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,

The authors would like to express their appreciation for the constructive comments - addressing them will have increased the overall quality of the revised manuscript. Furthermore, we are grateful for the positive feedback and the interest in our work. A thorough revision of the manuscript was conducted.

Please find enclosed below detailed answers to the reviewers' comments, as well as the corresponding actions performed to the original manuscript submission. Each response is structured according to the key aspects of the comment, with references to the relevant manuscript sections provided in parentheses, indicating the corresponding line numbers from the originally submitted version.

Sincerely,

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

Reviewer #1:

Comment 1.1:

Overall, I think this is extremely valuable study on differences in dune grass traits to inform modeling. However, I think the current framing of the study narrows the audience of the paper more than is needed. Some careful reframing of the introduction and discussion would make the paper more interesting to readers who are not intimately familiar with dune models. For example, I think the discussion could elaborate on how the findings alter our understanding of dune resistance and recovery. Additionally, can these findings inform modeling in dunes with different grass species or other coastal ecosystems?

Answer to Comment 1.1:

Thank you for your valuable feedback. To address your suggestion, we have carefully refined both the introduction and discussion to better highlight the broader relevance of our findings beyond dune modeling. As Comment 1.2: provided a more detailed discussion on the introduction, we implemented multiple individual revisions in response. To maintain clarity and provide an overview of all changes, we have presented the entire revised Introduction in Answer to Comment 1.2:. We kindly refer you to this response for the full updated version. Additionally, we conducted a detailed review of the entire discussion to ensure that it more effectively conveys the implications of our findings. Below are the key revisions that best align with the reviewer's suggestions:

At the end of the subsection 'Seasonal variations in biomechanical traits' in the discussion, we have added the following sentence to strengthen the connection to the understanding of dune resistance and recovery:

> [Line 421] "~~Overall, our findings support the literature~~ Similar to findings on salt marsh vegetation, our results show that during ~~the~~ summer, vegetation density significantly increases, while in ~~the~~ winter, the stiffness of the vegetation is greater and the outer diameter smaller (Koch et al., 2009; Vuik et al., 2017; Foster-Martinez et al., 2018; Keimer et al., 2024; Li et al., 2024). ~~However, we observed that the length of vegetation, particularly green and brown leaves, tends to be greater in winter, contrasting those findings.~~ Instead, our observations suggest that leaves, which lengthen in winter, 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 dynamic adaptability of marram grass, with increased stiffness in winter for erosion resistance and greater density in summer to enhance accretion, supports the natural processes of dune formation and recovery, reinforcing the role of vegetation in maintaining dune resilience."

Additionally, we have introduced the subsection 'General relevance for foredune vegetation' to the discussion to emphasize the applicability of our results to other dune grass species and coastal ecosystems.

> [Line 527] "**4.5 General relevance for foredune vegetation**
>
> Marram grass is widely distributed across European sandy coastlines, making our findings highly representative for a broad range of coastal environments. Additionally, closely related species such as *Ammophila breviligulata* in North America share similar ecological functions (Mostow et al., 2021; Stalter and Lonard, 2024). Foredunes, which form the first line of defense against coastal erosion, host a variety of grass species worldwide, many of which exhibit comparable biomechanical adaptations to stabilize sediments and withstand environmental forces (Mostow et al., 2021). Our study provides a valuable framework for understanding the biomechanical differentiation among plant components and their seasonal variations. The observed shifts in stiffness, canopy density, and seasonal growth dynamics are likely key factors for dune stability in

other dune grass species as well, underlining the importance of plant trait-based approaches in coastal protection research.”

Comment 1.2:

I found the introduction overly lengthy. I have some specific suggestions below, but I generally think the readability of this section could be improved if extra details were removed. This paper is likely written for someone familiar with sand dunes, and certainly someone familiar with coastal vegetation, so think about what background is common knowledge to the reader. Briefly, you want to convey that dune vegetation traits modulate sediment dynamics, and that some traits are not well understood while others vary with season, mechanical stressors, and soil properties. Some of these main points are currently buried because there’s so much info in the intro. Also, there is no mention of different grass components and how these are important, but differences between plant parts (sprouts, leaves, stems) are a key part of the study that could use introducing.

Answer to Comment 1.2:

Thank you very much for drawing that to our attention. In response, we have thoroughly reviewed the introduction and made several revisions to improve readability and focus. Specifically, we have significantly shortened or removed passages that covered common knowledge, reducing the overall length from 146 to 134 lines. Throughout the introduction, we have also refined phrasing to emphasize the key research points and knowledge gaps more clearly. Additionally, we have incorporated an explicit mention of the different plant components (sprouts, leaves, stems) to better align the introduction with the study’s focus. Below, we provide the revised introduction with all modifications clearly marked.

> [Line 18] “Coastal dunes ~~occur worldwide and belong to~~ are among the most dynamic ecosystems on Earth~~.~~, shaped by the ~~Their morphology is governed by an intricate~~ interplay between physical and biological processes (Hesp, 2002; Hacker et al., 2012; Zarnetske et al., 2015; Strypsteen et al., 2019). ~~Sufficient sediment supply and strong onshore winds, together with pioneer vegetation, create a constantly changing topography with dunes often reaching heights of tens of meters (Hacker et al., 2012; Duarte et al., 2013; Strypsteen et al., 2019; Mehrtens et al., 2023).~~
>
> ~~After reaching a certain height, coastal dunes~~ They act as natural coastal barriers, mitigating storm impacts and protecting inland areas from flooding ~~the impacts of storm tides by mitigating increased water levels and wave heights. This natural defense is crucial for safeguarding people, infrastructure, and the economy from flooding and related damages~~ (Martínez and Psuty, 2004; Feagin et al., 2015; Ruggiero et al., 2018). Besides their ~~economic value for coastal protection and tourism~~ protective function, ~~coastal~~ dunes ~~also represent an important ecosystem with~~ support high ecological diversity and provide essential ecosystem services, including ~~value regarding~~ freshwater provision and sediment stabilization~~, biodiversity conservation, and providing habitat for coastal vegetation as well as animals, especially nesting seabirds~~ (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). 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 (de Vries et al., 2012; Feagin et al., 2015; de Battisti, 2021). Both short-term changes in dune morphology from individual storm events, such as erosion and deposition of sediment, and long-term trends influenced by sea

level rise, sediment supply, 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).

~~One of the greatest challenges of this century pertains to deepening the understanding of and developing adaptation measures against the vicissitudes caused by climate change regarding coastal protection levels (sea level, storm frequency) and biodiversity (Dangendorf et al., 2019). The advantages of~~ Coastal dunes, unlike ~~over~~ engineered ~~hard~~ structures~~ (e.g., dikes and sea walls),~~ adapt ~~lie in their ability to form and stabilize~~ dynamically through natural processes~~, such as~~ like ~~aeolian~~ sediment transport and vegetation growth~~.~~, enabling post-storm recovery and resilience to sea-level rise ~~Furthermore, the dynamic processes of dune erosion and accretion lead to the assumption that, through vertical growth~~ (van Gent et al., 2008; van IJzendoorn et al., 2021; Mehrtens et al., 2022, 2023). ~~or landward migration, dunes can withstand sea level rise through adaptation under favorable conditions. Nowadays, sand nourishments are frequently used to artificially supply sediment for dune growth (Staudt et al., 2021); this way, dune systems are enabled to re-establish their former shape or geometry after storm damage (Keijsers et al., 2015).~~

~~With this d~~Dynamic dune management~~, the natural~~ supports these processes while promoting ~~governed by sediment supply, aeolian transport rates, and vegetation cover are used exclusively for dune reconstruction (Keijsers et al., 2015). However, nature-based solutions (Nbs) in coastal protection are nowadays thought to serve the demands for both coastal protection and~~ biodiversity ~~preservation~~ and ecosystem services. ~~Therefore, an enhanced understanding of the natural processes supports the integration of coastal protection measures and concepts.~~

~~Furthermore, c~~Climate change ~~also has an~~ impacts ~~on the~~ dune vegetation ~~itself and may lead to alterations in~~ altering species distribution and traits (Carter, 1991; Duarte et al., 2013; Gao et al., 2020; de Battisti, 2021; Biel and Hacker, 2021). Carter (1991), ~~for example~~ e.g., stated that species tolerant to higher temperatures, drought, and sand burial may become more dominant in the future.

~~The enhanced u~~Understanding ~~of~~ these vegetation development and characteristics is ~~of particular importance~~ crucial, ~~given that vegetation plays an essential role in the~~ as plants not only shape dune formation ~~and evolution of coastal dunes and~~ but also provide~~s~~ ~~significant additional~~ 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 ~~Numerous~~ numerical models, e.g., DUBEVEG (Keijsers et al., 2016; Husemann et al., 2024), AeoLIS (van Westen et al., 2024), ~~or implementations in~~ and XBeach implementations (Schweiger and Schuettrumpf, 2021), as well as physical models, have been developed~~ to simulate the interactions between vegetation, sand, wind, and water in dune environments~~. However, the accuracy of these models strongly depends on high-quality datasets derived from field observations, which, to date, have not been systematically collected for the specific biomechanical properties of dune vegetation. In physical experiments, dune vegetation is ~~most~~ often either neglected (van Gent et al., 2007; Tomasicchio et al., 2011; Figlus et al., 2011; Mehrtens et al., 2024) or represented ~~either by~~ using real vegetation (Figlus et al., 2014; de Battisti and Griffin, 2020; Silva et al., 2016; Maximiliano-Cordova et al., 2019; Feagin et al., 2019) or simplistic mimics such as wooden dowels (Bryant et al., 2019; Kobayashi et al., 2013; Türker et al., 2019), which presents~~ing~~ ~~the~~ challenges ~~of either dealing with non-scalable materials or inadequately representing the actual~~ in terms of scalability and accurately replicating biomechanical properties of the vegetation (Garzon et al., 2021). ~~Recent research in~~ Most vegetation modelling efforts in ~~for~~ NbS ~~in~~ for coastal protection have~~s~~ focused on salt marsh vegetation, aiming to improve~~ing~~ the representation of plant physiology, morphology, and hydrology (Liu et al., 2021; Keimer et al., 2024). These models ~~aim~~ 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 density and mechanical properties such as stiffness have been identified as key factors influencing wave attenuation and shoreline stabilization (Shepard et al., 2011). However, salt marsh plants differ significantly from dune vegetation in terms of morphology, biomechanical properties, and response to hydrodynamic and aeolian forces. While salt marsh plants typically exhibit high flexibility and resistance to hydrodynamic forces (Vuik et al., 2017; Bouma et al., 2014), dune grasses primarily contribute to sediment stabilization through their aboveground stiffness and extensive rhizome networks (Zarnetske et al., 2012; Figlus et al., 2022). Consequently, the transferability of existing vegetation parameterizations from salt marshes to dune environments is therefore limited, necessitating a more refined biomechanical representation of dune vegetation in coastal models. Despite the recognized importance of plant morphology, research on the biomechanical role of dune vegetation remains limited. 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. ~~For instance, s~~Several studies, for instance, have employed three-point bending tests for investigating the biomechanics of salt marsh vegetation~~ and~~, assessing seasonal and species-specific differences (see Table A1 in the Appendix) ~~(Rupprecht et al., 2015, 2017; Zhu et al., 2020; Liu et al., 2021; Paul et al., 2022; Keimer et al., 2023, 2024)~~. 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 regarding density of cover and rooting depth; since then, little further research has appeared to fill the gap, and a~~ with~~ better understanding of the biomechanics of dune vegetation remains crucial for ~~facilitating~~ improving modelling efforts.

