosion of the tested soil material was low) or the global up-scaling.

R2R2. *We agree that the representativeness of the soil was not clearly discussed in the initial draft of the manuscript. Please see:*

- *comment **R1Q1** and **R1Q4** and the responses **R1R1** and **R1R4**, regarding the effect of roots and how the roots of salt marsh species used in our flume experiment (*Elymus athericus*) compare with the root zone from other salt marsh vegetation species.*
- *comment **R1Q2** and the response **R1R2**, regarding organic matter in the soil and similarities and differences, and the potential impact on erodibility when comparing the organic matter content from our salt marsh substrate to other regions worldwide.*

The representativeness of the soil is extensively discussed in the rebuttal and clarified in the revised manuscript.

R2Q3. The methodology of obtaining the 1/100 and 1/1000 wave heights based on the storm surge observations is not clearly described.

R2R3. *Please see the response **R2R12** to the comment **R2Q12** “Wave action durations” below. The derivation of the hydrodynamic conditions when damage starts is now more clearly described in the methods section.*

- *(Methods: lines 755 - 760) “Since stem height damage in the Delta Flume experiment started already during the most tranquil hydrodynamic conditions ($h = 1.5$ m; $H_{m0} = 0.75$ m), initiation of stem height damage in the global model was set following previous controlled flume experiments (Rupprecht et al., 2017). In these previous experiments, starting at water depths of 1 m and wave heights of 0.1 m, first, significant stem damage was observed after water depths of 1 m and wave heights of 0.5 m on average (Rupprecht et al., 2017).”*

Subsequent derivation of exposure duration is now further described in the Methods section.

- *(methods: lines 760 - 766) “Using the local storm surge hydrographs, exposure duration for vegetation damage is calculated over the time window during which wave heights at the marsh exceed 0.5 m from the start of the storm until the point in time when the highest waves occur, i.e. at the peak of the storm surge hydrograph. The maximum incoming wave height at the marsh edge is calculated at the peak of the storm, with the most severe estimate for the wave height being 50% of the water depth (Van Zelst et al., 2021; Massel, 1996; Nelson et al., 1994). Finally, wave attenuation at the peak of the storm is calculated using the GLM, as the highest depth-limited waves potentially occur at this point.”*

R2Q4. It appears that statistical tests were rigorously completed, but in some cases number of data are limited: N=6 for biomass and N=20 for stem height. The rather low number of specimens likely explains why only few significant differences were observed (Table S2).

R2R4. *Indeed, dry biomass was collected at 6 locations in a 20 cm x 20 cm plot, (1) close to the seaward marsh edge, (2) at the center of the marsh and (3) at the landward marsh edge, distributed over the two transects. To obtain stem properties over time, 20 stems per measurement were collected from randomly distributed locations over the marsh. Per*

measurement, $20 \times 20 \text{ cm} \times 6 = 0.24 \text{ m}^2$ was removed. Including stem removal, this results in a total loss of less than 1% of the full marsh cover. While we agree that this resulted in a small sample size, this choice was made deliberately. Destructive measurements were minimized, to not damage the marsh too much which would prevent comparison between runs. A short explanation is provided in the main body of text. Further explanation is provided in the Methods section 1.4:

- (main body of text: lines 161 - 162) “Vegetation biomass and stem length were collected by destructive measurements, affecting a negligible marsh surface (see Methods).”
- (methods: lines 642 - 644) “The destructive measurements for biomass (vegetation measurement 2) and stem length (vegetation measurement 3) affected a marsh area smaller than 1% of the total salt marsh in the physical model.”

Although we agree that a larger sample size would have been beneficial, we ensured that our sample size was comparable with, or higher than, other peer-reviewed studies focusing on plant samples either in plots or in individual stems from a salt marsh, including:

- Zhu et al. (2020): $n = 10$ per species per location.
- Reents et al. (2022): $n = 5$ per species - treatment combination.
- van Veelen et al. (2020): $n = 5 - 15$ per species.
- Mason et al. (2025): $n = 8$.
- Paul et al. (2022): $n = 10$.

R2Q5. The manuscript does not specifically address the uncertainties related to the global up-scaling. The uncertainty could be addressed e.g. through different upscaling scenarios, in which the properties of vegetation or wave heights are varied. How much larger is the wave attenuation considering “less conservative” vegetation, e.g. stronger species or those with larger biomass/stem length (cf. Figure S1), or summer conditions with higher biomass and longer stems expected.

R2R5. Please see response **R1R3** to comment **R1Q3**.

Conclusions:

The conclusions are supported by the data. However, some clarifications are needed:

R2Q6. - Row 231: 10% attenuation appears small to have any significant impact. Which attenuation level must be achieved for significant positive impacts?

R2R6. We agree that the contribution of vegetation to wave attenuation seems rather small at some locations. However, the impact does not scale linearly with relative wave attenuation.

For incoming significant wave heights up to 1 m, the attenuation generally ranges between 10% and 40%, equaling a decrease of 0.1 to 0.4 m for a 1 m wave. For incoming waves exceeding 1 m, attenuation is approximately 0.1 to 0.5 m. Focusing on impact:

- 1) If coastal protection infrastructure is present landward of the salt marsh, overtopping discharge can substantially be reduced by marsh vegetation. Coastal protection costs by vegetation are sensitive to critical overtopping discharge, as the crest height scales non-linearly with the wave height in front of the coastal protection infrastructure (Pullen et al., 2007). Because of reduced overtopping rates, preventing a dike heightening of 1 m, saves approximately 7 million USD₂₀₀₅ PPP (Purchasing

Power Parity) per stretch of 1 km dike (Ward et al., 2017; Van Zelst et al., 2021). When interpolating this linearly, preventing 0.2 m of dike heightening saves 1.4 million USD. At present, depending on the economy, this can be multiplied by an average factor of more than two (<https://data.worldbank.org/indicator/NY.GDP.MKTP.PP.CD?end=2024&start=2005>). Thus, wave attenuation by marsh vegetation could yield considerable cost savings, even for relatively small reductions in wave height. In the absence of coastal protection infrastructure, small relative reductions in wave height can still make a meaningful impact in terms of shoreline stabilization, as the bed shear stress (erosional force) also scales non-linearly with the wave height.

- 2) The impact of wave attenuation by vegetation compared to the global average sea-level rise of 0.49 cm in the year 2100 (DeConto & Pollard, 2016), emphasizes that a small reduction of the incoming wave height might already offset a large part of the expected sea-level rise for the coming decades.

Both cost reduction and wave attenuation by vegetation potentially offsetting the impacts of sea level rise are discussed in the last section of the main body of text:

- (main body of text: lines 278 - 288) “Our results emphasize that restoration and conservation of salt marshes as a Nature-based Solution (NbS), supporting biodiversity, protect against extreme storms more effectively at low-energy coasts than at high-energy coasts. Hence, application at low-energy coasts should be prioritized, but even at high-energy coasts potential cost reduction is considerable as preventing 1 km dike heightening by 0.2 m, already saves 1.4 million USD2005 PPP (Purchasing Power Parity), because of reduced overtopping rates (van Zelst et al., 2021; Ward et al., 2017). In addition, reduction of the wave height by decimeters offsets predicted average sea level rise of 0.49 m in 2100 (RCP4.5) by decades (DeConto & Pollard, 2016). This cost reduction can motivate continuous support and maintenance that is required for salt marshes to prevent long-term erosion and guarantee their persistence at high-energy coasts.”

