Subject: Responses to reviewers' comments and suggestions

Manuscript Number: egusphere-2024-2688

Title: Biomechanical parameters of marram grass (*Calamagrostis arenaria*) for advanced modeling of dune vegetation

Dear Reviewers, dear Editor,

We sincerely thank you for your continued engagement with our manuscript and your positive assessment of the substantial revisions made in response to the first round of review. We appreciate your final suggestions for improving clarity and readability, and we have carefully addressed each of them in the revised version.

Please find enclosed below detailed answers to the reviewers' comments, as well as the corresponding actions performed to the revised manuscript. Each response is structured according to the key aspects of the comment, with references to the relevant manuscript sections provided in parentheses, including the corresponding line numbers and brief explanatory notes where appropriate, based on the previously submitted revised version. Please note that the mark-up may appear extensive, but no new content was added. The changes are primarily stylistic (sentence reordering and streamlining) and do not affect the scientific content.

Sincerely,

V. Kosmalla, O. Lojek, J. Carus, K. Keimer, L. Ahrenbeck, B. Mehrtens, D. Schürenkamp, B. Schröder, and N. Goseberg

Reviewer #2:

Comment 2.1:

The revision of the manuscript has meant that some repetition and long paragraphs and minor typos are present and the technical corrections I recommend are simply a solid proofread and reedit of the new bodies of text to ensure clarity of expression.
The authors have undergone a substantial revision of the original manuscript and addressed my comments satisfactory. My only comment is that these revisions could benefit from a second edit to correct minor typos, remove repetition, and ensure that the main messages of each paragraph are easily extracted by the reader.

Answer to Comment 2.1:

Thank you for your positive assessment and your helpful suggestion to further improve the clarity of the revised manuscript. We conducted an additional round of proofreading and editing to eliminate minor typographical errors, reduce repetition, and improve the clarity of expression where needed.

Most of the changes made in response to your overarching remark relate to the Introduction, which was restructured and refined. These specific changes are detailed in the responses to Comments 2.2 to 2.5, where we address the individual suggestions regarding sentence content, paragraph structure, and wording.

Comment 2.2:

For example - Line 35: Consider inserting "may" after climate change and replace e.g with "for example"; Line 38: Feel free to disagree with me here but I'm not sure the sentence "Understanding these vegetation development and characteristics is crucial, as plants not only shape dune formation but also provide essential ecosystem services, such as carbon sequestration (Barbier et al., 2011)." is needed as you have largely already said this in the preceding paragraphs; Line 38-72. I commend the authors of the substantive revision of this text. However, this paragraph is now very long and has lost some readability. I recommend revision to remove repetition and to refocus around key messages. Consider splitting into two or more shorter paragraphs.

Answer to Comment 2.2:

We sincerely thank you for this detailed and constructive feedback. In response, we carefully reworked the relevant section of the Introduction with a clear focus on reducing redundancy and emphasizing the key scientific messages. This included both linguistic improvements and content-related adjustments. Specifically, we have:

- removed the sentence you identified in Line 38, as its content was indeed already covered earlier;
- revised and shortened overly complex or repetitive passages;
- and restructured the longer paragraph spanning Lines 38–72 of the previously revised version into three thematically focused paragraphs to improve clarity and readability.

These changes apply to the part of the Introduction up to Line 88 in the previously submitted revised version. We are confident that the revised structure now better guides the reader through the key background and rationale of our study.

Please note that the mark-up may appear extensive, but no new content was added. The changes are primarily stylistic (sentence reordering and streamlining) and do not affect the scientific content.