Field data from the literature provides valuable insights into the characteristics of marram grass, though their~~y~~ ~~can be difficult to~~ interpretation is often complicated by~~ due to~~ inconsistent terminology and ~~often~~ missing methodological descriptions~~ of methodologies~~. Previous studies have primarily focused on geometric and external plant traits, while biomechanical properties remain largely understudied. Histological examinations have been conducted by Andrade et al. (2021) and Chergui et al. (2017)~~. A~~, and a review by McGuirk et al. (2022) summarizes current knowledge on the role of vegetation in dune dynamics, including quantitative studies on marram grass ~~by Hesp (1981, 1989), Hacker et al. (2012), Seabloom and Wiedemann (1994), Zarnetske et al. (2012), Biel et al. (2019), and Feagin et al. (2019)~~. A comprehensive overview of key paramteres, such as growth height, horizontal density, and belowground biomass, is provided in Table A2 in the Appendix. ~~Key parameters examined include vegetation cover percentage (Bressolier and Thomas, 1977; Konlechner and Hilton, 2022; Chergui et al., 2017; Costas et al., 2024), aboveground and belowground biomass (de Battisti and Griffin, 2020; Mostow et al., 2021), tiller density (i.e., tillers per rhizome) (Hacker et al., 2012), plant density (Huiskes, 1979; Biel et al., 2019), stem density (Feagin et al., 2019), and stem and flower numbers per square meter (Seabloom and Wiedemann, 1994). Additionally, parameters such as stem length (Feagin et al., 2019; Mostow et al., 2021), and various height measurements (Hesp, 1981; Bressolier and Thomas, 1977; Mostow et al., 2021) have been reported. Feagin et al. (2019) explicitly addresses modelling and laboratory considerations of vegetation traits and provides additional information about~~

~~marram grass, including stem diameter (3 ± 1 mm), leaves per square meter (1516 ± 8 leaves m−2), leaves per stem (1 ± 3), leaf area (1605 ± 7 mm2), and fine roots (288 ± 14 g m−2). Growth heights range from 50 up to 100 cm (Bressolier and Thomas, 1977; Hesp, 1981). Stem height was reported to range up to 195 mm (Feagin et al., 2019), and stem lengths can reach up to 200 cm (Mostow et al., 2021). Plant density has been recorded up to 1000 tillers m−2 (Zarnetske et al., 2012), up to 200 tillers m−2 (Huiskes, 1979), up to 556 tillers m−2 (Biel et al., 2019), 260 stems m−2 (Feagin et al., 2019), and approximately 203 stems m−2, with about 30 flowers m−2 (Seabloom and Wiedemann, 1994).~~ 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. ~~To accurately model the physical interactions between vegetation and the environment, it is also crucial to understand mechanical plant traits.~~ 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 ~~interactions between organisms and their~~ 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 ~~plant biomechanics and their~~ its impact on dune stability and resilience to environmental stressors ~~such as water or wind~~ 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. ~~These mechanical traits are crucial for accurately modeling how vegetation interacts with and mitigates the effects of these stressors on dune systems.~~

Vegetation in coastal ecosystems, such as salt marshes, exhibits marked seasonality in its traits. For example, during the summer, plant length and density significantly increase, while in the 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). The effects of seasonality and vitality on vegetation traits can significantly impact their biomechanical properties, which in turn may influence ~~the~~ dune~~’s~~ stability and ~~ability~~ resilience to ~~withstand~~ environmental stressors (Baas and Nield, 2010; de Jong et al., 2014; Biel and Hacker, 2021). Similarly, dune dynamics also follow ~~are also subject to~~ seasonal ~~variations~~ patterns. Dunes typically experience erosion during ~~the~~ winter and accretion during ~~the~~ summer, ~~creating a seasonal~~ leading to cycleic variations in dune morphology (Montreuil et al., 2013; Pye and Blott, 2016; Rader et al., 2018). These processes are driven by seasonal variations in wind and wave action, which shape the dune landscape. Although there is limited specific information on the seasonality of dune vegetation traits, it is known that marram grass has adapted to these dynamic processes. ~~Marram grass requires r~~Regular sand burial is essential for its healthy growth, and without it, ~~their~~ growth rates and relative abundance decrease significantly (Maun, 1998; Bonte et al., 2021), indicating an "escape" mechanism against certain nematode species (van der Putten and Troelstra, 1990; Bonte et al., 2021). During ~~the~~ winter, the extensive root system~~s~~ of ~~these plants~~ marram grass plays a crucial role in stabilizing the dunes by enhancing ~~the~~ sediment~~’s physical~~ properties, such as porosity, shear strength, and slope stability, thus reducing erosion and preventing uprooting during storm surges (Davidson et al., 2020; Walker and Zinnert, 2022). ~~In conclusion, the seasonality of vegetation traits combined with the seasonal dynamics of dune processes underscores~~ These interactions between seasonal vegetation traits and dune processes highlight the importance of incorporating seasonal variations into~~ the~~ stud~~y~~ies of dune vegetation properties ~~for accurate modeling and~~ to improve our understanding of their role ~~of dune vegetation~~ in coastal defense.

In addition to seasonal influences, dune vegetation is subjected to ~~varying~~ external mechanical forces, ~~loads~~ such as wind or hydrodynamic~~s~~ loads, which can ~~influence~~ impact plant growth and biomechanical properties (Puijalon et al., 2005, 2011; Gardiner et al., 2016; Telewski, 2016; Du and Jiao, 2020; Kouhen et al., 2023). ~~The mechanical stresses experienced by these plants can lead to~~ Plants respond to mechanical stress through different adaptive strategies~~.~~, primarily classified as ~~The reconfiguration of plants due to wind loads can be classified as either an~~ avoidance ~~strategy –~~ (minimizing frontal area)~~ –~~ or ~~a~~ tolerance ~~strategy –~~ (maximizing resistance to breakage). ~~Plants~~ Species following the avoidance strategy tend~~s~~ to ~~have~~ exhibit higher bending stiffness (Puijalon et al., 2011). Understanding these strategies is crucial for biomechanical characterization, as they ~~influence~~ determine how plants interact with environmental forces such as wind and waves. However, most studies on ~~the impact of~~ wind-induced biomechanical adaptations ~~properties~~ have focused on woody vegetation, such as trees, ~~rather than on~~ whereas their applicability to dune vegetation remains largely ~~The extent to which these adaptive strategies apply to dune plants, such as marram grass, remains~~ unclear. Given the significant role of wind in coastal environments, it is essential to investigate how dune vegetation responds to wind-induced mechanical stresses to ~~better understand and model their~~ improve our understanding of its biomechanical behavior.

~~Besides~~ Beyond ~~wind~~ mechanical forces, soil characteristics also ~~affect~~ shape vegetation properties. As dunes develop, changes in soil composition influence ~~Regarding dunes, the succession from younger white dunes to older gray or brown dunes alters the soil and thus the~~ vegetation cover over the long-term (Isermann, 2011). In Europe, dune succession is often classified into ~~Within~~ white dunes, which are younger, more dynamic systems with active sand movement, and gray dunes, which are older, more stabilized formations with increased organic matter content ~~there are also differences, as they can be fixed or more mobile dunes~~ (Isermann and Cordes, 1997). ~~Whether these differences also have an effect on the biomechanical properties of the vegetation remains unclear.~~ However, such classifications are not universally applied, and comparable successional stages may differ depending on regional environmental conditions. Whether these environmental differences influence the biomechanical properties of dune vegetation remains an open question, highlighting the need for site-specific assessments when integrating vegetation traits into coastal studies.

By addressing the following research questions, this study aims to fill the aforementioned knowledge gaps by providing a comprehensive biomechanical characterization of marram grass.~~,~~ This serves as ~~the~~ a basis for ~~accurate~~ improving vegetation modeling in experiments~~, thus~~ and contributes~~ing~~ to ~~the~~ a better understanding of dune vegetation dynamics, ultimately~~ and~~ supporting the development of effective nature-based coastal protection strategies:

1. Are there significant seasonal variations in the biomechanical properties of dune vegetation that ~~need to~~ must be considered separately ~~for~~ when modeling accretion processes (~~in~~ summer) and erosion processes (~~in~~ winter)?

2. Do ~~the~~ different plant parts (sprouts, green leaves, brown leaves, flower stems) exhibit distinct biomechanical properties, or are they similar enough to be considered equivalent in biomechanical models of dune vegetation?

3. Does wind exposure (e.g., windward vs. leeward sides of dunes) or geographical exposition (e.g., north-west vs. south-east) affect the biomechanical traits of vegetation, and, if so, how should these factors be considered in biomechanical modeling?

4. How do biomechanical properties differ between vegetation in fixed, established dune systems and more dynamic dune systems, and how does this variation influence the accuracy and transferability of surrogate models ~~in representing~~ for dune vegetation?”

Comment 1.3:

Line 32: "Short term changes" to what?

Answer to Comment 1.3:

Thank you for pointing this out. We agree that the term "short-term changes" lacks specificity in this context. To clarify, we revised the sentence to explicitly state what these changes refer to. The updated sentence now reads:

> [Line 32] "Both short-term changes in dune morphology from individual storm events, such as erosion and deposition of sediment, and long-term trends influenced by sea level rise, sediment supply, 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)."

Comment 1.4:

Paragraph 2: The first half of this paragraph feels very drawn out, especially to a reader knowledgeable about dunes or Nbs. I think distilling to the key points would be valuable, especially since vegetation and models are not mentioned until the 2nd half of the paragraph

Answer to Comment 1.4:

Thank you for your helpful feedback. We have significantly shortened this section to enhance clarity and ensure that the key points are more prominently highlighted. The revised paragraph now focuses on the essential aspects relevant to the discussion, avoiding unnecessary elaboration. These changes have already been incorporated and presented in Answer to Comment 1.2:.

Comment 1.5:

Paragraph beginning line 66: This has a lot of good info summarizing what has been done, but it is challenging to read with all the parentheticals and citations. Could it be summarized or presented in a supplementary table? Most readers will not need all this info I don't think.

Answer to Comment 1.5:

Thank you for this valuable comment. We have addressed this issue by adding two supplementary tables (Table A1 and Table A2) in the appendix, which concisely summarize the literature information. This allowed us to streamline the main text and reduce the number of in-text citations, making it more readable. These changes have already been incorporated and are reflected in Answer to Comment 1.2:, to which we refer at this point.

Comment 1.6:

Intro generally: Why are dune models important and what are current models missing? Addressing this will explain why this paper is so valuable

Answer to Comment 1.6:

Thank you for pointing this out. We have revised the entire introduction to better highlight the existing gaps and weaknesses in current knowledge, as well as to emphasize the significance of our study. This includes a clearer explanation of the importance of dune models and what current models are missing. These improvements have already been presented in Answer to Comment 1.2:, to which we refer at this point.

Comment 1.7:

Paragraph beginning 182: Are these conditions representative of other sites dominated by marram grass? In other words, do you expect that the properties measured in this study will apply to marram grass elsewhere?

Answer to Comment 1.7:

Thank you for this comment. This aspect has not been explicitly addressed in the methodology section, but we now discuss it in more detail in the revised introduction. Specifically, we acknowledge that dune succession and environmental conditions vary regionally, which may influence the biomechanical properties of vegetation. We kindly refer to Answer to Comment 1.1:, where we have already taken steps to clarify the regional context of our study. Additionally, in the introduction, we now explicitly address regional differences in dune succession and their potential influence on vegetation properties, as reflected in the following revised section:

> [Line 129] "~~Besides~~ Beyond ~~wind~~ mechanical forces, soil characteristics also ~~affect~~ shape vegetation properties. As dunes develop, changes in soil composition influence ~~Regarding dunes, the succession from younger white dunes to older gray or brown dunes alters the soil and thus the~~ vegetation cover over the long-term (Isermann, 2011). In Europe, dune succession is often classified into ~~Within~~ white dunes, which are younger, more dynamic systems with active sand movement, and gray dunes, which are older, more stabilized formations with increased organic matter content ~~there are also differences, as they can be fixed or more mobile dunes~~ (Isermann and Cordes, 1997). ~~Whether these differences also have an effect on the biomechanical properties of the vegetation remains unclear.~~ However, such classifications are not universally applied, and comparable successional stages may differ depending on regional environmental conditions. Whether these environmental differences influence the biomechanical properties of dune vegetation remains an open question, highlighting the need for site-specific assessments when integrating vegetation traits into coastal studies."

Comment 1.8:

Methods: Great distilling of methods and use of supplementary information.

Answer to Comment 1.8:

Thank you!

Comment 1.9:

Line 252: the name of the universal testing machine did not proof correctly.

Answer to Comment 1.9:

Thank you for this valuable comment. We acknowledge the incorrect naming of the universal testing machine. The correct name is "zwickiLine Z0.5" by ZwickRoell GmbH & Co.KG, not "zwickiLine 500 N". We have updated the manuscript:

> [Line 252] "The bending tests utilized a universal testing machine, the „zwickiLine Z0.5500 N" by ZwickRoell GmbH & Co.KG."