R2Q7. - Can you elaborate on the uncertainty/sensitivity regarding the 10% wave attenuation, referring to the stated “conservative estimates based on using plant species with low breaking force (i.e., “weak”)”.

R2R7. Please see the response **R1R3** to comment **R1Q3**.

R2Q8. - R250-263: Improve the discussion by amending with management implications. Obviously salt marshes should be protected, but would some vegetation management/maintenance be useful and realistic in certain areas? Is this 10% reduction result cost-effective to support large-scale restorations? Can restoration activities be prioritized based on certain criteria?

R2R8. Please see response **R2R6** to the above comment **R2Q6**. Low-energy coasts should be prioritized, but nevertheless potential cost reduction for dike heightening at high-energy coasts can be considerable. So, this can motivate restoration and management/maintenance efforts for marshes at high-energy coasts.

- (main body of text: lines 278 - 288) “Our results emphasize that restoration and conservation of salt marshes as a Nature-based Solution (NbS), supporting biodiversity, protect against extreme storms more effectively at low-energy coasts than at high-energy coasts. Hence, application at low-energy coasts should be

prioritized, but even at high-energy coasts potential cost reduction is considerable as preventing 1 km dike heightening by 0.2 m, already saves 1.4 million USD2005 PPP (Purchasing Power Parity), because of reduced overtopping rates (van Zelst et al., 2021; Ward et al., 2017). In addition, reduction of the wave height by decimeters offsets predicted average sea level rise of 0.49 m in 2100 (RCP4.5) by decades (DeConto & Pollard, 2016). This cost reduction can motivate continuous support and maintenance that is required for salt marshes to prevent long-term erosion and guarantee their persistence at high-energy coasts.”

R2Q9. - Fig 4: Africa and South America are not well represented on the map. It remains unclear, how biased the global analyses are.

R2R9. *Africa and South America indeed represent a small proportion of global marsh area on the map. The global distribution of salt marshes, including Africa and South America, is captured in the data from Worthington et al. (2024) which we use in our global analysis. The data in Worthington et al. (2024) is represented in Marine ecoregions:*

- South America is captured in Marine ecoregions:
 - o Temperate South America 3790 km² (7.2% of global total)
 - o Partly in Tropical Eastern Pacific: 80 km² (0.2% of global total)
 - o Partly in Tropical Atlantic 4810 km² (9.1% of global total)
- Africa
 - o Temperate Southern Africa 80 km² (0.2% of global total)
 - o Partly in Western Indo-Pacific 1920 km² (3.6% of global total)
 - o Partly in Tropical Atlantic 4810 km² (9.1% of global total)

This shows that only a very limited part of the world’s salt marshes is located in South America and Africa.

Further, to ensure that the lower area of marshes in Africa and South America did not lead to underrepresentation in our analysis, we checked the filtering of our data. After filtering the transects for the global analysis, as described in Methods subsection 2.3, exclusion of transects in South America and Africa is in the same order as for the other continents.

- o (methods: lines 730 - 741) *“We incorporated several updates; (1) elevation data from DeltaDTM was used³² instead of MERIT⁷¹ and vegetation extent data was updated³³, (2) we filtered foreshores that are preceded by waterbodies with a minimal length of 1km using a global water mask⁷² to assure that foreshore data are derived at the right location, (3) salt marsh areas sheltered behind higher landscape features, such as dunes, were excluded by flagging vegetation presence false if the mean elevation in the vegetated zone is lower than the mean elevation of the preceding non-vegetated foreshore data points, and (4) false positives of vegetation presence in areas with steep transitions (e.g., steep coastal slopes or cliffs) were corrected by applying an Interquartile Range filter on elevation within vegetated areas with a multiplier of 1.5. In general, this filtering resulted in an equal reduction across continents.”*

This notwithstanding, to address the concern and to increase the representation of Africa and South America in the maps (Figure 4 and Extended Data Figure 2, as well as new figures added to the Extended Data, 3 – 6), the projection has been changed to “Robinson” for a balance between visibility and equal area (see e.g. <https://pro.arcgis.com/en/pro-app/latest/help/mapping/properties/robinson.htm>) and figures are updated accordingly.

- (main body of text: lines 489 - 494) “Figure 4. **Storm events lead to decreasing wave attenuation due to vegetation damage**. Water depth at the seaward salt marsh edge, and distribution of water depths over all transects (a), exposure duration for progressive vegetation damage and distribution (b), relative stem height decrease and distribution (c) and GLM-predicted attenuation by vegetation and distribution per wave attenuation percentage class and incoming wave height bin (d) for a return period of 100 years.”
- (Extended Data: lines 952 - 957) “**Figure 2. Storm events lead to decreasing wave attenuation due to vegetation damage (return period of 1000 years)**. Water depth at the seaward salt marsh edge, and distribution of water depths over all transects (a), exposure duration for progressive vegetation damage and distribution (b), relative stem height decrease and distribution (c) and GLM-predicted attenuation by vegetation and distribution per wave attenuation percentage class and incoming wave height bin (d) for a return period of 1000 years.”

Suggested improvements:

Improve logical flow, some explanations should appear earlier in the text:

R2Q10- Short description of different salt marsh vegetation types/conditions globally

R2R10. This is now very shortly described in the introduction, because of limited available space. Further general information about the importance of vegetation and dependence on local physical conditions has been added in the methods section.

- (main body of text: lines 68 – 70) “Green-grey flood protection employs the natural capacity of ecosystems to buffer extreme wave events and consequently reduce flood risk. Specifically, salt marshes with unique salt-tolerant vegetation (Adam, 1993), often located in the temperate climate zone at muddy coasts, serve to: ...”
- (methods: lines 698 – 700) “Key for the functionality of the marsh is the presence of salt-tolerant vegetation (halophytes), such as herbs, grasses and shrubs, of which the distribution typically depends on salinity and inundation gradients (Adam, 1993).”

R2Q11. - Basis for 1 m wave height limit used?

R2R11. The 1 m wave height limit, that marks the distinction between low-energy and high-energy coasts, is a result of the experimental data and global assessment. The results from the flume experiment emphasize a higher wave attenuation capacity for lower incoming waves (Figure 3D). Subsequently, the 1 m wave height limit clearly appears in the global assessment (Figure 4D): marsh vegetation at locations that are relatively sheltered (with a wave height below 1 m; i.e. low-energy) have a large wave attenuating capacity (generally exceeding 10% wave attenuation), whereas relatively exposed locations where wave heights of 1 m are exceeded (i.e. high-energy conditions) contribute up to 10% of wave attenuation only. To address this comment and to better explain that this boundary proceeds from the analysis, the text is rephrased.