> [Line 18] "Coastal dunes are among the most dynamic ecosystems on Earth, ~~shaped by the interplay between physical and biological processes~~ characterized by various types of feedback between aeolian transport, vegetation growth, and sediment dynamics (Hesp, 2002; Hacker et al., 2012;

Zarnetske et al., 2015; Strypsteen et al., 2019). They act as natural coastal barriers, mitigating storm impacts and protecting inland areas from flooding (Martínez and Psuty, 2004; Feagin et al., 2015; Ruggiero et al., 2018). Besides their protective function, dunes support high ecological diversity and provide essential ecosystem services, including freshwater provision, carbon sequestration, and sediment stabilization (Martínez and Psuty, 2004; Everard et al., 2010; Barbier et al., 2011; Röper et al., 2013; Ruggiero et al., 2018). The dynamic interactions between physical and biological processes result in high spatio-temporal complexity within dune systems (de Vries et al., 2012).

[Paragraph split: Coastal dunes / dune dynamics]

Understanding ~~the dynamics of~~ dune erosion and accretion is essential~~, as these processes determine the safety level of coastal dunes against hinterland flooding due to storm surges (González-Villanueva et al., 2023), forming the basis for their integration as ecosystem-based coastal defense measures~~ for defining their role in nature-based coastal defense strategies (de Vries et al., 2012; Feagin et al., 2015; de Battisti, 2021; González-Villanueva et al., 2023). Both short-term changes in dune morphology through~~from~~ individual storm events, such as erosion and deposition of sediment, and long-term trends influenced by sea level rise, sediment supply, wind field, human activity, and the stabilizing effects of vegetation (Keijsers et al., 2016; Gao et al., 2020; Hovenga et al., 2021; González-Villanueva et al., 2023) are crucial for accurately assessing and managing the protective functions of coastal dunes (Keijsers et al., 2016; Gao et al., 2020; Farrell et al., 2023; Husemann et al., 2024).

Coastal dunes, unlike engineered structures, adapt dynamically through natural processes like sediment transport and vegetation growth, enabling post-storm recovery and offering a system-dependent resilience to sea-level rise (van Gent et al., 2008; van IJzendoorn et al., 2021; Mehrtens et al., 2022, 2023). Dynamic dune management supports these processes while promoting biodiversity and ecosystem services. Climate change may impact~~s~~ dune vegetation, altering species distribution and traits (Carter, 1991; Duarte et al., 2013; Gao et al., 2020; de Battisti, 2021; Biel and Hacker, 2021). Carter (1991), ~~e.g.~~ for example, stated that species tolerant to higher temperatures, drought, and sand burial may become more dominant in the future.

~~Understanding these vegetation development and characteristics is crucial, as plants not only shape dune formation but also provide essential ecosystem services, such as carbon sequestration (Barbier et al., 2011).~~ To simulate the interactions between vegetation, sand, wind, and water in dune environments, ~~various~~ a range of numerical models, ~~e.g.,~~ such as DUBEVEG (Keijsers et al., 2016; Husemann et al., 2024), AeoLIS (vanWesten et al., 2024), and XBeach implementations (Schweiger and Schuettrumpf, 2021), as well as physical models have been developed. However, the accuracy of these models ~~strongly~~ depends strongly on high-quality ~~datasets derived from~~ field data ~~observations~~, which, to date, have not been systematically collected for the specific biomechanical properties of dune vegetation. In physical experiments, dune vegetation is ~~often~~ commonly either ~~neglected~~ omitted (van Gent et al., 2007; Tomasicchio et al., 2011; Figlus et al., 2011; Mehrtens et al., 2024), ~~or represented~~ modeled using real vegetation despite its limited scalability (Figlus et al., 2014; de Battisti and Griffin, 2020; Silva et al., 2016; Maximiliano-Cordova et al., 2019; Feagin et al., 2019), or substituted with simpli~~stic~~fied mimics such as wooden dowels (Bryant et al., 2019; Kobayashi et al., 2013; Türker et al., 2019)~~,~~ that inadequately reflect ~~which presents challenges in terms of scalability and accurately replicating bio~~mechanical plant behavior ~~properties of the vegetation~~ (Garzon et al., 2021). To overcome these limitations, physical models increasingly rely on surrogate vegetation, meaning non-withering, physically stable structures derived from in-situ characteristics of live plants and used in laboratory experiments. The accuracy of such representations depends not only on geometric traits but also on mechanical properties such as shoot stiffness and flexibility, which govern how vegetation interacts with environmental stressors like wind and water flow (Bouma et al., 2013).