Comment 1.10:
Line 260: define Young's modulus.

Answer to Comment 1.10:
Thank you for highlighting the need to provide a clearer definition of Young's modulus. To address this, we have expanded the text to include a concise definition and its relevance to the study of plant components. Below is the revised text:

> [Line 258] "The bending tests produced force-deflection curves, which were essential for analyzing the mechanical properties of each sample. From these curves, the force (F) and deflection (D) were used to compute the bending stiffness (KB = F/D, hereafter referred to as stiffness) and the Young's modulus (E) of each sample, calculated from the initial slope of the force-deflection curve. The Young's modulus, also known as the elastic modulus, quantifies the stiffness of a material and describes its resistance to deformation under an applied load. For plant components, it provides insight into their structural role, with a higher Young's modulus indicating stiffer materials that deform less under mechanical stress, enhancing stability, and a lower modulus reflecting greater flexibility, enabling reconfiguration to reduce mechanical damage. In this study, the experimental determination of Young's modulus includes the geometry of the plant components through the second moment of area (I), which assumes a solid circular cross-section based on the outer diameter (d_o) of the sample:
>
> $$I = \frac{\pi(do)^4}{64}$$
>
> The following equation was used to calculate the Young's modulus:
>
> $$E = \frac{4(\Delta s)^3 F}{3D\pi(do)^4}$$
>
> In this study, the deflection range selected was between 0.4 mm and 1.2 mm, based on the initial linear portion of the force-deflection curve observed across all samples. ~~Assuming an approximately circular solid cross-sections of the plant components, the Young's modulus was determined using the following equation:~~
>
> ~~$$E = \frac{4(\Delta s)^3 F}{3D\pi(do)^4}$$~~
>
> ~~The outer diameter (do) was used to simplify the calculation of the second moment of inertia (I), using the equation:~~
>
> ~~$$I = \frac{\pi(do)^4}{64}$$~~"

Comment 1.11:
Line 273: elaborate on why these specific metrics are important. What does a different *EI* mean for dune growth, for instance. It may be helpful to mention this earlier in the bending test section.

Answer to Comment 1.11:

Thank you for highlighting the need to further explain the relevance of the biomechanical parameters assessed in our study. In response, we have expanded the methodological section to clarify the significance of Young's modulus (*E*) in understanding the mechanical properties of marram grass. Specifically, we now explain how *E* relates to the plant's ability to resist mechanical stress and maintain structural integrity under wind and sediment transport forces, which may contribute to dune stability. The text was revised as follows:

> [Line 273] "These parameters are vital for understanding the mechanical behavior of marram grass, which plays a crucial role in the resilience and adaptation of dune ecosystems. In particular, Young's modulus (*E*) reflects the material stiffness of plant tissues, determining their ability to withstand mechanical stress, with higher *E* values indicating increased resistance to bending and deformation under waves, wind and sediment transport forces. Previous studies have shown that plant stiffness is a key factor in counteracting mechanical forces in coastal environments (Bouma et al., 2005; Paul et al., 2016), highlighting its potential role in dune stabilization."

Comment 1.12:

Line 278: I support grouping into summer and winter seasons, but in Fig. 2 and 3 the terms spring and autumn are used, which does not match this grouping.

Answer to Comment 1.12:

Thank you for your valuable observation. Upon reviewing the figures, we identified that the terms "spring" and "autumn" were only present in the caption of Figure 3 and not in the figure itself or in Figure 2. In the figures, months are directly indicated, which align with our later definition of summer and winter seasons. To ensure consistency and clarity, we revised the captions to directly reference the months displayed in the photos. This eliminates any potential confusion between seasonal terms and our grouping approach.

> "**Figure 2.** (a) Dune ridge sectors with elevation based on a 2022 DEM (NLWKN, 2023), and positioning of the soil sensor. (b-e) View of the luv-side of the dune ~~during different seasons~~ at different months. (f) Cross shore profile based on 2022 DEM, vertically superelevated by a factor of 3. For details on soil sensor information see Appendix C."

> "**Figure 3.** (a) Cusp dune outline and sectors with elevation based on a 2022 DEM (NLWKN, 2023), and positioning of the soil sensor. (b) View of the western slope of the dune in ~~spring~~ April and (c) in ~~summer~~ June. (d) View of the north-western edge in ~~autumn~~ November and (e) view of the north-eastern edge in ~~winter~~ December. View angles are indicated on (a) in red. (f) Cross shore profile based on 2022 DEM. For details on soil sensor information see Appendix C."

Comment 1.13:

Fig 4: mention in caption that no flowering was observed in winter so it doesn't look like a bar is missing from the graph.

Answer to Comment 1.13:

Thank you for this valuable comment. We agree that the absence of a bar for winter in panel (c) of Figure 4 could lead to confusion. To address this, we have revised the caption to explicitly state that no flowering was observed during the winter season. This clarification ensures that readers understand why a corresponding bar is not present.

“**Figure 4.** Combined data from both dune sites showing (a) Canopy height in cm, (b) Horizontal density in shoots per m^2, and (c) Number of flowers in flowers per m^2, comparing summer and winter illustrated as boxplots. Note that no flowering was observed in winter, and thus no corresponding bar is shown for this season in (c).”

Comment 1.14:

Section beginning Line 230: Present these results in the order they appear in Fig 5 or re-order fig. 5 to match the presentation of results here. Going from sprouts to leaves to stems felt odd when the figure was sprouts, stems, leaves. Same for the stiffness figure.

Answer to Comment 1.14:

Thank you for pointing out the mismatch between the order of the plant components in the text and figures. To address this, we have unified the sequence throughout the text and figures to improve clarity and consistency. We chose the order sprouts, green leaves, brown leaves, stems**,** as sprouts and leaves are both derived from shoots and stems are measured only in summer, making them a separate category with specific seasonal relevance. This grouping ensures a logical progression from components closely related to the shoot system to stems, which have distinct seasonal relevance. Several changes were implemented, as listed below.

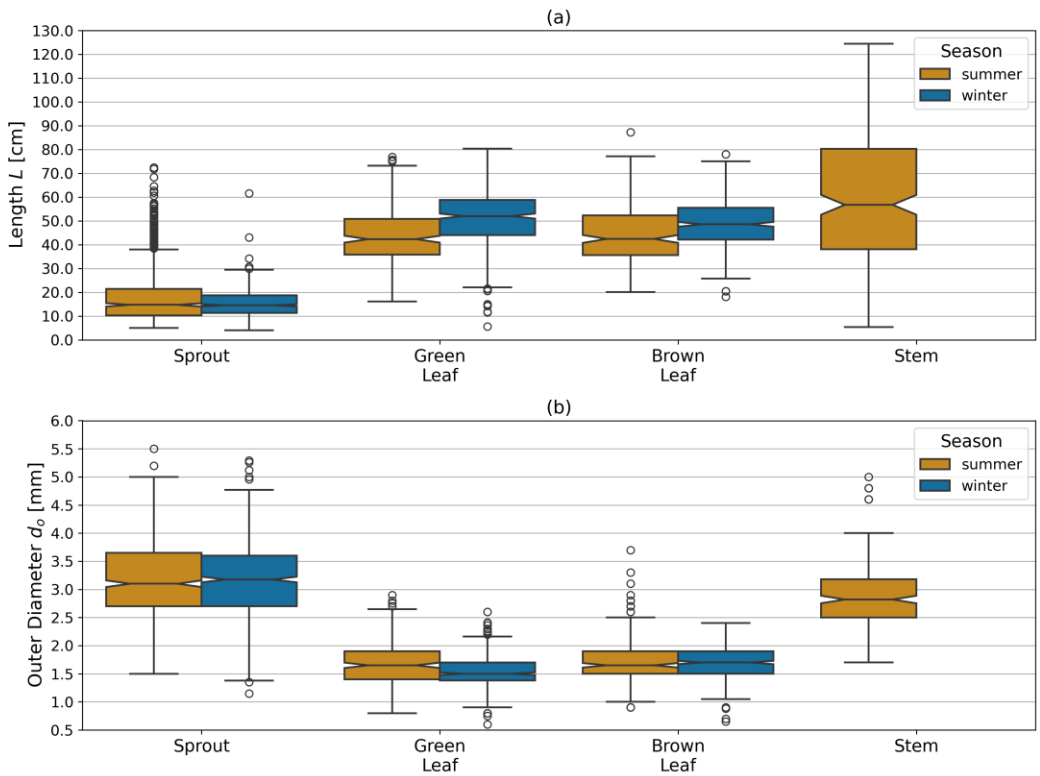
The order of plant components was revised in the following sentence for consistency:

> [Line 284] “This includes parameters such as canopy height, horizontal density, number of flowers, and the biomechanically relevant properties of the individual plant components (sprout, ~~stem,~~ green/brown leaf, stem): Length, outer diameter, stiffness, and Young’s modulus. “

Similarly, the following sequence was adjusted:

> [Line 292] “In total, 1543 sprout samples (Dune Ridge: 491, Cusp Dune: 1052), ~~389 stem samples (Dune Ridge: 115, Cusp Dune: 274),~~ 831 green leaf samples (Dune Ridge: 227, Cusp Dune: 614), ~~and~~ 823 brown leaf samples (Dune Ridge: 224, Cusp Dune: 599), and 389 stem samples (Dune Ridge: 115, Cusp Dune: 274) were investigated. “

Furthermore, the sequence of plant components in Figure 5 has been adjusted to reflect the order (sprout, green leaf, brown leaf, stem). Additionally, changes suggested in Comment 1.13: and Comment 1.15: have been incorporated here. Specifically, the caption for Figure 5 has been updated to clarify that no flowering was observed during the winter season:



"**Figure 5.** Combined data from both dune sites showing (a) mean length L and (b) mean outer diameter d_o of plant components (sprout, ~~stem,~~ green leaf, brown leaf, stem) comparing summer and winter illustrated as boxplots. Note that no stems were observed in winter."

In Figure 6, an exception regarding the order of plant components was made: sprouts and stems are presented in one plot due to their similar stiffness characteristics, while green and brown leaves are shown in a separate plot to emphasize their distinct mechanical behavior. This exception is explained in the text:

> [Line 333] "Stiffness showed significant seasonal variations in some plant components ~~(see Fig. 6)~~. To highlight the similarities between sprouts and stems, these components are displayed together, while green and brown leaves, which exhibit distinct stiffness patterns, are presented in a separate plot (see Fig. 6)."

The adjustments to the sequence of plant components have also been applied to Figures 7–14 to maintain consistency across all visualizations. Since these figures are further addressed in Comment 1.15:-Comment 1.17:, which include additional modifications such as figure combinations and the handling of outliers, the revised versions will be presented later in the responses to those comments.

The order of plant components was also revised in the following sentence:

> [Line 348] "Significant differences in the biomechanical parameters stiffness (K_B), Young's modulus (E), outer diameter (d_o), and length (L) were found between all plant components (sprout~~s~~, ~~stems,~~ green leaf~~ves~~, brown leaf~~ves~~, stem) in both summer and winter (all $p < 0.001$), with the exception of Young's modulus between sprouts and green leaves in summer ($p = 0.319$), Young's modulus between green and brown leaves in winter ($p = 0.399$), and the outer diameter and length between green and brown leaves in summer ($p = 0.830$ and $p = 0.611$, respectively)."

In Section 4.1 (Seasonal variations in biomechanical traits), we have also adjusted the text to reflect the order sprouts, green leaves, brown leaves, stems. Specifically, the section discussing stems has been moved to the end to ensure consistency.

In the conclusion, the text was adjusted to ensure that the order of the plant parts is consistent across the entire manuscript:

> [Line 609] "By analyzing 1543 sprouts, 841 green leaves, 823 brown leaves, ~~1543 sprouts,~~ and 389 stems, we address the critical need for accurate representations of vegetation in the modeling of dune processes."