- (main body of text: lines 223 - 232) “The damaged stems, both as a result of exposure duration and from incoming waves during a storm, highlight a clear distinction in the wave attenuating capacity of the local marsh calculated using the GLM resulting from the flume experiment (Fig. 4D; Extended Data Fig. 2D): waves are effectively attenuated at lower energy salt marsh coasts with incoming waves up to 1 m. At these low-energy marsh coasts, wave attenuation by vegetation generally exceeds 10% (up

to 50%), covering up to half of the analyzed transects (46% - 34%, for return periods of 100 and 1000 years, respectively). In contrast, at high-energy marsh coasts, where incoming wave heights exceed 1 m, wave attenuation is limited to only 10%."

- (main body of text: lines 234 - 236) "projecting results from the flume experiments to a global scale suggests that in general, salt marsh vegetation enhances the resistance of low-energy marsh coasts to extreme conditions. At almost all low-energy marsh coast with waves up to 1 m, waves are attenuated by more than 10%"
- (abstract: lines 46 – 55) "Experimental results emphasize that vegetation was most effective in attenuating lower waves (up to approximately 1.0 m). The contribution of marsh vegetation to wave attenuation exceeds 10% (up to 50%) for low energetic marsh coasts (significant wave height, H_{m0} , at marsh edges <1 m). Vice versa attenuation at high-energy marsh coasts (H_{m0} >1 m) does not exceed 10%. This global assessment supports the differentiation between low- and high-energetic conditions resulting from the flume experiment."

R2Q12. - Wave action durations?

R2R12. The wave action duration is based on multiple processes and parameters:

- Regarding wave action for vegetation damage, in our experiment vegetation damage was observed already with the runs with lowest water depth and wave height combinations ($h = 1.5$ m and $H_{m0} = 0.75$ m). In previous controlled experiments lower wave heights and water levels were tested (Möller et al., 2014; Rupprecht et al., 2017). Starting at water depths of 1 m and wave heights of 0.1 m, the first significant stem damage was observed at water depths of 1 m and wave heights of on average 0.5 m. This is added very shortly in the main body of text and more extensively in the methods section.
 - (main body of text: lines 200 - 202) "Exposure duration, vegetation stem height damage and subsequent wave attenuation by vegetation was calculated at the storm surge peak for storms with a return period of 100 and 1000 years (see Methods)."
 - (methods: lines 749 - 753) "Globally observed peak water levels (exceeding 1 m water depth) at the globally derived salt marsh locations remain for the larger part (~90%) within the water level range applied in the wave flume. Globally observed exposure duration with water levels exceeding the threshold of 1.0 m (with H_{m0} of 0.5 m) did not exceed 1000 minutes (16.67 hours), which is within the duration of the flume experiment (21 hours)."
- Subsequently, based on global datasets the water depth and potential largest wave height above the marsh is determined. Using the local storm surge hydrographs, exposure duration (or wave action duration) is calculated over the time that wave heights at the marsh exceed 0.5 m from the start of the storm until the point in time the highest waves occur, i.e. at the peak of the storm surge hydrograph. This has been added in the methods section, where it is now more extensively discussed. Therefore, and to limit the length of the manuscript, the short explanation is removed from the main body of text.
 - (Methods: lines 755 - 766) "Since stem height damage in the Delta Flume experiment started already during the most tranquil hydrodynamic conditions ($h = 1.5$ m; $H_{m0} = 0.75$ m), initiation of stem height damage in the global model was set following previous controlled flume experiments (Rupprecht et al., 2017). In those previous experiments, starting at water depths of 1 m and wave heights of 0.1 m, first, significant stem damage was observed after

water depths of 1 m and wave heights of 0.5 m on average (Rupprecht et al., 2017). Using the local storm surge hydrographs, exposure duration for vegetation damage is calculated over the time window during which wave heights at the marsh exceed 0.5 m from the start of the storm until the point in time when the highest waves occur, i.e. at the peak of the storm surge hydrograph. The maximum incoming wave height at the marsh edge is calculated at the peak of the storm, with the most severe estimate for the wave height being 50% of the water depth (Van Zelst et al., 2021; Massel, 1996; Nelson et al., 1994). Finally, wave attenuation at the peak of the storm is calculated using the GLM, as the highest depth-limited waves potentially occur at this point.”

Suggestions and notes for clarification:

R2Q13. - Extended vegetation characterization would be helpful (cf. comment above). Optical, remote sensing, LAI, PAI -> global analyses of coastal vegetation change possible?

R2R13. *We agree that extended vegetation characterization would be helpful. In our current study we used the state-of-the-art global salt marsh distribution map from Worthington et al. (2024). So, in our global analysis the most recent global available salt marsh distribution is used. More detailed marsh distribution from remote sensing data, including vegetation species, is currently not available at a global scale. The spatially and temporally dynamic environment (tidal coverage of the intertidal zone, seasonal dynamics in water level and marsh development, as well as environmental/climate parameters including temperature salinity and precipitation) makes classification a complex process. Within the literature, studies exist that:*

- I. classified vegetation species at a national level (Hu et al., 2021)*
 - II. classified change between vegetated marsh and bare mudflat (Laenger et al., 2020)*
 - III. highlighted the importance of local ground truthing, which is a large effort on the global scale (Hu et al., 2021)*
 - IV. explored global marsh edge change between 2000 and 2019 (Campbell et al., 2022).*
- Each of those studies represents a large step forward in the field, but nonetheless data on species distribution at a global scale remains unavailable, and thus we could not incorporate this in our study. We therefore chose to work with the data of Worthington et al. (2024), which, critically, used the most recent data for the global distribution of marshes. All in all, these studies highlight that methods are being developed that might lead towards a global quantification of salt marsh species distribution, but they are not yet available, which explains our decision to use the most recent global salt marsh distribution combined with recent globally available DEMs in the coastal zone (Worthington et al., 2024; Pronk et al., 2024).*

R2Q14. - How much time is needed for vegetation recovery after various storms?

[REDACTION]

[REDACTION]

[REDACTION]

R2Q15. - Comment on the representativeness of the tested vegetation in winter state (did the global up-scaling also consider hydrodynamics in winter?)

R2R15. *Almost 70% of all worldwide salt marshes are located in the temperate climate zone (Worthington et al., 2024). Storm surges (i.e. extreme hydrodynamics) with a return period of 1/100 and 1/1000 years (Dullaart et al., 2023) were considered in the current study. In the northern hemisphere (75% of marshes including the Arctic) the storm waves occur in winter, whereas in the southern hemisphere the storm waves occur all year round (11.3% of the marshes) (Davies, 1980; Bosboom & Stive, 2015; Worthington et al., 2024). So, the largest proportion of the global marsh-relevant storms presented in Dullaart et al. (2023) occur during winter. For other locations, the (end of) Winter state of vegetation yields a conservative estimate of storm protection, as vegetation outside the winter season, e.g. in the growing season, is more resistant (Reents et al., 2022). To clarify this in the manuscript, this has been added to the methods subsection 2.2. “stem height in salt marshes as proxy for wave attenuation”. This methods subsection specifically discusses aboveground vegetation in a wider perspective (methods: lines 697 - 725):*

- *(methods: lines 716 - 725) “70% of the salt marshes globally present are found in the temperate climate zone and therefore experience a winter season (Worthington et al., 2024). In general, the vegetation state at the end of the winter can be considered to yield a conservative estimate for vegetation stem height as vegetation outside the winter season, e.g. in the growing season, is more resistant (Reents et al., 2022). Furthermore, *E. athericus* in our experiment can be considered to yield a conservative estimate of wave attenuation, because its breaking force is relatively low (weak) compared to other salt marsh vegetation species (Zhu et al., 2019). Less vegetation damage leads to longer stems persisting and hence a higher wave attenuation capacity. In addition, we tested a single salt marsh zones, whereas salt marshes in general contain multiple zones that enhance the wave attenuation capacity (Schoutens et al., in preparation). Finally, only a small (70 m) part of the marsh was considered for wave attenuation.”*

R2Q16. - From wave attenuation point of view, clarify how salt marsh vegetation differs from brackish water conditions (note e.g. Baltic Sea shown in map figures)

R2R16. *Marsh vegetation at a gradient from saline to brackish to fresh shows a tendency towards longer stems that can have a high flexural stiffness (Zhu et al., 2020; Dijkema 1990). These are important traits for contributing to wave attenuation, which is evident from our flume experiment and builds upon previous literature (e.g. Vuik et al., 2018). As a result, wave attenuation is likely to increase, although damage might also increase due to the larger presence of vegetation in the water column. This trade-off is assessed with a proxy by rerunning the model with a doubled (i.e. 200%) stem height and a doubled (i.e. 200%) stem height + doubled (i.e. 200%) progressive damage. Both scenarios result in an increased wave attenuating capacity of the marsh (Extended Data Figures 3-6). A more extensive discussion regarding this additional model analysis can be found in response **R1R3** to referee comment **R1Q3**. The results of the additional model analysis are discussed in the main body of text, section “Marsh vegetation reducing extremes”:*

- *(main body of text: lines 245 - 248) “Both higher species diversity and the shift to longer and less flexible stems enhance wave attenuation, even under higher vegetation damage. This agrees with the result of our sensitivity analysis (Extended Data Figures 3-6).”*

R2Q17. - Check that terminology is consistently used/defined: green-grey, NBS, ecosystem services

R2R17. *Consistent use of terminology is checked, and the terminology is now clearly defined:*

- (main body of text: lines (65 – 67) “Therefore, so-called green-grey flood protection – combining traditional grey-protection with green-ecosystems - is increasingly considered as a more sustainable strategy to keep coastal regions safe from coastal storm events with extreme waves (Borsje et al., 2011).”
- (main body of text: lines 278 - 280) “Our results emphasize that restoration and conservation of salt marshes as a Nature-based Solution (NbS), supporting biodiversity, protect against extreme storms more effectively at low-energy coasts than at high-energy coasts.”
- (main body of text: lines 253 - 254) “In general, our study implies that nature's services to society (ecosystem services) depend on the stability of the salt marsh substrate...”

R2Q18. Fig1: remove photos A and D as unnecessary (save space to enlarge B and C); WHM and scale bars are over-sized; could show waves instead of horizontal water surface;

R2R18. *To improve clarity, photos A and D are removed and photos B and C are enlarged. WHM and scale-bar size is decreased. To further improve the figure, schematic waves are added (lines 464 - 470).*

R2Q19. - Fig1 option for more informative cross sectional and plan views: add conceptual descriptions of the key physical processes controlling erosion and wave attenuation

R2R19. *Extending from response (R2R18) to the previous comment (R2Q18), (conceptual) information is added in figure 1 and the caption of figure 1. Conceptual waves and orbital velocities, that touch the vegetation to visualize the feedback between progressive vegetation damage and subsequent decreasing wave attenuation, are added. This is also described in the caption. In the top view (figure 1D), width dimensions (total and path) are now included.*

- (main body of text: lines 464 - 470) “Figure 1. Development of a large-scale salt marsh experiment. Obtaining the salt marsh blocks in the field at the Dutch mainland Wadden Sea coast (a); storing the blocks next to the Delta Flume at Deltares, Delft, the Netherlands (b); inundating the full physical model (c); schematic picture of the physical model with the salt marsh blocks from the field in the Delta Flume, , with the wave paddle at $X = 0$ m and a visualization of the wave forcing and attenuation by vegetation drag and roughness (d).”

R2Q20. - R130-131: To allow easy comparisons, instead of absolute mm values, use time bound mm/h.

R2R20. *Thank you for your suggestion. This has been added to the manuscript. In our experiment with significant wave heights between 0.75 and 2.00 m surface lowering was 7 mm (0.33 mm/h), which is in the same order of magnitude as previous studies with smaller wave heights (4.4 mm surface lowering; 0.16 mm/h) (Möller et al., 2014; Spencer et al., 2015).*

- (main body of text: lines 129 - 133) “Elevation measurements at 32 fixed locations at the salt marsh show, on average, a decreasing marsh surface over the total experimental time of 21 hours with damaged vegetation (7 mm; 0.33 mm/h), which is in the same order of magnitude as previous studies with smaller wave heights (4.4 mm surface lowering; 0.16 mm/h) (Möller et al., 2014; Spencer et al., 2015) ”

R2R21. - Fig3 is not easy to follow as it does not directly follow the logic/naming of the cases of Table S1.

R2Q21. Yes, thank you for highlighting this - we understand the previous lack of clarity. In Table S1 (Supplementary Information) a column is added emphasizing the vegetation measurements corresponding to Figure 3.

- (Supplementary Information: lines 26 - 32) “Table S1. **Experimental program for the Delta Flume tests at Deltares (Delft, the Netherlands)**”

R2Q22. - FigS1: consider directly using references as subscripts in the Fig rather than abbreviations to the references, which makes reading the figure quite difficult

R2R22. Figure 1 in the Extended Data and the caption of the figure (Extended Data) are adapted accordingly (i.e. references are directly numbered in the figure, and removed from the caption).

- (Extended Data: lines 939 – 948) “Figure 1. **Global salt marsh vegetation comparison.** Vegetation aboveground biomass (a) and vegetation stem length (b) measurements before the storm season between late August and November (“BS (Before Storm)”) and after the storm season in March and April (“AS (After Storm)”). *Elymus athericus* is measured during our experiment (“Ely DF”) at the start in the field and flume and at the end in the flume. For verification *Elymus athericus* is compared with other studies quantifying *Elymus* spp. and salt marsh vegetation species with stems, including *Spartina* spp. and *Phragmites* spp. Numbers indicate references to the studies where vegetation data is derived from.”

R2Q23. - Fig3C: clarify why the relationship is shown for stem length only, and not for biomass. Why was vegetation biomass not used in the regression model? Biomass appears to be a more direct proxy of the vegetation density than stem height. These two variables might complement each other in explaining bulk resistance to breaking and erosion (as found in the fluvial context).

R2R23. Stem length is used as a proxy for wave attenuation because penetration of the stem in the water column is considered an important predictor of wave attenuation, especially with extreme wave heights and water levels (Vuik et al., 2018). As a result, damage to vegetation by a decreasing stem height will have a direct impact on wave attenuation and thus was the preferred predictor for this analysis. When expanded across species, total biomass could include, for example, higher biomass species which are extremely flexible and exhibit a wave ‘avoidance’ strategy in which they lay down to avoid wave forcing, contributing minimally to wave attenuation (Bouma et al. 2010, Puijalon et al. 2011, Silinski et al. 2018). In such a case, biomass may be a poor predictor of wave attenuation capacity. In other words, the vertical distribution of biomass over the water column will impact the wave attenuation capacity more so than the biomass itself. To avoid this kind of overestimation of attenuation capacity, we preferred to use vegetation height. To

improve clarity regarding the use of stem height, in Methods section 2.1 (lines 482 - 492), biomass is removed and it is stated that stem length is used as predictor.

- (methods: lines 678 - 681) *~~"Biomass loss and Stem height decrease of E. athericus through exposure duration in this large scale experiment (Fig. 3) is used as a conservative estimator of wave attenuation by aboveground vegetation under the most severe conditions (water level to wave height ratio of 0.5)."~~*

Further explanation is provided in section 2.2 (dedicated to a wider perspective on aboveground vegetation, including why stem height is used).

- (methods: lines 700 - 704) *"Stem height is used as a proxy for wave attenuation as penetration of the stem in the water column is considered a strong predictor of wave attenuation, especially with extreme wave heights and water levels (Vuik et al., 2018). As a result, damage to vegetation by a decreasing stem height will have a direct impact on wave attenuation."*

R2Q24. - Extrapolation in Fig3D to durations larger than 15-20 h appears rather uncertain due to data scatter at lower durations. Consider removing the extrapolations since these are mostly not required in the upscaling.

R2R24. Thank you for noticing, Figure 3D (lines 480 - 486) is changed accordingly by limiting the setting the upper x-axis limit to 25 hours.

R2Q25. - Justify the physical basis of considering wave attenuation by vegetation as relative share (%) of the total rather than as absolute value. Also clarify for the audience not so familiar with the topic why only wave height was considered, and not e.g. wave height in relation to water depth.

R2R25. Wave attenuation is indeed considered as the relative share of the incoming wave height, and attenuation by vegetation is specifically assessed as this was uncertain until now. Absolute values can be calculated, but we prefer relative attenuation as (1) we would like to assess and compare the wave attenuating capacity by vegetation under a range of exposure scenarios in the Delta Flume and (2) relative values enable a comparison of attenuation at geographical locations in the global analysis, where the potential maximum incoming wave height is location specific. To improve the clarity of this choice to the audience, the use of wave height is clarified in Methods section 1.4.

- (methods: lines 668 – 669) *"Wave attenuation by vegetation was calculated as the relative share of the incoming wave to enable comparison of different experimental runs and global scenarios."*

R2Q26. - Comment the role of day-to-day and other less extreme wave action in causing progressive vegetation damage and erosion of the substrate. How does the 7 mm of erosion in 21 hours in the experiment scale over storms of different frequencies occurring through decadal time-scales?

R2R26. This is difficult to assess, as over decadal timescales processes of accretion and recovery are intertwined with potential erosion. Our current experiment, previous flume experiments of Möller et al. (2014), and data from field measurements after hurricanes Katrina and Rita (Howes et al., 2010), emphasize that storms with a location-dependent return period of a decadal to centennial time scale, already result in minimal surface erosion in salt marshes. Even if under extreme conditions surface erosion occurs, vegetation is found to regrow over the subsequent growing season (please see response **R2R14** to

reviewer comment **R2Q14**). As extreme conditions have already minor effect, it can be expected that daily conditions have a negligible effect on surface erosion.

Although surface erosion under day-to-day conditions is expected to be minor, other processes at longer time scales might affect the persistence of the salt marsh. These longer-term erosive processes in marshes are generally focusing on lateral (cliff) erosion and drowning (not keeping up with sea level rise). At the same time, the longer-term erosive processes can also be counteracted by salt marsh accretion during periodic tidal inundations which might be elevated during storms. Accretion up to several millimeters can be measured during a storm with a return period of approximately 5 years (e.g. Zhu et al., 2020). So, on the long-term time scale accretive and erosive processes play a role that might counteract each other, but might also result in net erosion, especially at high-energy coasts. The importance of counteracting long-term erosive processes when using salt marshes for wave attenuation is discussed in the main body of text. The discussion focusing on the long-term perspective of NbS regarding sediment trapping and growing with sea level rise has been omitted as suggested by referee 1 in comment **R1Q3** (also see the response to this comment **R1R3**).

- (main body of text: lines 286 – 288) *“This cost reduction might enable continuous support and maintenance required for the salt marsh to prevent long-term erosion and guarantee persistence at high-energy coasts.”*

R2Q27. - The authors should consider the uncertainty arising from extrapolating the results obtained with the tested sediment to global sediment conditions. The comment applies overall but specifically referring to L233-235.

R2R27. *We agree that the representativeness and uncertainty of the soil was not clearly discussed in the perspective of the global analysis in the manuscript. Please see:*

- *Comment **R1Q1** and **R1Q4** and the response **R1R1** and **R1R4**, regarding the effect of roots and how the roots of salt marsh species used in our flume experiment (*Elymus athericus*) compares with the root zone from other salt marsh vegetation species.*
- *Comment **R1Q2** and the response **R1R2**, regarding organic matter in the soil and similarities and differences, and the potential impact on erodibility when comparing the organic matter content from our salt marsh substrate to other regions worldwide.*

This topic is now extensively discussed in the rebuttal and clarified in the revised manuscript.

Further remarks:

R2Q28. Regarding the references, the manuscript appropriately incorporates previous literature on coastal environments but appears overly confined to this domain. It would benefit from engaging more extensively with research on fluvial and wetland environments, particularly recent advances in the parameterization of natural vegetation and in the characterization of drag and flow resistance associated with natural plants.

R2R28. *Thank you for raising this. Other environments, including seagrass meadows, brackish and freshwater marshes, as well as riverine settings and the (potential) contribution to wave attenuation are now discussed in the last section of the main body of text. In addition, a comparison is made with the key messages from these environments and our findings.*

- (main body of text: lines 236 - 248) “At almost all low-energy marsh coast with waves up to 1 m, waves are attenuated by more than 10% for *Elymus athericus*, which can be considered a conservative wave attenuation estimator for salt marshes in general (SI Figure S1). This wave attenuation functionality is also found in seagrass environments under low-energy conditions (Bradley & Houser, 2009), and may also apply in freshwater settings (Ren et al., 2021). Decreasing salinity induces an increase in species diversity, because species diversity increases with decreasing environmental stress (Więski et al., 2010). Also, it leads to a shift towards species with longer and less flexible stems compared to *Elymus athericus*, such as the common reed *Phragmites australis* (Zhu et al., 2019; Dijkema et al., 1990). Both higher species diversity and the shift to longer and less flexible stems enhance wave attenuation, even under higher vegetation damage. This corresponds with the result of our sensitivity analysis (Extended Data Figures 3-6).”