[Paragraph split: Dune modeling approaches / transfer limitations of salt marsh models]

Most advances in vegetation modeling ~~efforts in NbS~~ for nature-based solutions (NbS) in coastal protection have focused on salt marsh species ~~vegetation~~, aiming to improve ~~the~~ representations of plant ~~physiology,~~ morphology, physiology, and hydrology (Liu et al., 2021; Keimer et al., 2024). These ~~models seek to capture the complex feedback mechanisms between vegetation and the environment, including the effects of plant traits on sediment transport, wind erosion, and water availability. In salt marsh ecosystems, vegetation~~ studies show that plant density and ~~mechanical properties such as~~ stiffness ~~have been identified as~~ are key ~~factors~~ parameters influencing wave attenuation and shoreline protection ~~stabilization~~ (Shepard et al., 2011). Several have employed three-point bending tests to quantify biomechanical traits and assess seasonal or species-specific differences (see Table A1 in the Appendix). However, salt marsh and dune vegetation ~~plants~~ differ fundamentally: ~~significantly from dune vegetation in terms of morphology, biomechanical properties, and response to hydrodynamic and aeolian forces. W~~while salt marsh plants ~~typically~~ exhibit high flexibility and typically cope with ~~resistance to~~ hydrodynamic forces (Vuik et al., 2017; Bouma et al., 2014), dune grasses stabilize sediment primarily through ~~contribute to sediment stabilization through their aboveground stiffness~~ stiffer shoots and extensive rhizome networks (Zarnetske et al., 2012; Figlus et al., 2022). As a result~~Consequently~~, ~~the transferability of existing vegetation~~ transferring parameterizations from salt marsh~~es~~ systems to dune ~~environments~~ models is ~~therefore limited, necessitating a more refined~~ problematic and calls for dedicated biomechanical ~~representation of~~ datasets for dune vegetation ~~in coastal models~~.

[Paragraph split: transfer limitations of salt marsh models / dune-focused knowledge gap]

Despite the ~~recognized importance of plant morphology, research on the biomechanical~~ critical role of dune ~~vegetation remains~~ grasses such as marram grass (*Calamagrostis arenaria*, formerly *Ammophila arenaria*) in coastal defense, their biomechanical properties have received limited scientific attention to date (Feagin et al., 2015; Davidson et al., 2020; de Battisti and Griffin, 2020). ~~On a cellular level, differences between plant components have been highlighted, with stems providing structural stability, while leaves exhibit greater flexibility and resistance to wind exposure (Chergui et al., 2017). Given these functional differences, a biomechanical characterization of dune vegetation that explicitly accounts for the mechanical roles of different plant components is essential to improve its representation in coastal models. However, most biomechanical studies on coastal vegetation to date have focused on plant species commonly found in salt marshes, seagrass meadows, or mangrove forests. Several studies, for instance, have employed three-point bending tests for investigating the biomechanics of salt marsh vegetation, assessing seasonal and species-specific differences (see Table A1 in the Appendix). In contrast, dune plants, such as European beachgrass, marram grass (*Calamagrostis arenaria*, formerly *Ammophila arenaria*, hereafter referred to as marram grass), have received much less attention, despite its critical role in dune stabilization and protection (Feagin et al., 2015; Davidson et al., 2020; de Battisti and Griffin, 2020).~~ De Jong et al. (2014) explicitly emphasized the lack of research and highlighted the importance of studying vegetation development, particularly with regard to~~regarding~~ vegetation density ~~of cover~~ and rooting depth.~~; since then, little further research has appeared to fill the gap, and a better understanding of the biomechanics of dune vegetation remains crucial for improving modeling efforts. Field data from the literature provide valuable insights into the characteristics of marram grass, though their interpretation is often complicated by inconsistent terminology and missing methodological descriptions. P~~Most previous ~~studies have~~ work has ~~primarily~~ focused on geometric and external ~~plant~~ traits, such as shoot height, while ~~bio~~mechanical properties of individual plant components have rarely been quantified~~ remain largely understudied~~. Histological ~~examinations have been conducted~~ studies by Andrade et al. (2021) and Chergui et al. (2017), have explored internal structures, showing that stems mainly provide structural stability, while leaves exhibit high flexibility, allowing them to bend under wind exposure without structural failure. Given these functional differences, a biomechanical characterization that explicitly considers the mechanical role of each plant component is essential for improving the representation of dune vegetation in coastal models. ~~and a~~ A review by McGuirk et al. (2022) summarizes ~~current~~ existing knowledge on dune ~~the role of~~ vegetation and its role in ~~dune~~ sediment dynamics~~, including quantitative studies on marram grass~~. However, methodological inconsistencies and imprecise terminology often complicate comparisons between studies. A~~n~~ ~~comprehensive~~ overview of ~~key parameters~~ commonly reported traits for marram grass~~, such as growth height, horizontal density, and belowground biomass,~~ is provided in Table A2 in the Appendix~~.~~; since then, little further research has appeared to fill the gap, and a better understanding of the biomechanics of dune vegetation remain crucial for improving modeling efforts.