Additionally, the content of Table 1 showing the summary of marram grass parameters for surrogate modeling was rearranged:

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

General vegetation traits	**Season**	**Value**		
Canopy height (cm)	Annual	80 ± 15		
Horizontal density (shoots m^{-2})	Summer	494 ± 218		
	Winter	446 ± 210		
Number of flowers (flowers m^{-2})	Summer	109 ± 93		
	Winter	Not applicable		
Plant Part		**Length (cm)**	**Outer diameter (mm)**	**Stiffness (N/mm)**
Sprouts	Annual	17 ± 5	3.2 ± 0.5	4.1 ± 1.5
(Green and brown) Leaves	Summer	44 ± 8	1.7 ± 0.2	0.45 ± 0.2
	Winter	50 ± 9		
(Flower) Stems	Summer	65 ± 11	2.8 ± 0.4	5.3 ± 1.7
	Winter	Not applicable		

Comment 1.15:
Fig 5: Explain why there are no winter stems in the caption

Answer to Comment 1.15:
Thank you for this helpful comment, which significantly improves the clarity and comprehensibility of the figures for the readers. The revised version of the caption for Figure 5 was already presented in our Answer to Comment 1.14:. We have identified Figures 6 and 7 as the other relevant figures where this clarification applies. However, as Figures 6 and 7 are also undergoing additional adjustments in response to Comment 1.17: (regarding the handling of outliers), the final revised versions of these figures, incorporating all updates, will be presented later.

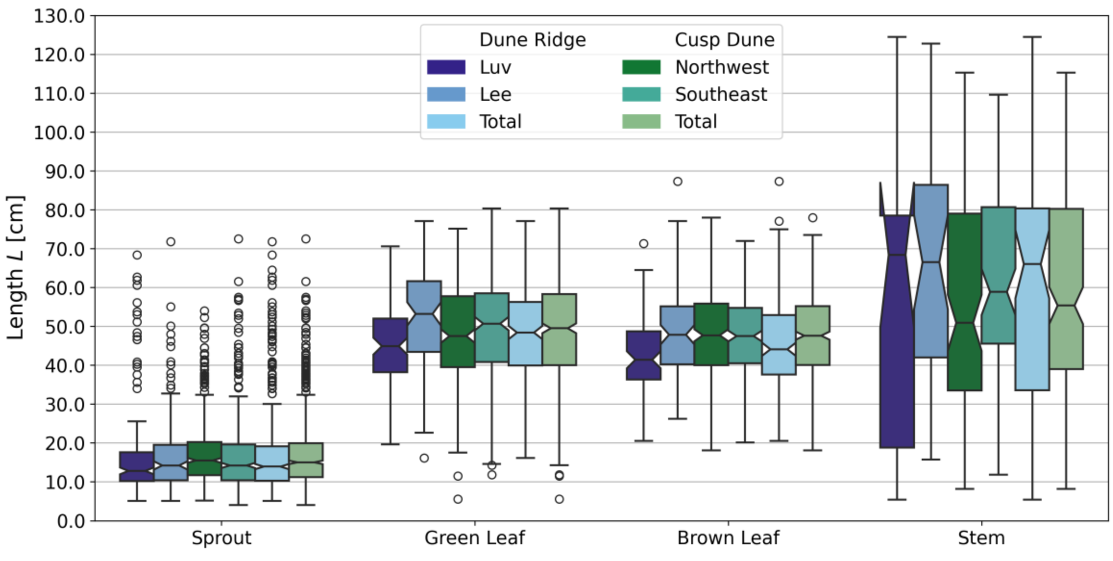
Comment 1.16:
Figures 8-13: I'm wondering if the figures with the same metric can be combined. For instance, can Fig. 8 and 9 be combines with the Dune Ridge site shown in darker colors than the Cusp Dune site? This will facilitate better comparisons between the sites and eliminate the need for Fig. 14.

Answer to Comment 1.16:

Thank you for this valuable suggestion. Combining the figures with the same metric has significantly improved the comparability between the two dune sites while also reducing the total number of figures. Based on this feedback, we have created new Figures 8, 9, and 10, which consolidate the data from the original Figures 8–14 as follows:

- Figure 8 combines the previous Figures 8 and 9.
- Figure 9 combines the previous Figures 10 and 11.
- Figure 10 combines the previous Figures 12, 13, and 14.

Additionally, we ensured that the adjustments suggested in Comment 1.14:, particularly the consistent order of plant parts (sprout, green leaf, brown leaf, stem), were implemented wherever applicable. However, as with the previous Figure 6 (see Answer to Comment 1.14:), the new Figure 9 makes an exception to this order to preserve readability of the results. We included an explanation of this exception directly in the figure caption to ensure clarity for readers. As Figures 9 and 10 also incorporate adjustments related to outlier treatment as suggested in Comment 1.17:, we will present these figures along with the corresponding explanations in the Answer to Comment 1.17:. Below, we present the new Figure 8 along with its updated caption:



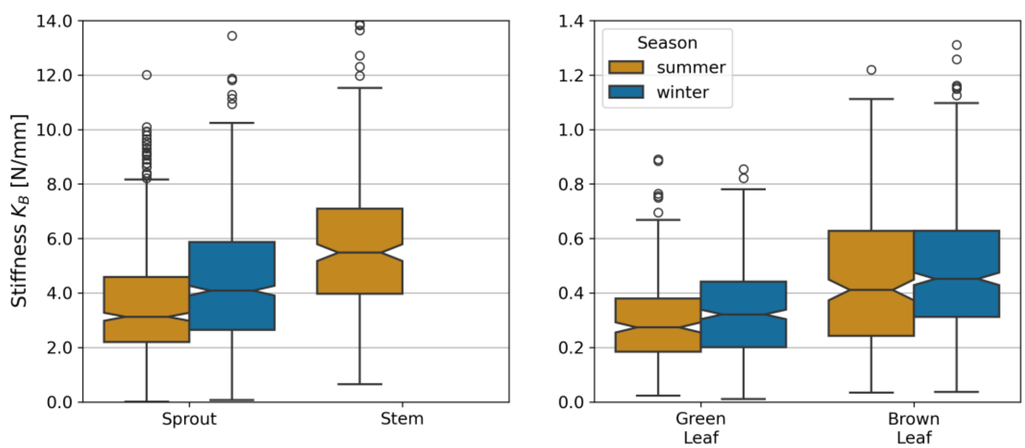
"**Figure 8.** Comparison of "luv"-side and "lee"-side at Dune Ridge as well as "Northwest"-side and "Southeast"-side at Cusp Dune with boxplots showing length L for each plant component, based on year-round data."

Comment 1.17:

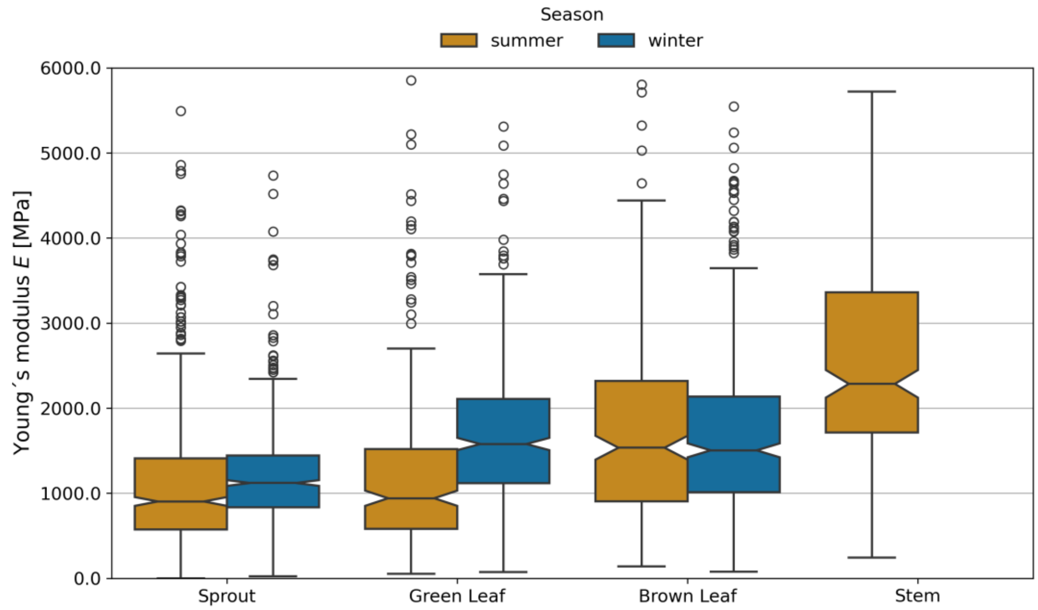
All data figures: You can absolutely disagree with this, but I think it may be beneficial to remove some of the extreme values from the graphs. This would allow you to keep the scales consistent and zoom in on the majority of the data. For example, in Figure 11, it's hard to see how the data differs because the plots are so small. I think you can say "Seven extreme values from Brown Leaves fell outside the scale of this figure and were excluded to enable better visualization.".

Answer to Comment 1.17:

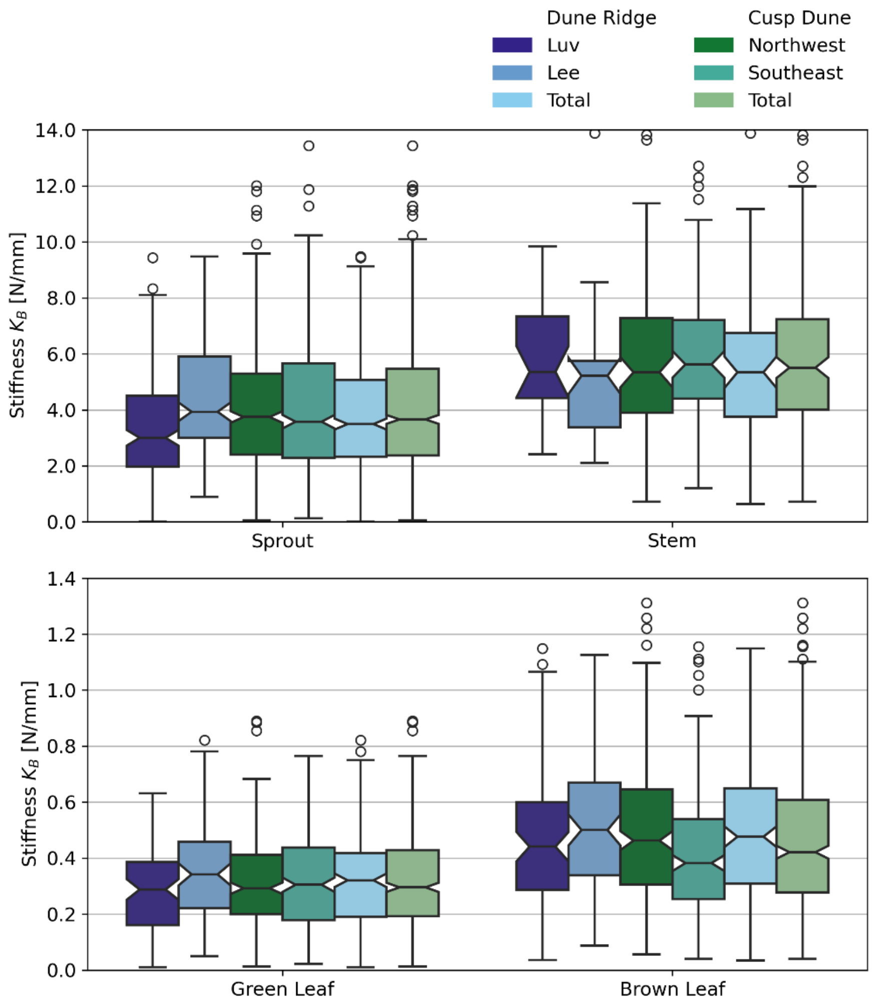
Thank you for this suggestion. We agree that excluding extreme values can significantly improve the readability of the graphs and highlight the key trends within the majority of the data. Based on your feedback, we have adjusted the scales and excluded extreme outliers in revised Figures 6, 7, 9, and 10. The number of excluded outliers for each plant component is specified in the respective figure captions for transparency. In addition, the adjustments suggested in Comment 1.14: (plant component order) and Comment 1.15: (absence of stem data in winter) have been incorporated into Figure 7 and 10 For Figure 6, the exception to the standard plant component order has been detailed in the text, as discussed in the Answer to Comment 1.14:. For Figure 9, where a similar exception was necessary to preserve readability, this has been explained directly in the figure caption, as finding a suitable place for this explanation in the text proved more challenging. Below, we present the updated figures and their captions:



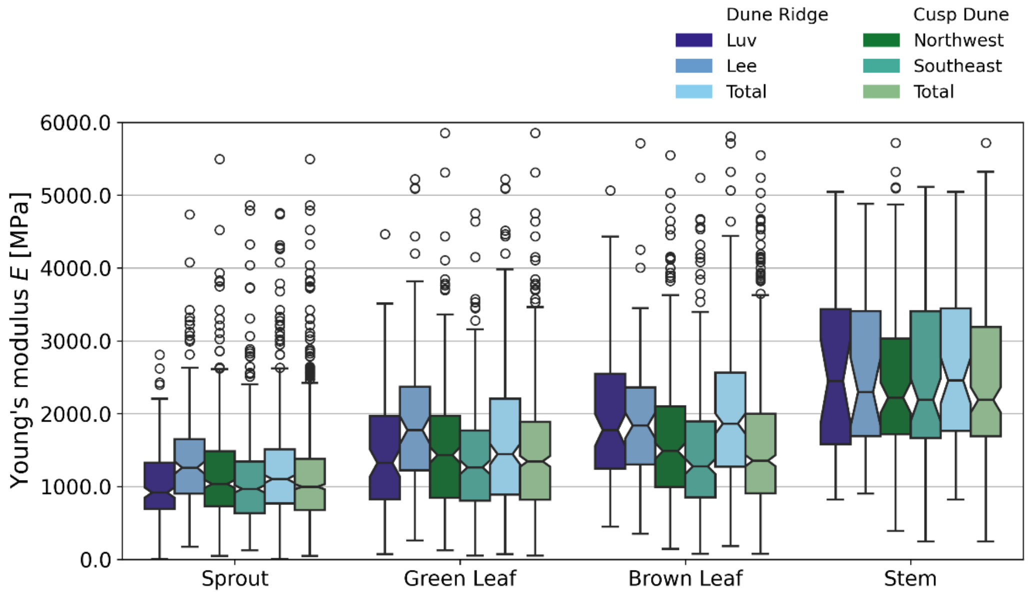
"**Figure 6.** Stiffness K_B of each plant component in summer and winter months, based on combined data from both dune sites. 18 outlier values for brown leaves and 1 for stems were excluded for visual clarity. Note that no stems were observed in winter."



“**Figure 7.** Young’s modulus *E* of each plant component in summer and winter months, based on combined data from both dune sites. One outlier value for sprouts, four for green leaves, nine for brown leaves, and five for stems were excluded for visual clarity. Note that no stems were observed in winter.”



“**Figure ~~10~~9.** Comparison of luv-side and lee-side at Dune Ridge as well as Northwest-side and Southeast-side at Cusp Dune with boxplots showing stiffness K_B for each plant component, based on year-round data. To improve clarity, sprouts and stems are grouped together due to their similar mechanical characteristics, while green and brown leaves are shown separately to emphasize their distinct behavior. Note that 33 outlier values for brown leaves, and 2 for stems were excluded for visual clarity.”



"**Figure ~~12~~10.** Comparison of luv-side and lee-side at Dune Ridge as well as Northwest-side and Southeast-side at Cusp Dune with boxplots showing Young's modulus *E* for each plant component, based on year-round data. Note that 2 outlier values for sprouts, 8 for green leaves, 17 for brown leaves, and 10 for stems were excluded for visual clarity."

Comment 1.18:

Discussion: Generally, somewhat repetitive of the results section. I'd recommend removing some areas that only restate the results and instead focusing on the implications of these findings. What does this finding mean for dune evolution or dune modeling? What critical factors were learned here and how do these findings improve our understanding of dune systems?

Answer to Comment 1.18:

Thank you for your constructive feedback. We appreciate your observation that parts of the discussion were repetitive of the results section and lacked sufficient emphasis on the broader implications of our findings. To address this, we have revised the discussion to focus more on the significance of the results for understanding dune evolution and improving biomechanical modeling. The following changes were made:

> [Line 415] "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 in dune stabilization and coastal defense strategies. Additionally, our findings underscore the relevance of biomechanical diversity among plant parts for improving the fidelity of dune models. In the following sections, we discuss our findings in detail, exploring the implications for improving the accuracy of dune vegetation models."

> [Line 421] "~~Overall, our findings support the literature~~ Similar to findings on salt marsh vegetation, our results show that during ~~the~~ summer, vegetation density significantly increases, while in ~~the~~ winter, the stiffness of the vegetation is greater and the outer diameter smaller (Koch et al., 2009; Vuik et al., 2017; Foster-Martinez et al., 2018; Keimer et al., 2024; Li et al., 2024). ~~However, we~~

observed that the length of vegetation, particularly green and brown leaves, tends to be greater in winter, contrasting those findings. Instead, our observations suggest that leaves, which lengthen in winter, 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 storm hydrodynamics in salt marshes. Overall, our findings confirm that while some parameters exhibit seasonal variability, others can be simplified for modeling purposes without losing accuracy.

For cCanopy height, showed no significant seasonal differences was observed between summer and winter, allowing the use of an (annual average of 80±15 cm), further specifying results aligning with the growth range reported by Hesp (1981) and Bressolier and Thomas (1977). who reported growth heights ranging from 50 to 100 cm.

Horizontal density was significantly higher in summer compared to winter, consistent with findings by Li et al. (2024) and Vuik et al. (2017), who noted increased vegetation density during the growth season. However, the density observed in this study was within the upper range of previous studies (Seabloom and Wiedemann, 1994; Zarnetske et al., 2012; Feagin et al., 2019) higher than the values reported by Seabloom and Wiedemann (1994) (203 stemsm−2) and Feagin et al. (2019) (260 stemsm−2), but fell within the range provided by Zarnetske et al. (2012) (up to 1000 tillersm−2) and Hacker et al. (2012) (480 plantsm−2). Our results showed that the number of flowers, observed only in summer, averaged 109±93 flower m^{-2}, which is significantly higher than the approximately 30 flowers m^{-2} reported by Seabloom and Wiedemann (1994). This seasonal occurrence of flowers must be taken into account in modeling efforts."

[Line 440] "However, the differences identified in the findings are not substantial enough to significantly impact surrogate modeling, indicating that seasonal variations in these parameters are negligible for modeling purposes and thus can be averaged annually. Seasonal variations in sprout parameters were minor and can be averaged annually for modeling purposes."

[Line 447] "For green leaves, significant seasonal differences were observed in length, stiffness, and outer diameter. Besides stiffness, the length of green leaves was significantly greater in winter, which contrasts with the general trend observed in salt marsh vegetation, where lengths peak in summer (Li et al., 2024; Koch et al., 2009). This discrepancy may be due to the specific growth patterns of marram grass, where older leaves persist through winter, contributing to greater overall lengths. Furthermore, this could also be attributed to the presence of younger, shorter plant parts during the growth phase in summer, which lowers the average length measurements. Green leaves were longer in winter, likely due to older leaves persisting through the season, contrasting trends observed in salt marsh species (Li et al., 2024, Koch et al., 2009). Conversely, the outer diameter of green leaves was larger in summer, which aligns with the findings of Vuik et al. (2017). However, the differences in stiffness and outer diameter between summer and winter were minor (summer: 0.29±0.11 kN/m and 1.7±0.2 mm; winter: 0.33±0.13 kN/m and 1.6±0.2 mm), making it practical to use an annual average for these parameters in modeling efforts, especially for physical models where replicating such minor variations may be challenging.

For brown leaves, the only significant seasonal difference observed was in length, with brown leaves also being longer in winter, while stiffness and outer diameter remained constant, allowing for their annual averaging. The stiffness and outer diameter of brown leaves did not exhibit significant seasonal variation, allowing these parameters to be averaged annually.

For stems, specifically flower stems, the summer-only presence highlights their importance for models representing the summer state. Their significant contribution to overall plant density, length height, and high stiffness make them critical components in summer models where their structural contribution to dune dynamics accretion processes is essential. Since flower stems are only present in summer, these characteristics must be integrated into seasonal models but can be omitted in winter representations.

Overall, stiffness exhibited significant seasonal variations for both sprouts and green leaves, with higher values in winter compared to summer."

[Line 485] "The significant differences in stiffness and Young's modulus between plant parts also underscore the need to model each component separately. Stems, with their highest values for both parameters, provide the greatest structural support. In contrast, green and brown leaves, which showed lower stiffness and Young's modulus, contribute more to flexibility and dynamic responses to environmental forces. These differences highlight the importance of including specific biomechanical properties for each plant part in models to accurately simulate their roles in dune stabilization and dynamics.

However, iIgnoring these differences could lead to inaccuracies in predicting vegetation behavior and its impact on dune dynamics, resulting in models that do not adequately reflect the true mechanical properties and structural roles of the vegetation, though in some cases, a simplified approach may be appropriate without compromising model accuracy. It is crucial to distinguish between the biomechanical traits of each plant component to ensure the reliability of the models. The only exception to this are the green and brown leaves in summer, where the similarities suggest that a simplified approach may be appropriate without compromising model accuracy."

[Line 496] "The impact of wind exposure on the biomechanical traits of dune vegetation reveals significant variations between windward and leeward sides of the dunes, most notably in stiffness and Young's modulus. Stems exhibited no significant differences in any measured parameters between wind-exposed and sheltered sides, indicating uniform structural response, while the greatest variations occurred in sprouts. However, the greatest differences were observed in sprouts, with varying degrees of difference in green and brown leaves.

Significant differences in stiffness and Young's modulus between windward and leeward sides suggest these parameters are most sensitive to wind exposure. The higher values on the leeward side at Dune Ridge and in the northwest zone at Cusp Dune indicate different adaptive strategies. At Dune Ridge, the leeward side exhibited greater stiffness and Young's modulus, which may indicate an avoidance strategy, where vegetation increases flexibility minimizes the forces encountered by reducing exposure to wind through increased flexibility on the windward side to reduce wind impact. Conversely, at Cusp Dune, the more wind-exposed Northwest zone, which is more exposed to wind, showed higher stiffness and Young's modulus, suggesting a tolerance strategy with vegetation maximizing its resistance to breakage to withstand wind forces.

Wind data from 2022 indicate that strong winds were showed predominantly west-dominated winds, with the highest frequency from the northwest during summer, while in winter, southwest winds were more prevalent, though the strongest winds (≥ Bft 6) predominantly originated from northwest (see also Sect. C1 in the Appendix). As a result, the southwest-facing Dune Ridge coastline complicates wind exposure impact assessment. In general, and comparisons between Northwest and Southeast zones showed few significant differences, suggesting no strong wind exposure effect on plant biomechanics. Consequently, wind influence will not be included in the biomechanical parameterization of marram grass~~, serving as the basis for further surrogate modeling efforts~~.”

[Line 513] “~~The h~~Higher stem density and increased flower production in the Cusp Dune suggest favorable conditions for plant growth, ~~such as~~ likely influenced by frequent sand burial~~. This burial~~, which enhances ~~the~~ plant health and germination potential ~~of the plants~~ (Maun, 1998; Bonte et al., 2021; van der Putten and Troelstra, 1990; Huiskes, 1979)~~,~~. This dynamic environment lead~~sing~~ to more frequent production of inflorescences compared to ~~older, vegetative plants in~~ the more stable conditions of fixed dunes. Higher canopy height in the North zone of the Cusp Dune suggests landward dune migration, emphasizing its categorization as a more mobile ~~dune~~ system. ~~The presence of more flowers supports the view that the Cusp Dune is more dynamic, experiencing frequent morphological changes and higher sand deposition rates.~~ In contrast, the Dune Ridge, as part of the fixed dunes, remains more stable (Isermannn and Cordes, 1997; Pollmann et al., 2018).

The biomechanical properties of marram grass show some variations between dune types.~~, particularly~~ Young's modulus~~, exhibit~~ values indicate higher stiffness on the fixed dune (Dune Ridge)~~. However~~, but this trend is not consistently confirmed by stiffness measurements, ~~indicating no clear trend~~ suggesting that biomechanical differences may not be substantial enough to affect~~. The absence of a clear trend in these properties is beneficial for~~ transferability. The absence of ~~a~~ clear biomechanical trend~~s in these properties is beneficial for transferability~~ across dune types supports the robustness of marram grass in European coastal dune systems, indicating its broad applicability within these environments~~., as it suggests that the same vegetation type (marram grass) exhibits robust biomechanical properties across different dune types.~~

~~Stems show no significant trends, further supporting the idea of broad applicability of these findings.~~ However, ~~it is important to note that~~ freshly planted marram grass ~~for dune stabilization~~ or newly constructed dunes with planted vegetation ~~might behave differently~~ may exhibit different biomechanical responses, which should be~~. This necessitates careful~~ considered~~ation~~ in modeling and practical applications.”

Comment 1.19:

Section 4.5: I think these considerations could be summarized in a single paragraph, this section is very detailed for a general reader.

Answer to Comment 1.19:

Thank you for this helpful suggestion. We acknowledge that Section 4.5 is quite detailed, and we agree that a more concise summary will improve readability while still conveying the key methodological considerations. To address this, we have condensed the discussion into a single, streamlined paragraph that maintains the essential points while removing redundancy and some details. The revised text now reads:

[Line 529] “The choice of marram grass for biomechanical parameterization was based on its widespread occurrence, historical use in dune stabilization, and resilience to extreme environmental conditions (Huiskes, 1979; Feagin et al., 2015; Battisti and Griffin, 2020; Bonte et al., 2021; Strypsteen et al., 2024). Field investigations revealed seasonal variations in plant morphology, influenced by accretion and erosion processes, but lacked high-resolution Digital Elevation Models (DEMs), highlighting the need for enhanced monitoring methods. The interaction between measured canopy height and sand burial dynamics plays a crucial role in understanding vegetation growth, as sediment accumulation can counteract vertical plant development, influencing overall dune stability. Laboratory investigations confirmed that length and outer diameter of plant parts showed minimal seasonal variation, supporting simplified modeling approaches, but also underscored measurement challenges, e.g., due to plant structures with non-circular cross-sections. While stiffness (K_B) emerged as a more reliable parameter than Young's modulus (E), histological analyses emphasized the complexity of plant architecture and the limitations of assuming idealized cross-sectional geometries. Future research should focus on improving the representation of these structural intricacies to enhance biomechanical modeling accuracy."

Comment 1.20:

Conclusions: Can the conclusions highlight concrete guidance rather than a summary of the results? For example, how should models be adjusted to account for seasonal variation. Should managers collect data on plant parts in order to accurately model these dynamics?

Answer to Comment 1.20:

Thank you for pointing this out. We agree that the conclusions should provide more concrete guidance rather than just summarizing the results. To address this, we have revised the section to include specific recommendations on how models should account for seasonal biomechanical variations of marram grass. Additionally, we now outline targeted data collection strategies for field measurements, emphasizing the importance of capturing seasonal shifts in plant stiffness, density, and structural components to enhance model accuracy. Furthermore, we provide clearer insights into the application of our findings in dune management, suggesting how seasonal vegetation dynamics can inform restoration and stabilization efforts. While our study found no significant influence of wind exposure on plant biomechanics, we also acknowledge the need for future site-specific analyses in high-wind environments.

The updated section also maintains the summary table, which serves as a direct reference for implementing the biomechanical parameters (based on *Ammophila arenaria*) in dune modeling and field assessments.

[Line 612]

- "**Seasonal variations and model integration:** The biomechanical properties of marram grass vary seasonally, influencing its role in dune stability. To improve model accuracy, we recommend integrating seasonally adjusted stiffness and density values, as these factors influence sediment capture and dune resilience. Computational models should incorporate temporal shifts in biomechanical traits to reflect changing dune-vegetation interactions.
- **Targeted data collection:** Given the biomechanical differentiation between plant components, field measurements should focus on collecting data on plant structures with the highest seasonal variability, such as flower stems, sprout stiffness, and canopy density. Additionally, repeated seasonal surveys should be prioritized in future monitoring programs. These data will enhance model precision and allow for improved predictions of dune stabilization dynamics.
- **Refinement of wind interaction modeling**: Although our study found no consistent effect of wind exposure on plant biomechanics, future research should further investigate localized wind-vegetation interactions, particularly in environments with high wind variability. While wind exposure is not a key biomechanical driver in our findings, site-specific analyses may be necessary for broader applications.

- **Application to dune management strategies:** The findings reinforce the necessity of adaptive dune management, where seasonal vegetation changes inform conservation and stabilization efforts. Coastal managers should incorporate seasonal shifts in vegetation stiffness and density into dune conservation policies, ensuring that restoration projects align with natural growth cycles to maximize stability.”

Reviewer #2:

Comment 2.1:
This study addresses a relevant and timely subject: refined biomechanical parameterization of a common coastal sand dune plant. With increasing concern about climate change, sea-level rise, and the role of dunes in coastal hazard mitigation, there are growing calls for robust modelling of dune dynamics. As the authors note, this requires appropriate parameterization of vegetation. I really like the concept behind this study, and the selection of parameters to measure is robust and well-justified. However, the authors need to make it clear when they are referring to studies on salt marsh vegetation. These studies are heavily drawn upon to justify the research, but it requires familiarity with the literature to recognize that the authors are referring to different coastal environments with distinct physical processes. The transferability of findings from salt marsh systems to dune ecosystems is not always straightforward and should be explicitly discussed.

Answer to Comment 2.1:
Thank you for your thoughtful and constructive feedback. We appreciate your observation regarding the distinction between salt marsh and dune vegetation studies, as this is indeed an important aspect that required further clarification.

In response to your comment, we have revised both the introduction and discussion to make it explicitly clear when we are referring to findings from salt marsh ecosystems versus those from dune vegetation studies. For example, in the introduction, we now state:

> [Line 62] "~~Recent research in~~ Most vegetation modelling efforts in ~~for~~ NbS ~~in~~ for coastal protection ha~~s~~ve focused on salt marsh vegetation, aiming to improv~~eing~~ the representation of plant physiology, morphology, and hydrology (Liu et al., 2021; Keimer et al., 2024)."

Similarly, in the discussion, we have added explicit differentiation when drawing comparisons between our findings and existing research on salt marsh vegetation. For instance:

> [Line 421] "~~Overall, our findings support the literature~~ Similar to findings on salt marsh vegetation, our results show that during ~~the~~ summer, vegetation density significantly increases, while in ~~the~~ winter, the stiffness of the vegetation is greater and the outer diameter smaller (Koch et al., 2009; Vuik et al., 2017; Foster-Martinez et al., 2018; Keimer et al., 2024; Li et al., 2024)."

For a full overview of these revisions in the introduction and discussion, please refer to Answer to Comment 1.1: and Answer to Comment 1.18:. These changes ensure a clearer differentiation between coastal environments with distinct physical processes and improve the precision of our argumentation. We sincerely appreciate your keen attention to this detail, as it has helped us enhance the clarity and scientific rigor of our manuscript.

Comment 2.2:
Overall, I found the situating of this study within the broader aeolian dune literature to be a weakness. One specific issue was the classification of the two sampling sites as "fixed" and "dynamic." While this might be accurate for the broader landscape in which they were sampled, the biomechanical parameters of the plants themselves will reflect local patterns of sediment deposition and wind exposure. Dynamic dunes can contain areas with low sediment accumulation, while parts of fixed dunes (e.g., the crest of foredunes) can

experience relatively high deposition. It is unclear from the site descriptions or the provided photos whether the sampling locations differ substantially in sediment deposition/erosion regimes. This is important because sand deposition is a strong determinant of marram vigour. Consequently, the conclusion that biomechanical properties of marram are broadly transferable between fixed and dynamic dunes seems somewhat overstated. Greater consideration of the relationship between sand deposition and above-ground plant properties in dune environments, as well as aeolian processes, is needed.

Answer to Comment 2.2:

The authors extend their gratitude for pointing out this weak link in the study at hand. The two sampled dune sites differ in geographic exposure given their location on the island and orientation towards the North Sea and its impeding wave and wind energy with predominant North-West character. The authors agree that the sampling sites were not sufficiently described regarding their net sediment changes in time. Accordingly, available DEM data was acquired for the region and evaluated for the two sites from 2019 – 2023. Deposition and erosion volumes and patterns were calculated to underscore the dynamic character of the Cusp Dune site and relatively stable character of the Dune Ridge site.

To address this point, text modifications were made in Section 2.1 'Study Area' (line 183), Section 2.2 'Field data collection' (line 200), and throughout Section 4 'Discussion' to better contextualize the site characteristics and their sediment dynamics. Additionally, further details related to this topic are discussed in Answer to Comment 2.3:, where we provide additional context and explanations.

> [Line 183] "Approximately 800m north of the Dune Ridge, significant sand nourishments are periodically required to maintain the beach-dune system, with the most recent effort involving 80,000 m³ of sand in 2023 (NLWKN, 2023). The reoccurring maintenance nourishments to the north make this site relatively stable in terms of migration. In contrast, the Cusp Dune is part of a more dynamic system, situated at the edge of the *Ostplate*, which is characterized by wide beaches, young morphological changes, and is influenced by the west-to-east sediment drift typical for the North Frisian islands. Being a freestanding dune, the Cusp Dune is surrounded by water during storm surges and thus exposed to both erosion and accretion processes ~~from all directions~~. Erosion taking place mainly along the luv side facing the North Sea and sedimentation along its flanks along the blow outs."

> [Line 200] "Detailed measurements of environmental parameters, including soil temperatures via soil sensors at both dune sites (see Figures 2 and 3), air temperature and precipitation, as well as wind forces, were collected. Furthermore, digital elevation models were evaluated."

> [Line 437] "For sprouts, significant seasonal variations were observed in both stiffness and Young's modulus, with higher values in winter compared to summer. Furthermore, higher Young's modulus values were found for the exposed North-Western tip of the Cusp Dune site, coinciding with the area showing the larges erosion of the site (see Figure C2a in the Appendix). Interestingly for the Dune Ridge site, larger Young's modulus values were measured along the sheltered lee side, showing accretion in the DEM analysis (see Figure C2a in the Appendix), compared to the exposed luv side. The sprout length measurements can be compared to the stem heights up to 195mm reported by Feagin et al. (2019), highlighting the importance of precise definitions of plant parts in such studies. However, longer sprouts were measured for the exposed North-West tip of the Cusp Dune site, prone to erosion, compared to the South-West sector, which shows accretion. This might well coincide with morphological changes identified in the DEMs, meaning the erosion uncovers the sprouts at the northern edge, while the identified sedimentation buries them at the southern end (compare Figure C1a in the Appendix)."

[Line 452] "Conversely, the outer diameter of green leaves was larger in summer, which aligns with the findings of Vuik et al. (2017). Larger green leaf diameters were found along the sheltered lee side of the Ridge Dune site, whilst longer green leaves were identified at the sheltered South-West area of the Cusp Dune site. These findings indicate, that the plants develop larger phenological above ground canopy in wind sheltered areas compared to the exposed luv-oriented zones."

[Line 500] "Significant differences in stiffness and Young's modulus between windward and leeward sides suggest these parameters are most sensitive to wind exposure and likewise to coupled aeolian sediment transport (see Figure C1a and C2a in the Appendix)."

[Line 518] "In contrast, the Dune Ridge, as part of the fixed dunes, remains more stable (Isermann and Cordes, 1997; Pollmann et al., 2018). The distinction into dynamic and stable systems is also supported by the DEM analysis showing a clear migration for the Cusp Dune and a more stable situation for the Dune Ridge (see also Sect. C2 Morphology in the Appendix)."

Comment 2.3:

I also found the seasonal characterization of summer accretion and winter erosion to be overly simplistic. It needs to be made clear that you refer specifically to wave erosion, not aeolian erosion. Not all coastal systems exhibit strong seasonal patterns, and further, the link between above-ground biomechanical properties and wave erosion is not explicit. I can see how a focus on regrowth following scarping may have local effects on the most seaward plants, or how frequent overwash could alter above-ground properties, but it is not clear how this applies to the two study sites. Moreover, if the authors are attempting to link seasonal differences in abiotic disturbance regimes to seasonal biomechanical properties, then they need to explicitly describe the conditions at their study sites over the duration of the study. If winter erosion did not occur during the sampling period, then no conclusions can be drawn about seasonal erosion/accretion cycles and their effects on biomechanical properties. I recommend focusing this section more directly on seasonal growth patterns rather than attempting to link them to broad seasonal erosion trends.

Answer to Comment 2.3:

The authors thank the reviewer for pointing out the insufficient clarity regarding the seasonal classification character regarding the biomechanical properties of the marram grass surveyed on the two dune sites within the respective study. The authors primarily set out to first and foremost survey the two dune field sites on a monthly basis to acquire detailed vegetation related field data. This data was analysed for changes in biomechanical properties to investigate potential seasonality regardless of storm induced erosion patterns or aeolian accretion and dune built-up. During 2022, the field sites were exposed to five storm surge events all reaching 1.5 m above mean tidal high water, flooding the beach and reaching the dune toes located approximately at 1.7 m above mean tidal water level. In case of the Cusp Dune the two blowouts lining it were flooded with over 1m over storm surge water level.

Aeolian transport calculations based on van Rijn und Strypsteen (2020) for the Cusp Dune using federal wind speed and direction data from the German Weather Service station on Spiekeroog yielded an annual transport potential for both field sites taking into consideration the local sediment grain size, angle of attack of the wind, lag function for precipitation and area of the dune.

The Appendix has been updated with additional content in Section C 'Environmental parameters' (line 645) and the newly added Section C1 'Morphology' (line 663):

[Line 645] "Morphologic changes for the two field sites have been assessed based on DEM model data for the areas sourced from the NLWKN (2024) for the years 2019 and 2022. Deriving a difference map for the two DEMs yields vertical elevation changes between those two surveys, for the two field sites, Dune Ridge and Cusp Dune. Furthermore, ~~E~~environmental parameters included ~~soil temperature measurements taken at a depth of 20□30 cm using Soil Analysis Sensors (Digital) by Scanntronik Mugrauer GmbH. The measurement range for the temperature was -30 °C to +80 °C, with an average resolution of 0.1 °C and an accuracy of +/-1 °C. The positions of these sensors are marked in Figures 2a and 3a. Soil temperature was recorded at 10-minute intervals with a Thermofox Universal data logger by Scanntronik Mugrauer GmbH, using Softfox (version 3.05) for setup. These recordings were first averaged over 60-minute periods to calculate hourly temperatures. For analysis purposes, the hourly temperatures were subsequently categorized into daytime and nighttime temperatures. Daytime temperatures were defined as those recorded between 06:00 and 17:59, while nighttime temperatures were defined as those recorded between 18:00 and 05:59. This separation of data allowed for a detailed examination of diurnal temperature variations and their potential impact on dune vegetation. Due to a sensor failure at the Cusp Dune, there was a significant data loss from May 2nd to July 13th, likely affecting the recorded temperatures in May, June, and July. In addition to the soil sensor data,~~ weather data that were used to further describe the environmental conditions at study sites. The weather data included wind measurements at 10m height, air temperature, and precipitation for the years 2017-2022, with a particular focus on wind data due to its presumed relevance to the biomechanical properties of the vegetation and its influence on accretion processes. Wind data were obtained from a weather station operated by the Deutscher Wetterdienst (DWD), located at 53.7674°N, 7.6721°E on Spiekeroog. Air temperature and precipitation data were sourced from another weather station operated by the Institute for Chemistry and Biology of the Marine Environment (ICBM) of the University of Oldenburg, located nearby at 53.7762°N, 7.6880°E. Notably, all measurements were recorded at 10-minute intervals. Temperature and precipitation data was subsequently averaged to monthly mean values. In addition to the weather data, soil temperature measurements were taken at a depth of 20-30 cm using Soil Analysis Sensors (Digital) by Scanntronik Mugrauer GmbH. The measurement range for the temperature was -30 °C to +80 °C, with an average resolution of 0.1 °C and an accuracy of +/-1 °C. The positions of these sensors are marked in Figures 2a and 3a. Soil temperature was recorded at 10-minute intervals with a Thermofox Universal data logger by Scanntronik Mugrauer GmbH, using Softfox (version 3.05) for setup. These recordings were first averaged over 60-minute periods to calculate hourly temperatures. For analysis purposes, the hourly temperatures were subsequently categorized into daytime and nighttime temperatures. Daytime temperatures were defined as those recorded between 06:00 and 17:59, while nighttime temperatures were defined as those recorded between 18:00 and 05:59. This separation of data allowed for a detailed examination of diurnal temperature variations and their potential impact on dune vegetation. Due to a sensor failure at the Cusp Dune, there was a significant data loss from May 2nd to July 13th, likely affecting the recorded temperatures in May, June, and July."

[Line 663] "**C1 Morphology**

For the Cusp Dune situated at the northern beach of the island a clear southward migration can be identified based on the compiled sedimentation erosion maps. The northern part of the dune along the luv or seaward side being the most exposed part, is eroded up to -2.85 m within three years becoming level with the beach north of it. The former dune toe zone has migrated 28 m inland between 2019 and 2022. The central and southern part of the Cusp Dune shows significant vertical accretion with an average of +1.45 m over three years. Apart from the dune itself, the beach north of it shows erosion of an average -0.4 m during this period. Meanwhile, the blow outs left and right of the Cusp Dune show accretion of 0.5 m along the western blowout and 0.6 m on average along the eastern blowout. This overall pattern clearly mimics the impact of the predominant north-western angle of wave and wind attack, eroding the northern beach and exposed dune slopes, while accumulating sediments within the more sheltered blow out sections and on the lee ward side of the dune ridges.

In addition to the sedimentation-erosion maps, aeolian transport volume for the field site has been calculated and is compiled in Fig. C1b with monthly intervals. The calculation is based on the revised transport formulae found in (van Rijn and Strypsteen, 2020). Wind speed and direction have been sourced from the weather station 6091 No. operated by the German Weather Service (DWD), located at 53.7674°N, 7.6721°E on Spiekeroog. Transport volumes are calculated with the formulae and consider wind angle of attack in relation to the dune location, exposure and area. For the Cusp Dune a total of 1606 m^3 was calculated, which equates to 0.3m elevation increase per year on average, well corresponding to the DEM values.

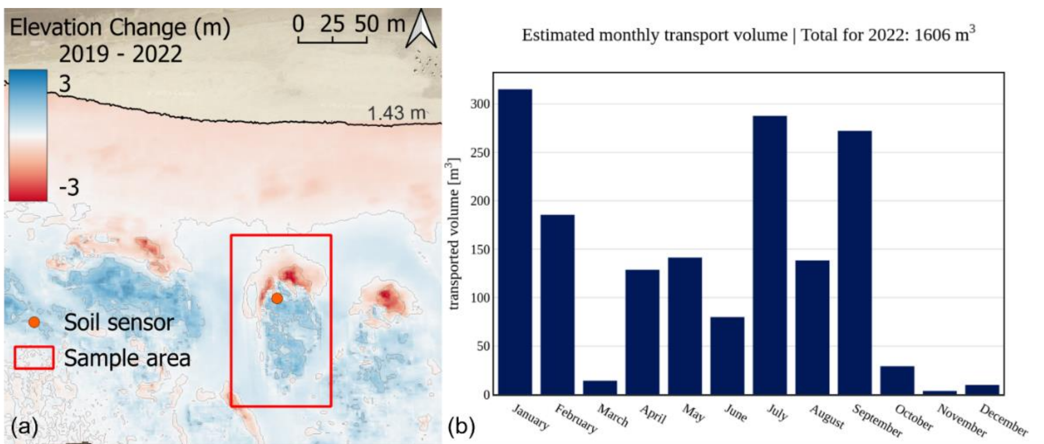


Figure C1: Morphological changes 2019-2022 for the cusp dune (a) based on DEM data with a 1m x 1m raster resolution provided by the Lower Saxony Water Management, Coastal and Nature Protection Agency (NLWKN). Aeolian transport volume calculation for 2022 based on wind speed and direction data been sourced from the German Weather Service (DWD) station on Spiekeroog situated between the two field sites.

In comparison, the southern Dune Ridge is relatively stable over multiple years, which is expressed in a gradual vertical increase of 0.3-0.7 m along the ridge line and larger depositions on the lee side with up to 1.4 m (see Figure C2a). Maximum erosion occurs near the luv side dune toe area ranging between -0.4 m and -1.2 m. The beach in front of the dune shows gradual vertical increase with an average 0.24 m over three years.

The aeolian transport volume calculated the same way for the dune ridge yields a total sedimentation volume of 2225 m^3 per year, which corresponds to a vertical increase of 0.6 m. This value is higher than for the cusp dune site but still within the DEM range for the period. From the map in Figure C2a the blow out is clearly visible in the middle of the dune ridge sampling area, which exhibits strong erosion, while the surrounding crest and land ward side of the dune experience sedimentation, corroborating the average net sedimentation value.

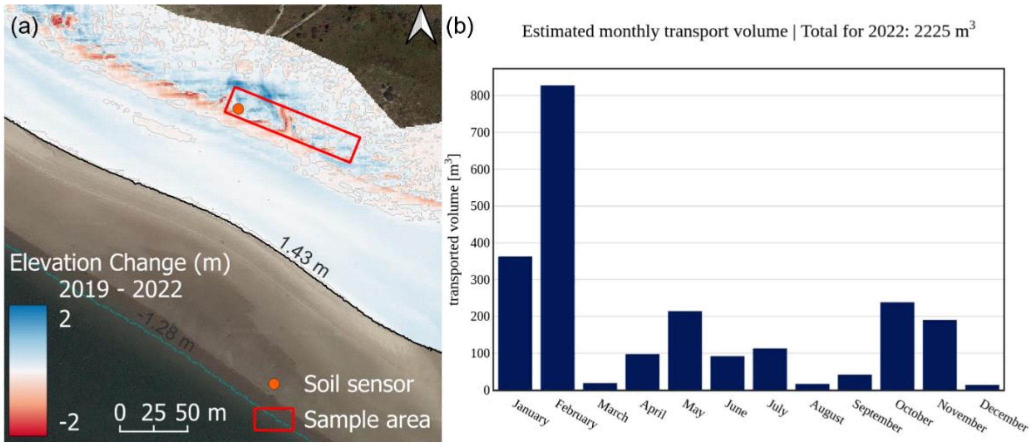


Figure C2: Morphological changes 2019 - 2022 for the ridge dune (a) based on DEM data with a 1 m x 1 m raster resolution provided by the Lower Saxony Water Management, Coastal and Nature Protection Agency (NLWKN). Aeolian transport volume calculation for 2022 based on wind speed and direction data sourced from the German Weather Service (DWD) station on Spiekeroog situated between the two field sites.

Both field sites were exposed to five storm surge events during 2022 of which all five reached the dune toe areas and induced erosion (Federal Maritime and Hydrographic Agency, 2025)."

Comment 2.4:

The results are presented as many pairwise comparisons in boxplots. As a minor comment, I found these somewhat difficult to follow. The authors should consider how to consolidate some figures and emphasize the results that show significant differences. The appendices contain several results, and it should be reconsidered whether these should be included in the main text.

Answer to Comment 2.4:

Thank you for this helpful suggestion. To improve clarity and comparability, we have consolidated several figures, reduced the total number while emphasized key results. Specifically:

- Figure 8 now combines the previous Figures 8 and 9.
- Figure 9 combines Figures 10 and 11.
- Figure 10 merges Figures 12, 13, and 14.

This restructuring enhances readability and highlights significant differences more effectively. For details, please refer to Answer to Comment 1.16:. Regarding the appendix, we have opted to keep certain results there rather than integrating them into the main text. This decision helps maintain clarity in the core manuscript while ensuring that additional context remains accessible without overloading the primary discussion. We appreciate your attention to improving the presentation and organization of our findings.

Comment 2.5:

Additionally, the manuscript lacks justification for the selection of the Mann-Whitney test over other statistical approaches. This is critical for interpreting the significance of the findings. Furthermore, the full results of the Mann-Whitney test need to be provided. The appendices currently include only p-values, which are insufficient for assessing the practical significance of the tests.

Answer to Comment 2.5:
Thank you for your helpful comment. We have revised the manuscript to provide a clear rationale for choosing the Mann-Whitney test over other statistical methods. Specifically, we selected this test because it is a non-parametric alternative to the independent t-test, which does not assume normality of the data. As our data did not meet the assumption of normality, the Mann-Whitney test was considered the most appropriate choice for assessing differences between groups. Additionally, we have updated the tables in the appendix to include sample sizes alongside the p-values, addressing the concern regarding the practical significance of the statistical tests.

The following changes were made in the text starting at line 290:

> [Line 290] "For the comparison between dune sites, the data for each site were aggregated across all months and zones. Given that our data were not normally distributed, the nonparametric Mann-Whitney test was employed to assess the significance of observed differences among our samples. The Mann-Whitney statistics tests for differences between two groups on a single, ordinal variable without assuming a specific distribution of the data (Bauer, 1972)."

Comment 2.6:
Overall, while I have no particular issues with the sampling strategy or characterization of biophysical properties, I find that the significance of the findings and their broader application is overstated. My concerns fall into two main areas:

1) The study's perspective on marram behavior, and dune system dynamics in general, is quite Eurocentric. White and grey dunes need to be clearly defined, as these terms are not widely used outside of Europe—no equivalent grey dune classification exists in New Zealand, for example. Based on my experience with marram and its congeners, seasonal growth patterns vary considerably between arid environments (such as Australia), temperate regions (such as New Zealand), and areas with cold winters (such as the Great Lakes). Therefore, the absolute biomechanical values provided at the end of the manuscript as potential modelling inputs may not be representative of environments beyond the study area.

2) Despite statistically significant differences in several measured parameters, the magnitude of these differences is small. Examination of the boxplots shows substantial overlap in the range of measured values, and the reported differences in means or medians (it is unclear which are used in the text) are relatively minor. Given that the study is framed as addressing a need for improved vegetation proxies in aeolian modelling, it is unclear whether these differences are meaningful in a practical sense. Does an average canopy height difference of 6 cm between summer and winter significantly impact aeolian processes? The authors do not explore this question. The paper would benefit greatly from either testing the importance of these differences within an aeolian model or at least conceptually discussing what constitutes a meaningful variation for modelling purposes. As it stands, the study can only conclude that significant differences exist in some variables, and models should take these into account—but without further analysis, it cannot definitively state the practical implications of these differences.

Answer to Comment 2.6:
Thank you for your thoughtful feedback. We appreciate your concerns regarding the broader application of our findings and have carefully revised the manuscript to address these points.

1) We fully agree that the study's focus is on European coastal dunes, and we have reviewed the text to ensure that this is more explicitly stated (see also Answer to Comment 1.7:). In particular, we have added a dedicated section in the discussion (see also Answer to Comment 1.1:):

> [Line 527] "**4.5 General relevance for foredune vegetation**
>
> Marram grass is widely distributed across European sandy coastlines, making our findings highly representative for a broad range of coastal environments. Additionally, closely related species such as *Ammophila breviligulata* in North America share similar ecological functions. Foredunes, which form the first line of defense against coastal erosion, host a variety of grass species worldwide, many of which exhibit comparable biomechanical adaptations to stabilize sediments and withstand environmental forces. Our study provides a valuable framework for understanding the biomechanical differentiation among plant components and their seasonal variations. The observed shifts in stiffness, canopy density, and seasonal growth dynamics are likely key factors for dune stability in other dune grass species as well, underlining the importance of plant trait-based approaches in coastal protection research."

Additionally, we have clarified in another section of the discussion (see also Answer to Comment 1.18:):

> [Line 62] "The absence of ~~a~~ clear biomechanical trend~~s in these properties is beneficial for transferability~~ across dune types supports the robustness of marram grass in European coastal dune systems, indicating its broad applicability within these environments~~., as it suggests that the same vegetation type (marram grass) exhibits robust biomechanical properties across different dune types.~~"

2) We acknowledge the importance of discussing how the observed differences in biomechanical parameters relate to their significance in dune modeling. While we demonstrate statistically significant differences in several traits, we have carefully adjusted the discussion to emphasize their relevance for modeling purposes**,** particularly in relation to sediment stabilization and plant contributions to dune accretion processes.

For example, we have refined the discussion as follows (see also Answer to Comment 1.18: and Answer to Comment 1.20:):

> [Line 443] "For stems, specifically flower stems, the summer-only presence highlights their importance for models representing the summer state. Their significant contribution to overall plant density, ~~length~~ height, and ~~high~~ stiffness make them critical components in summer models where their structural contribution to ~~dune dynamics~~ accretion processes is essential. ~~Since flower stems are only present in summer, these characteristics must be integrated into seasonal models but can be omitted in winter representations.~~"

We also recognize that directly implementing these findings in an aeolian model would be a valuable next step but was beyond the scope of this study. To reflect this, we have included a recommendation in the Future Research section:

> [Line 583] "While this study provides detailed biomechanical insights into marram grass across seasons and dune environments, future research could integrate these findings into aeolian models to assess their practical impact on sediment transport and dune stability. Investigating how variations in plant stiffness, density, and height influence aeolian processes would provide valuable guidance for refining vegetation parameterization in dune modeling frameworks."

Comment 2.7:

Presentation-wise, the manuscript is well-organized, with a logical flow from background to methods, results, and discussion. However, a large amount of information is placed in the appendix, and it should be reconsidered whether some of this should be integrated into the main text. The introduction is rather long and could be streamlined to focus more directly on the study's key contributions while maintaining necessary background context. Additionally, the discussion section should move beyond simply restating results to consider the practical implications for modelling. Specifically, the authors should address whether the observed differences will have a meaningful impact on model outputs. If so, what do the results suggest about the most important vegetation attributes—e.g., height, flexibility, or horizontal coverage?

Answer to Comment 2.7:

Thank you for your constructive feedback. We appreciate your suggestions on improving the manuscript's structure and clarity and have carefully considered each of these points. Regarding the appendix, as noted in Answer to Comment 2.4:, we have opted to keep certain results there rather than integrating them into the main text. This decision was made to maintain clarity and conciseness in the core manuscript while ensuring that additional contextual information remains accessible without overloading the primary discussion. The appendix primarily contains supplementary details that support, but do not centralize, the main findings. For the introduction, we have already undertaken a thorough revision to streamline its content, not only making it more concise but also emphasizing the key points more clearly. For details on these changes, please refer to Answer to Comment 1.2:, where we outline the restructuring process. Similarly, the discussion section has been revised to move beyond a simple restatement of results and instead focus on their implications for dune modeling and vegetation dynamics. Instead of repeating findings, we now provide a stronger interpretation of their relevance. Given the extensive nature of these revisions, we kindly refer to Answer to Comment 1.18:, Answer to Comment 1.20:, and Answer to Comment 2.6:, where we detail how we have ensured that the discussion highlights the practical significance of the observed biomechanical differences. We appreciate your attention to these structural and presentation aspects, as it has helped us refine the manuscript for improved clarity and impact.

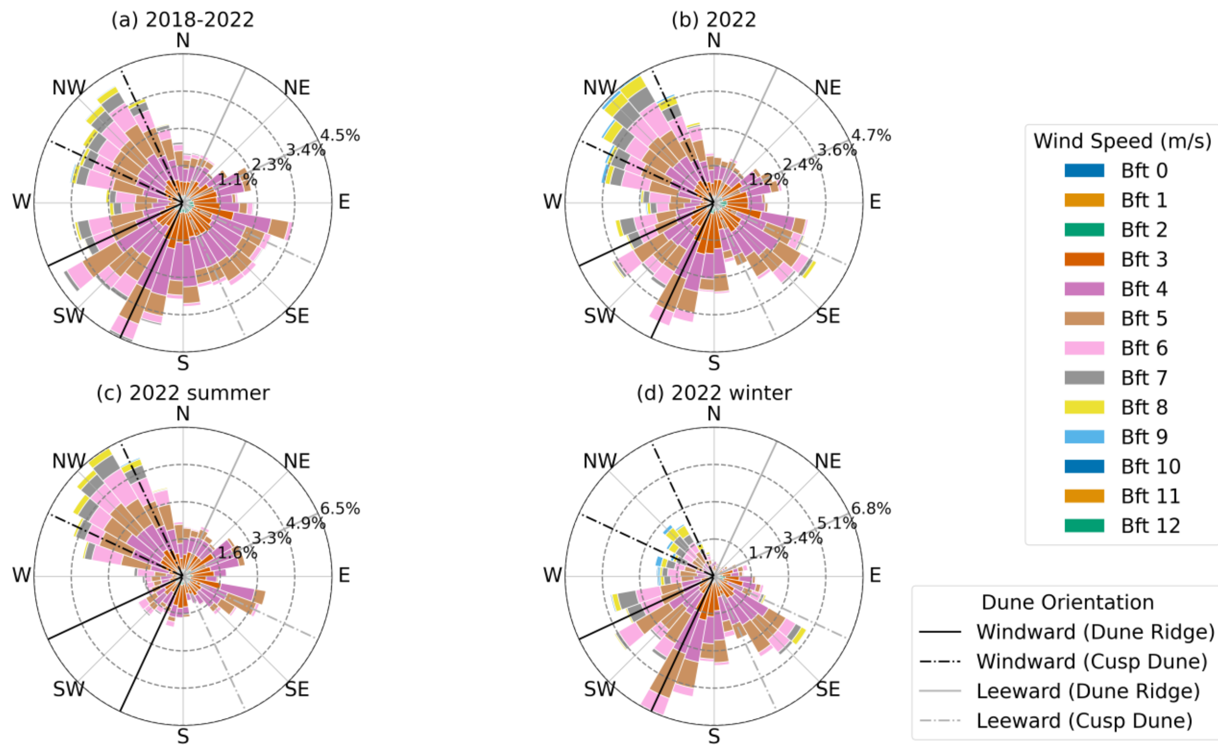
Comment 2.8:

Finally, the inclusion of soil data seems out of place. Since it is not linked to the main findings, I suggest removing it. Additionally, the wind data for the active site should be presented in terms of windward and leeward exposure, or another metric that conveys wind impact. Simply listing wind directions does not provide sufficient insight into exposure levels, making the significance of the results difficult to interpret.

Answer to Comment 2.8:

We acknowledge the reviewer's concern regarding the inclusion of soil data. While no direct links to the main findings are drawn, these data serve as contextual information to characterize the study year and site conditions, which may be relevant for future simulations or comparative studies. Therefore, they remain in the appendix. Regarding the wind data, we agree that the visualization should better reflect the manuscript's research focus.

Consequently, the figure has been revised to highlight windward and leeward exposures based on the assumption that the seaward side is generally more exposed to wind. For the Dune Ridge, SW was emphasized, and for the Cusp Dune, NW was highlighted, as these directions align perpendicularly with the delineation of windward and leeward sides at each site:



> "**Figure C~~1~~3.** Wind roses showing wind direction and frequency for various time periods (Deutscher Wetterdienst): (a) wind rose for 2018-2022, (b) wind rose for 2022, (c) wind rose for summer months of 2022 (April-September), (d) wind rose for winter months of 2022 (October-March). Windward (black) and leeward (light gray) directions are indicated for each dune site. Solid lines represent Dune Ridge, and dot-dashed lines represent Cusp Dune, highlighting the directions perpendicular to the wind-exposed and wind-sheltered dune sides."

Additionally, we will integrate key insights from the wind data into the main text (Section 4.3) to enhance the study's relevance:

> [Line 507] "Wind data from 2022 ~~indicate that strongs were~~ showed predominantly west-dominated winds, with the highest frequency from the northwest during summer, while in winter, southwest winds were more prevalent, though the strongest winds (≥ Bft 6) predominantly originated from northwest (see also Sect. C1 in the Appendix)."

Comment 2.9:

Overall, this study presents useful data on dune vegetation biomechanics with clear relevance for coastal modelling. Its main contribution lies in providing a framework to decompose the different components of plant structure that influence sedimentation and in highlighting the need to consider population-level variation. It takes an important step toward identifying which biomechanical traits matter most, but the discussion does not provide sufficient generalization beyond the two studied populations. Additionally, the study must better address the practical significance of the identified statistical differences in terms of sediment capture and aeolian processes.

Answer to Comment 2.9:

Thank you for your thoughtful comment and for highlighting these important aspects. We agree that the broader applicability of our findings and the practical significance of statistical differences are key considerations. We have aimed to clarify these points in our revisions. For the generalization of our results beyond the studied populations, we refer to Answer to Comment 2.6: and Answer to Comment 1.1:. The discussion on the practical relevance of the observed differences in relation to sediment capture and aeolian processes has been further refined in Answer to Comment 2.6: and Answer to Comment 1.18:. We appreciate your input and hope that these clarifications strengthen the manuscript.

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