R2Q29. Overall, the abstract, introduction and conclusions are well written. However, see the comments/suggestions above for improvement. As a minor further detail in the abstract, the 1 m height limit is not explained/reasoned.

R2R29. *The manuscript has been updated to reflect the comments/suggestions above. Regarding the 1 m wave height limit, please see response **R2R11** to comment **R2Q11** “Basis for 1 m wave height limit used?”.*

R2Q30. Please note that some of the statistical tests and interpretations fall outside the reviewer’s core expertise.

R2R30. *Thank you for noting, the statistics have been checked thoroughly once again. Additions have been made, for example inclusion of sample size in figures and statistical analyses. In the Supplementary Information, table S2, information is added regarding tests, variance, distribution and U values of statistical tests.*

- (Supplementary Information: lines 34 - 39) **“Table S2. Overview of statistical significance between measurements in between experimental runs for vegetation stem height and biomass, with a Student’s t-test for normal distributed samples with equal variance and a Welch t-test for normal distributed samples assumed without equal variance and Mann-Whitney U test for not normal distributed samples. A Benjamini–Hochberg FDR p-value correction is applied. With a corrected p-value<0.05 for significant differences. ”**

Referee #3 (Remarks to the Author):

R3Q0. I co-reviewed this manuscript with one of the reviewers who provided the listed reports.

R3R0. Thank you.

Referee #4 (Remarks to the Author):

R4Q0. Overall, this is quality research on an important topic, within a nuanced conclusion that I believe represents the truth about how the salt marsh surface versus vegetation provides protection. I like how the MS reveals something new, that we have all suspected but not yet proven. However, the title does not reflect the nuanced finding very well and it obscures this truth in a manner that perpetuates overly simple thinking. A better title that alludes to the conditional finding of the research would provide a more lasting, real-world value to its publication. Moreover, there could be a stronger emphasis throughout the beginning and ending of the text on the flume work versus the global analysis effort. The global analysis effort is a bit tacked onto the flume work.

The flume work is a serious, high quality study that likely required enormous effort. The fundamental contribution to the literature originates from the flume work, which is then extrapolated into the global analysis in a derivative manner. The finding that lower energy marshes provide quality vegetative-driven wave attenuation, whereas higher energy marshes do not, seems to be based on the flume study work. The relationships then play out at the global scale in that analysis. Thus, I'm not sure if there is anything emergent in the global analysis, and if there is, it should be better enunciated as to how that happened analytically.

R4R0. Thank you for taking the time to review the manuscript and providing valuable feedback. We appreciate and very much agree with the acknowledgement of the importance of the nuanced conclusion regarding salt marsh functioning for coastal protection. The points raised are processed and, in our opinion, have improved the manuscript .

To emphasize the results from the flume experiment relative to the global analysis, "globally" is removed from the title. The title (line 1) is now "How and where salt marshes protect against extreme storms". By this we aim to include nuances of wave attenuation related to dependency of the incoming wave height, i.e. lower or higher (where), and the mechanisms that play a role, i.e. related to damage of vegetation and stability of soil (how).

In the abstract, the text is changed to emphasize that the results show that the highest efficacy of wave attenuation by vegetation is valid for lower waves. The global analysis uses and builds upon these results.

- *(abstract: lines 46 - 47) "Experimental results emphasize that vegetation was most effective in attenuating lower waves (up to approximately 1.0 m)."*

- (abstract: lines 53 – 55) “This global assessment supports the differentiation between low- and high-energetic conditions resulting from the flume experiment”

Globally is removed from the aim and mentioned as an extension to the flume study.

- (main body of text: lines 96 - 105) “Based on flume experiments and projected storm simulations at a global scale, here, we aim to ~~globally~~ quantify the persistence of the marsh substrate and address the progressive vegetation damage and associated reduced wave attenuation under extreme storm conditions, by assessing:
 - I. The stability of salt marsh substrate under extreme wave events;
 - II. Progressive vegetation damage and associated wave attenuation under extreme events;
 - III. The global contribution of progressively damaged salt marsh vegetation to wave attenuation that proceeds from results of the flume experiments.”

When describing the results of the global analysis, it is mentioned that this is extending on the experimental results and that results emphasizing low incoming wave - large attenuation versus high incoming wave - low attenuation follow from the flume experiment. This is also done in the discussion in the last section of the main text.

- (main body of text: lines 196 - 197) “To analyze the contribution of vegetation to wave attenuation under extreme wave conditions, extending the experimental results to a global scale, ...”
- (main body of text: lines 223 – 227) “The damaged stems, both as a result of exposure duration and from incoming waves during a storm, highlight a clear distinction in the wave attenuating capacity of the local marsh calculated using the GLM resulting from the flume experiment (Fig. 4D; SI Fig. S2D): waves are effectively attenuated at lower energy salt marsh coasts with incoming waves up to 1 m.”
- (main body of text including subheading: lines 233 - 236) “**Global Marsh vegetation reducing extremes**
Projecting results from the flume experiments to a global scale suggests that in general, salt marsh vegetation enhances the resistance of low-energy marsh coasts to extreme conditions.”

Further review points are discussed below.

R4Q1. The figures could be improved in quality. They are strong but could be better.

R4R1. Thank you for the suggestion. Also based on other referee comments, the following improvements are implemented:

- Figure 1 (lines 464 - 470): unnecessary pictures have been removed and the remaining pictures (panels A – C) are increased in size; information has been added in the cross-section and top-view and elements have been resized.
- Figure 3 (lines 480 - 486) In panel D x axis limits are reduced to better fit the data range. The upper x-axis limit is now 25 hours instead of 40, to prevent extrapolation outside the range of observed data.
- Figure 4 (lines 489 - 494) and figure 2 in Extended Data (lines 952 – 958) and figures 3 – 6 in Extended Data (lines 959 - 986): projection is changed to have a better balance between visualization and the size of Africa and South America; a mistake in panel B regarding plotting the markers at the world map is improved, now showing the proper results. Markers are made smaller and transparent to better visualize differences.

- *Figure 1 (in Extended Data; lines 939 - 948): former extensive way of referencing in figure and caption has been improved.*

Furthermore, all figures are resized to have consistent figures and fit with the Nature requirements for figure formatting.

R4Q2. Line 84 - Should capitalize Gulf and East Coast

R4R2. *Done.*

- *(main body of text: line 91) “, and the Gulf and East coast of the United States”*

R4Q3. 103 – what is Winter (?), as capitalized it seems strange. Do you mean the season? Why capitalize?

R4R3. *Changed to lowercase.*

- *(main body of text: line 109 - 110) “A salt marsh in winter state was transplanted to two cross-shore transects using the first 200 m of the flume (Fig. 1).”*

R4Q4. Fig. 1 – it would be helpful to see the width dimensions of the flume in the top view. I have questions about the wave reflection. I’m not going to drill you on it, but I don’t fully like the pathway between the two surfaces. I’d rather see the center be the sampled area.

R4R4. *Thank you for this observation. Below our answers:*

- *The width dimensions of the physical model are now included in Figure 1, panel D (line 130) The width of the flume is 5 m and the width of the pathway is approximately 30 cm. The pathway is around 5 cm deeper compared to the vegetation surfaces, enabling the marsh to drain. This height difference is comparable to the variations in the vegetated surfaces related to variations in the clay height as well as the vegetation heights. Since the variations are similar in magnitude, we do not expect that the pathway results in any significant variations across the width. To address your comment and make this clearer to the reader, this information is added in the manuscript*
 - o *(methods: lines 503 – 507) “In between the two rows a path was constructed 5 cm below the surface of the marsh, to drain both marsh profiles and enabling access, maintenance and (manual) measurements. The height difference between the path and marsh surface was comparable to the variations in the vegetated marsh, i.e. the clay heights and the vegetation height.”*
- *We agree that a pathway in between the two transects might not be ideal for all measurements. From a practical point of view, we choose to use this setup to allow two transects with different substrates in terms of grain size characteristics (Extended Data Table 2: lines 929 - 936). For deploying sensors (not interfering with vegetation), maintenance and measurements, this was the most effective way. This was necessary to prevent having two pathways at the walls and to allow measurements to be taken without needing to get down with the crane (which would have been too time-consuming and limited the possible measurements).*
- *Wave reflection is being discussed in response **R4R10** to referee comment **R4Q10**.*

R4Q5. It would help to have a sentence about how you measured the vegetation in sections 145-154. When I look at Fig. 3, I wonder how did they get the dry biomass without destructive sampling (?). Perhaps this is in the Methods, but I'd like a sentence here.

R4R5. *We agree that this should be clarified in the main body of text. Destructive measurements were done (bi-)daily to collect dry biomass and stem length. Dry biomass was collected at 6 locations in a 20 cm x 20 cm plot, (1) close to the seaward marsh edge, (2) at the center of the marsh and (3) at the landward marsh edge distributed over the two transects. To obtain stem properties over time, 20 stems per measurement were collected from randomly distributed locations over the marsh. This data is presented in figure 3.*

*To enable comparison between runs, destructive measurements were minimized, to prevent substantial damage to the marsh. Per measurement, $20 \times 20 \text{ cm} \times 6 = 0.24 \text{ m}^2$ vegetation was removed. Including stem removal, this resulted in a total loss of less than 1% of the full marsh cover. A short explanation has been added to the main body of text. Further explanation has been provided in the Methods section. Please also see response **R2R4** to referee comment **R2Q4**.*

- *main body of text: lines 161 - 162) "Vegetation biomass and stem length were collected by destructive measurements, affecting a negligible marsh surface (see Methods)."*
- *(methods: lines 642 - 644) "The destructive measurements for biomass (vegetation measurement 2) and stem length (vegetation measurement 3) affected a marsh area smaller than 1% of the total salt marsh in the physical model."*

R4Q6. 200 - Not sure *E. athericus* is a conservative estimate, as compared with other species in global salt marshes. I would say it is pretty weak, low density, and low height compared with many other graminoids at least. This should be re-stated or made clear how.

R4R6. *Indeed, we agree that *E. athericus* is a rather "weak species" when considering biomass, individual stem height and strength of the stem and comparing with other graminoids. Therefore the physical contribution of this vegetation species to wave attenuation is expected to be in the lower range of wave attenuation by salt marsh vegetation. Stiffer, denser and taller species (see for example the comparison in Extended Data Figure 1) have been shown to contribute more to wave attenuation (Mendez & Losada, 2004; van Veelen et al., 2020; Zhang et al, 2022). Hence, *E. athericus* is assumed to be a conservative estimate, as more attenuation is expected with other vegetation species (c.f. Zhang et al., 2022). Please see response **R1R3** to comment **R1Q3**, in which your feedback is also addressed, for an extensive elaboration on this topic and how this is handled in the manuscript and Extended Data.*

R4Q7. Line 229. This is phrased strange, with emphasis on the 10% number, which is also used in line 226 but for high energy coasts. It just requires the reader to understand that you've switched the concept around. Suggest to reword.

R4R7. *We meant to state that wave attenuation generally exceeds 10% at low-energy marsh coast, but is limited to 10% at high-energy marsh coasts. In response to your comment and to improve the clarity in the text, the phrasing is adapted.*

- *(methods: lines 227 - 232) "At these low-energy marsh coasts, wave attenuation by vegetation generally exceeds 10% (up to 50%), covering up to half of the analyzed transects (46% - 34%, for return periods of 100 and 1000 years, respectively). In*

contrast, at high-energy marsh coasts, where incoming wave heights exceed 1 m, wave attenuation is limited to only 10%.”

R4Q8. 305 - State how you picked up the mold. I imagine they were thousands of kg. With heavy machinery, and if so how did you avoid damage and where in marsh were these samples taken. I assume you are doing this by land and your marsh is a bit higher in elevation, ie you are not extracting using a boat. This would be valuable information for those of us that like to do this kind of stuff.

R4R8. *We agree that this should be clearer in the text, and so this information is added in the Methods section.*

- *(methods: lines 539 - 549) “The salt marsh blocks were harvested by pushing a mold of 2.0 x 2.0 m² (depth of 0.7 m) or 2.2 x 2.2 m² (depth of 0.4 m) into the ground. The area around the mold was dug out using a 35 to 50 tons excavator. Subsequently, a steel bottom plate was slid under the mold to prevent disturbance of vegetation and the marsh substrate within the mold as much as possible. Subsequently, the 3000 to 6000 kg marsh blocks were lifted, deployed on a closed truck to prevent wind damage and then transported to the Delta Flume. The harvest location was elevated above spring tide to assure safe access over land. To work safely and minimize disturbances to the ecosystem, the harvest was executed after the breeding season and before the storm season, during daylight, in the shortest period possible. Temporary steel road plates were used to distribute the weight of the excavator and trucks, which minimized damage to the marsh”*

The mold was picked up by sliding a forklift, attached to a 35 to 50 tons excavator, under the steel bottom plate. Subsequently, the marsh block including mold was lifted and deployed on a closed truck. The salt marsh blocks including molds had a weight of approximately 3000 to 6000 kg. The excavator and trucks drove over temporary steel road plates to better distribute their weight over the marsh and minimize disturbance.

The marsh blocks were collected at the high marsh, elevated above spring tide to enable access for a period of multiple weeks. Collection took place after breeding season and before storm season, to minimize disturbance and chances of inundation by water level setup due to storms. Further disturbance was minimized by executing the work in the shortest period possible, by working only during daylight.

R4Q9. I can't (or can) imagine how fun and not fun this must have been to do this entire experiment. Having done these things, I am more strongly impressed by the flume work than the global analysis.

R4R9. *Thank you, your understanding is very much appreciated. Indeed it was complex and intense, but a lot of fun at the same time! The main message of the manuscript is now better emphasized as a result from the flume experiment, please see the response **R4R0** to point one of this review **R4Q0**.*

R4Q10. Please discuss wave reflection in Methods somewhere 319-338. How much observed? What about wave transformation in the width dimension across the pathway. Did you sample the whole section on either side? How did you avoid width dimensional effects?

R4R10. *We agree that it is necessary to further elaborate on here.*

First regarding reflection, the reflection coefficient in deep water varied between 0.2 (low waves and 4% wave steepness; experimental run SM-01 in Table S1 in Supplementary Information) and 0.35 (high waves and 2% wave steepness; experimental run SM-14 in Table S1 Supplementary Information)

- (methods: lines 609 – 613) “The motion of the wave paddle, compensates for reflected waves to avoid reflection back into the physical model. The reflection coefficient in deep water varies between 0,2 (low waves and 4% wave steepness; experimental run SM-01 in Table S1 in Supplementary Information) and 0.35 (high waves and 2% wave steepness; experimental run SM-14 in Table S1 in Supplementary Information).”

The wave height meters (WHM) were located on one side of the flume wall, so we do not have information on the variation in width. However, no variations in the width direction were discernible during experimental runs. As is the case in general for flumes, we assume no variations in width (as width (5 m) $\ll$ length (300 m)) (e.g. Van Gent, 2001). Wave flumes are used for studies uniform in width, whereas wave basins (width $\approx$ length) are used for 3D effects specifically. In the Delta Flume waves are created uniformly in the width direction and will stay uniformly in the width direction as long as there is no significant variation in the width direction in the physical model set-up. Since the model set-up is symmetrical in the width direction and the variations in height due to the pathway are similar to the variations in the vegetation surfaces, we do not expect any wave transformation in the width dimension. This information has been added to the methods section (also see response **R4R4** to previous comment **R4Q4**, regarding suggestions for improving the sketch of the setup in figure 1).

- (methods: lines 654 – 659) “Wave characteristics were measured using fixed resistance type wave gauges present in the Delta Flume at the left wall of the flume (looking from the wave paddle to the end of the flume) with a measurement accuracy smaller than 1 cm (Van Gent, 2001). No variations in the width direction were discernible during experimental runs, because the setup was symmetrical in the width direction. We assume no variations in width, as is the case in general for flumes (as width, 5 m $\ll$ length, 300 m) (Van Gent, 2001).”

The wave paddle is equipped with ARC (Active Reflection Compensation) that measures the water elevation in front of the wave generator. This water level elevation consists of the waves that are being generated at the wave generator and also the waves that are being reflected off the physical model. The motions of the wave paddle are then compensated for these waves in such a way that the waves are not being re-reflected back towards the physical model. The result is a wave field almost without model effects caused by re-reflection. This additional information has been added to the methods section.

- (methods: lines 607 – 610) “Waves were forced with a wave paddle equipped with an ARC (Active Reflection Compensation). The water level elevation in front of the wave paddle was continuously measured to observe the wave field including reflected waves. The motion of the wave paddle, compensates for reflected waves to avoid reflection back into the physical model.”

R4Q11. I also wonder, did you see differential loss in the marsh vegetation in the length dimension, as the waves progressed in time? Like, was there an area where it was grinded away specifically where wave breaking occurred, or did it happen homogeneously, and how did it evolve. It would be good to have a sentence or two up in the main text on this.

R4R11. Thank you. For stem characteristics quantifications, 20 stems were selected spatially random every measurement. Therefore, there is no specific location dedicated to stem length. Visually we observed slightly more vegetation damage closer to the seaward edge, which can be considered the breaking zone. This has been added to the main body of text.

- (main body of text: lines 171 – 172) “Throughout the experimental runs, visual inspection showed the largest vegetation damage close the seaward vegetation edge.”

R4Q12. 349-366- I don't understand how you did destructive sampling for biomass, and yet produced Fig. 3. I guess the experiment only involved specific wave height/water depth combinations and did not evolve over time? ...thus did not require repeated sampling for a given treatment? I think this could be better clarified up in the main text.

R4R12. Following your previous comment **R4Q4** we further clarified the destructive measurements.

- main body of text: lines 161 - 162) “Vegetation biomass and stem length were collected by destructive measurements, affecting a negligible marsh surface (see Methods).”
- (methods: lines 642 - 644) “The destructive measurements for biomass (vegetation measurement 2) and stem length (vegetation measurement 3) affected a marsh area smaller than 1% of the total salt marsh in the physical model.”

Please also see response **R2R4** to referee comment **R2Q4**.

Regarding experimental settings for wave height / water level combinations (full experimental program in Supplementary Information table S1), we aimed at collecting wave measurements for the same wave height / water level combinations with increasing vegetation damage. Repetition of the same wave height / water level combinations was impossible due to the inherent vegetation damage by wave impact. Therefore a set of wave height / water level combinations was repeated three times. This has been added to the main body of text and methods.

- (main body of text: lines 152 - 155) “The experimental runs are clustered into three distinct groups of repeating wave height and water depth combinations with increasing aboveground vegetation damage inherent to continuous wave impact in the first two groups and no aboveground vegetation in the last group (see SI Table S1 and Methods).”
- (methods: lines 595 - 602) “This sequence was executed three times to study marsh stability and wave attenuation under potentially increasing vegetation damage: 1) light vegetation damage; 2) substantial vegetation damage; and 3) removed aboveground vegetation (see SI Table S1). This allowed us to explicitly quantify wave attenuation by vegetation as a result of progressive damage of the aboveground biomass, by subtracting wave attenuation by the marsh elevation in experimental runs without aboveground biomass (percentage decrease of H_{m0}) from wave attenuation in runs with full and damaged vegetation.”

Furthermore, Supplementary Information, table S1 has been improved by consequently naming vegetation damage according to the repetition of the wave height / water level combination.

R4Q13. 405-414. Wave height is reasonable, but I'd think it would be just as easy to use wave power, like H and T_p , like H -squared times T , or some version. The period/wave length is very important, I think. But, I'm ok with it as first order guess.

R4R13. *We agree that other more in-depth indicators can be used to represent wave impact. Since the relations with wave height and wave height attenuation are a good predictor already (e.g. Figure 3D), we prefer to keep this relation. In addition, wave height and wave height attenuation by vegetation are the most tangible indicators for a reader, since they directly show what (damaged) vegetation contributes, i.e. a decrease in wave height. Wave height is more tangible than wave power for the audience that is less knowledgeable and experienced with wave mechanics/theory and/or works in a different field of research, for whom this manuscript is also written.*

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