~~While these parameters are essential for developing accurate surrogate models, which we depict as non-withering, permanent laboratory replacement structures derived from in-situ characteristics of live plants, they primarily address geometric and external characteristics rather than the mechanical properties that determine how vegetation interacts with environmental forces. Studies such as Bouma et al. (2013) have demonstrated the importance of traits like shoot stiffness, shoot density, and shoot length in influencing the intensity and scale of vegetation-environment interactions, particularly in salt marsh ecosystems. However, there is currently limited knowledge on the mechanical properties of marram grass, such as flexibility and stiffness, which are vital for understanding its impact on dune stability and resilience to environmental stressors like wind or water flow. A better understanding of these mechanical traits is essential for assessing the contribution of dune vegetation to sediment stabilization and ecosystem resilience.~~

Comment 2.3:

Line375, 387 and 398. Unusual to have a one sentence paragraph. Combine with the above.

Answer to Comment 2.3:

Thank you for pointing this out. We have revised the respective sections to eliminate one-sentence paragraphs by removing the paragraph breaks and integrating the content into the surrounding context. In doing so, the text now appears more cohesive and streamlined. Additionally, we reviewed the entire manuscript to ensure consistency and removed similar formatting throughout. These changes contribute to a more compact presentation and improved readability and are fully implemented in the newly revised version of the manuscript.

Comment 2.4:

Line 424. Reconsider the use of "Instead" here. The previous sentence highlights similarities between your findings and the salt marsh work, so its not clear what is different about your findings. I think this is just a simple awkward phrasing that can be easily corrected.

Answer to Comment 2.4:

Thank you for pointing out this inconsistency. We agree that the use of "Instead" at this point in the paragraph introduced an unintended contrast that did not align with the logical flow of the argument. To clarify the relationship between our findings and those from salt marsh vegetation studies, we revised the paragraph to explicitly frame the observed difference regarding leaf length as a contrast, while maintaining the broader similarities in other traits. The revised paragraph now reads as follows:

[Line 421] Understanding seasonal variations in plant properties is crucial for surrogate modeling because both dune dynamics and plant traits are subject to significant seasonal changes. Similar to findings on salt marsh vegetation, our results show that during summer, vegetation density significantly increases, while in winter, the stiffness of the vegetation is greater and the outer diameter smaller (Vuik et al., 2017; Foster-Martinez et al., 2018; Keimer et al., 2024; Li et al., 2024). ~~Instead,~~ However, in contrast to observations from salt marsh species, where plant length typically peaks in summer (Foster-Martinez et al., 2018; Schulze et al., 2019), our ~~observations~~ data show ~~suggest~~ that leaf length in marram grass is significantly greater in winter. ~~ves, which lengthen in winter,~~ From a functional perspective, these longer winter leaves may play a critical role in dune resistance to storm events, as they directly contribute to key factors highlighted by Feagin et al. (2015), such as leaf area, plant architecture, and aboveground biomass, which influence vegetation-wave interactions in salt marshes. This seasonal adaptability of marram grass, with increased stiffness in winter ~~for~~ enhancing erosion resistance and denser vegetation ~~greater density~~ in summer promoting ~~to enhance~~ accretion, ~~supports the natural processes of dune formation and recovery, reinforcing the role of vegetation in maintaining~~ reinforces the contribution of marram grass to dune resilience across dynamic environmental conditions.

Comment 2.5:

I really like Table 1, but would be more appropriate to place it towards the start of the discussion section, rather than at the end of the conclusion.

Answer to Comment 2.5:

Thank you for this helpful suggestion. We fully agree that placing Table 1 at the beginning of the Discussion section improves the structure of the manuscript and allows readers to better follow the interpretation of results in the subsequent subsections. As a result, we have removed the table and the accompanying paragraph from the Conclusion and integrated both into the introductory part of the Discussion section. Please note that the mark-up may appear extensive, but no new content was added. The changes are primarily stylistic (sentence reordering and streamlining) and do not affect the scientific content.

The beginning of the Discussion now reads as follows:

This study aims to provide detailed biomechanical parameters of marram grass to facilitate advanced modeling of dune vegetation. Current models often simplify or ignore traits in flexible vegetation, using surrogates like wooden dowels (e.g., Kobayashi et al., ~~(~~2013~~)~~; Bryant et al., ~~(~~2019~~)~~), which do not accurately reflect the dynamic interactions between vegetation and dune environments. By capturing seasonal variations in plant traits relevant to dune dynamics, such as stiffness and density, our data support ~~Our analysis incorporates the seasonality of dune dynamics, with accretion processes in summer and erosion processes in winter, as well as the growth cycles of the vegetation. This approach enables~~ a more realistic simulation of ~~the role of~~ vegetation effects in dune stabilization ~~and coastal defense strategies~~. Moreover, the differentiation of mechanical properties across ~~Additionally, our findings underscore the relevance of biomechanical diversity among~~ plant parts ~~for improving the fidelity of dune models~~ emphasizes the importance of trait-specific parameterization. ~~In the following sections, we discuss our findings in detail, exploring the implications for improving the accuracy of dune vegetation models.~~ The following table (Table 1) summarizes the biomechanical traits of marram grass by plant part and season. These values offer a reference for future modeling efforts and for the design of vegetation surrogates that reflect structural variability in dune systems.

Table 1. Summary of marram grass parameters for surrogate modeling to accurately represent seasonal variations in dune dynamics and vegetation.

Accordingly, the Conclusion section has been adjusted and no longer includes the full table or its description. Instead, it now contains only a brief reference to Table 1, which is already introduced in the Discussion:

> This study provides a comprehensive dataset of the biomechanical properties of marram grass over 12 months, highlighting significant seasonal variations and differences among precisely defined plant components (Table 1). By analyzing 1543 sprouts, 841 green leaves, 823 brown leaves, and 389 stems, we address a critical gap in the empirical basis for ~~the critical need for accurate representations of vegetation in the~~ modeling dune vegetation ~~of dune processes~~. The observed differences in biomechanical traits between distinct plant components, as well as their seasonal variability, offer valuable insights for the development of accurate aboveground vegetation surrogates and enhance the reliability of both physical and numerical models used to simulate dune stabilization and coastal defense processes. To translate these biomechanical insights into practical modeling and management strategies, we highlight the following key aspects: