nature portfolio

Peer Review File

Marsh restoration in front of seawalls is an economically-justified nature-based solution for coastal protection

Corresponding Author: Mr Ernie I. H. Lee

Attachments originally supplied by the reviewers can be found at the end of this file, in order by reviewer number and revision.

Version 0:

Decision Letter:

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

Dear Mr Lee,

First of all, please allow me to apologise for the delay in sending a decision on your manuscript title "Wave attenuation and economic benefit of marsh-fronted seawall for nature-based coastal protection". It has now been seen by 3 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised quite substantial concerns that must be addressed. In light of these comments, we cannot accept the manuscript for publication, but would be interested in considering a revised version that fully addresses these serious concerns.

We hope you will find the reviewers' comments useful as you decide how to proceed. Should additional work allow you to address these criticisms, we would be happy to look at a substantially revised manuscript.

In particular, for publication in Communications Earth & Environment we request that you:

*** Provide novel and fully supported insight into the cost-effectiveness of marsh-fronted seawalls in the US
*** Explore sensitivity of your estimated Benefit-Cost ratios to different conditions, such as different magnitudes of storm surges and inter-seasonal variability.

If you choose to take up this option, please either highlight all changes in the manuscript text file, or provide a list of the changes to the manuscript with your responses to the reviewers.

Please bear in mind that we will be reluctant to approach the reviewers again in the absence of substantial revisions.

If the revision process takes significantly longer than three months, we will be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We are committed to providing a fair and constructive peer-review process. Please do not hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the reviewers' comments with a list of your changes to the manuscript text (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and any completed checklist:

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Please do not hesitate to contact us if you have any questions or would like to discuss the required revisions further. Thank you for the opportunity to review your work.

Best regards,

Martina Grecequet, PhD
Associate Editor,
Communications Earth & Environment
@CommsEarth

EDITORIAL POLICIES AND FORMAT

If you decide to resubmit your paper, please ensure that your manuscript complies with our editorial policies and complete and upload the checklist below as a Related Manuscript file type with the revised article:

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• Life sciences
An updated and completed version of our Reporting Summary must be uploaded with the revised manuscript
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For your information, you can find some guidance regarding format requirements summarized on the following checklist: (https://www.nature.com/documents/commsj-phys-style-formatting-checklist-article.pdf) and formatting guide (https://www.nature.com/documents/commsj-phys-style-formatting-guide-accept.pdf).

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

This manuscript presents a new approach for determining wave dissipation by marsh plants that accounts for vegetation characteristics within a one-dimensional wave model. A benefit-cost analysis tool that accounts for avoided seawall heightening, marsh environmental services, and marsh creation and maintenance costs is used to determine the economic benefit of a marsh-fronted seawall. The primary finding is that marsh-fronted seawalls can be cost effective, but the discount rate used can affect a project's eligibility for federal funding. Overall, the manuscript is well-written, clearly organized, and addresses a topic of current interest to academics and practitioners working on designing and implementing nature-based and hybrid shoreline infrastructure. The use of vegetation-specific characteristics can provide a more refined and location-specific understanding of wave reduction for marsh systems and is an advantage over current approaches. However, there are a few gaps in the presentation of the results and the discussion that should be addressed before recommending the article for publication.

Major comments:
• The abstract includes very little information on the results of the study. I suggest expanding on the results to provide better clarity about the level of benefits provided and how benefits vary based on different factors (e.g., discount rate, vegetation species, etc.).
• The manuscript presents modeling results based on a number of assumed parameter values. While there is some comparison of results across feasible ranges for certain model parameters, such as for the benefits and costs, others are explored in less detail (e.g., water depth) or not at all (e.g., the parameters given in Figure 1b). The paper would benefit from a more complete sensitivity analysis that explores how changes in the choice of model parameter values influence the reported BCAs.
• The manuscript mentions that vegetation characteristics such as structural stiffness, plant morphology, and stem density vary across seasons and can affect wave attenuation. However, the likely variability across seasons was not considered in the analysis. Were the values used for a specific season? How would the results be affected considering the inter-seasonal variability?
• The effect of vegetation type on the BCA should be presented in the Results section. Currently, Figures 4e and f are only mentioned in the Discussion section. In addition, I suggest including the results for Phragmites australis since its wave reduction performance is different from Spartina alterniflora.
• The BCA calculation uses a 100-year evaluation period, during which the marsh would presumably be exposed to consistent hydrodynamic conditions and experience no shift in vegetation. However, this is unlikely to be the case in many areas due to sea level rise. There is currently no consideration of how sea level rise or other climate-change related impacts would affect the resilience of the marsh and the subsequent economic evaluation of the marsh-fronted seawall. I understand that a full analysis might be beyond the scope of the current manuscript, but the potential impacts on the findings and the implications for project evaluation should be discussed.

Minor comments:
• Line 269 and Line 511: “Disadvantage communities” should be “disadvantaged communities.”
• Line 206-210: The text switches between two citation formats. Please be consistent.
• Line 233-234: Is this true for all vegetation types?
• Line 243-244: I am not sure if this statement is accurate. It appears to me that the BCR values are higher for the USACE discount rate for Figures 4c and 4d.
• Line 193: Why was a water depth of 3m chosen? Please provide justification.

Reviewer #2 (Remarks to the Author):

Please see the attached document

Reviewer #3 (Remarks to the Author):

This paper analyzes the merit of marsh-fronted seawalls as a coastal protection measure relative to seawalls alone, utilizing a new model of wave attenuation by marsh plants and a benefit-cost analysis. The paper concludes that marsh-fronted seawalls are "a feasible, cost-effective, and nature-based" alternative to traditional hard-structure-only seawalls. The topic is certainly very important; the analysis has been carefully carried out; and the conclusion of the paper is mostly convincing. I do have several questions and comments that, hopefully, will help the paper become stronger.

(1) I find the design of the benefit-cost analysis to be rather unconventional; the discussion of the benefit-cost analysis needs to be modified, in my opinion. The authors calculate benefit and cost of marsh-fronted seawalls *** relative to *** traditional seawalls. In conventional benefit-cost analyses of coastal protection (see, for example, D. Min, D. Kim & K. Cho, "Cost-benefit analysis of seawalls in South Korea: A bottom-up assessment," Coastal Management, 2016 and references included there), benefit and cost of a protection measure is calculated relative to the case of no protection.

Following the authors' calculation, a benefit-cost ratio exceeding 1.0 does not mean that marsh-fronted seawalls can be justified economically. It only means that marsh-fronted seawalls are better than traditional seawalls. In the discussion section (and also in the methodology section), the authors mention the benefit-cost-ratio thresholds of 1.0 and 2.5 that the U.S. government agencies use. I do not believe that the benefit-cost ratios that the authors have calculated can be compared to these thresholds. These thresholds are meant to be applied to the ratio of total benefit to total cost, not to the ratio of incremental benefit to incremental cost. Thus, the authors need to modify their discussion of what could be said from their benefit-cost ratios.

The usefulness of the benefit-cost ratios reported in Figure 4 is limited for practitioners evaluating alternative coastal protection measures unless they know the benefit and cost of traditional seawalls as well.

(2) Figure 4 seems to show that benefit-cost ratios are higher when discount rates are lower. But the text following Figure 4 seems to say the opposite.

The following text seems not correct: "The value of environmental services … occur in the future time. Therefore, lower BCR values are present in low and medium estimates at USACE 2.25% discount rate than at federal 7% discount rate." If benefit occurs later, BCR values must be higher, not lower, with a lower discount rate.

Also, it is unclear whether the authors are saying the benefits of marsh-fronted seawalls occur earlier or later compared to traditional seawalls.

(3) Benefit-cost ratios reported in Figure 4 are based on a specific set of assumptions. So some discussion of where these numbers can be applied would be useful. Are they applicable to highly nonlinear coastlines as well as near-straight coastlines? Are they applicable to urban coastlines as well as rural coastlines?

More discussion of how to interpret high vs. low estimates in Figure 4 would be useful. Do they mostly reflect urban vs rural differences?

(4) Figure 2 (a) seems to be the main evidence showing the validity of the wave attenuation model. Given this figure is based on two specific sites, I wonder whether the data are used for model calibration as well as validation. That is, have certain features of the model been selected to achieve greater fit? Some discussion on this may be useful.

Also, does each dot in Figure 2(a) represent a specific sensor located at a specific location? Or an observation for a specific period?

(5) In my opinion, choosing a specific site and showing how to apply the analysis of this paper to that site would be very useful. In fact, most of my questions/comments can be addressed via such an example.

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Author Rebuttal letter: The author's response to these comments can be found at the end of this file.

Version 1:

Decision Letter:

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

Dear Mr Lee,

Your manuscript titled "Wave attenuation and economic benefit of marsh-fronted seawall for nature-based coastal protection" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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Please review our specific editorial comments and requests regarding your manuscript in the attached "Editorial Requests Table".

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Please outline your response to each request in the right hand column. Please upload the completed table with your manuscript files as a Related Manuscript file.

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Martina Grecequet, PhD
Associate Editor,
Communications Earth & Environment
@CommsEarth

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

I appreciate the authors' thorough response to the reviews, and I feel that the manuscript has been significantly improved. There are several minor comments that should still be addressed:

-In Lines 254-256, the authors' state "Again, because wave energy loss is proportional to wave height squared, the reduction in wave height is greater for larger waves, resulting in higher BCR for larger storm conditions." However, in Figure 4d, it appears that the BCR is higher for lower water level and wave height combinations for smaller vegetation widths. Please clarify.

-The discussion of sea level rise that was added is still rather limited, only mentioning the impact on wave height at the toe of the seawall. I believe it would be helpful to include a sample calculation of the BCR with an estimated rate of sea level rise and vertical marsh accretion for the Juniper Cove case study to demonstrate how sea level rise could affect the economic feasibility of the marsh-fronted seawall. As an alternative, the discussion could be expanded to include information on the types of data or additional modeling that would be needed (e.g., vertical accretion rates, vegetation succession, sediment dynamics) to properly evaluate the BCR with sea level rise.

Reviewer #2 (Remarks to the Author):

I want to congratulate the authors because they have done an important effort to improve the mansucript. They have managed to provide solid answers to my three most important concerns, namely, targeting for a broader audience (not only in the US), assess the impacts of variations in the vegetation and hydrodynamic conditions and including a case study to show the applicability of this study.
Just a minor comment. I noticed that the new text added some times the authors mix the results and discussion, I highlight some examples that should be moved to the discuss section

Therefore, after these small reviews, I recommend the manuscript for publication.

Reviewer #4 (Remarks to the Author):

I am mostly happy with the revised manuscript, and I really appreciate the authors' detailed responses.

I have three minor comments regarding the authors' response to my previous comment (1).
- I still think what the authors do will be clearer (to readers like me) if they emphasize the fact that their BCA analysis is for coastlines with existing seawalls (i.e. not for coastlines with no seawalls at all).
- Cooper et al. 2016 do not consider adding an extra design to existing seawalls. As written in the very first page of that article, Cooper et al. are comparing building an earthern wall to not building any structure at all. So, I do not believe that Cooper et al. are a good reference for showing wide uses of the "incremental BCA."
- If the authors could indicate the relevant page numbers of the URS Group BCA reference guide, that could be useful to some readers. (I couldn't determine which part of that guide corresponds to the authors' statement about incremental BCA.)

benefits**

Author Rebuttal letter: The author's response to these comments can be found at the end of this file.

Review article: Wave attenuation and economic benefit of marsh-fronted seawall for nature-based coastal protection.

In this manuscript, the authors present a benefit-cost analysis (BCA) of a marsh-fronted seawall design. The benefit-cost analysis was constructed to compare whether placing a marsh in front of a seawall would be more economically beneficial than heightening the seawall to deliver the same overtopping rate. The analysis includes a sophisticated 1D numerical model to simulate wave energy propagation within a vegetation field. This model was validated against field measurements resulting in very good agreement with that data. Then, the model was used to analyze the sensitivity of the wave attenuation to plant species. In my opinion, the methodology presented here has great potential to assess if a marsh restoration project is economically viable or not. However, some issues need to be further developed and investigated.

While some of the findings of the paper can be helpful in other regions, the methods and the conceptualization of the manuscript are mainly devoted to American readers. Thus, the target audience is not global, but regional (one country). For readers outside of the US is difficult to understand some terms such as USACE, Federal, FEMA, etc. In the conclusions, the authors state: “The present study provides a quantitative example of how ecosystems services can be quantified within the framework required by federal funding.” It seems that the ONLY audience of this journal is from the US (other readers might think of other federal states such as Argentina, Australia, Belgium, Bosnia and Herzegovina, Brazil, Canada, Germany, India, Iraq, Malaysia, Mexico, Micronesia, Nepal, Nigeria, Pakistan, Russia, Switzerland, the United Arab Emirates, and the United States).

In the BCA a project lifetime of 100 years was considered. At this time, the sea level is expected to rise considerably (depending on the scenario), but the authors have not even mentioned that or discussed the impact of this in their analysis. An important handicap of the marsh-seawall design is that the migration length of the marsh to adapt to the SLR can be very limited. Thus, the marsh width could be reduced. It is still not very clear if the marsh elevation can maintain the same path of the sea level rise. Thus, this brings some uncertainty but the authors have completely neglected that.

The authors claim that the model can be used to assess the variation of coastal protection due to the vegetation seasonality. However, it is not then included in the BCA. They could have added another line in the Figure 4 plots representing dormant and healthy conditions. Previous authors have found that marshes provide more protection against hurricanes than winter storms in the Chesapeake Bay because of the growth cycle of the Spartina Alterniflora.

The authors claim that "A novel design tool was developed for decision makers to visualize the Benefit Cost-Ratio (BCR) over a range of marsh width (measured in the direction perpendicular to the seawall) and avoided seawall heightening, considering different discount rates." This is only partially true because the decision makers can only assess the data shown in Figure 4. With other oceanic conditions or plant characteristics, this figure is no longer valid. It would be more beneficial if a comprehensive scenario of oceanic and plant conditions were considered and then the results summarised in one/more figures. All the analysis is based on one oceanic condition based on a previous paper and based on that, the authors present some conclusions supported by the BCA. Nevertheless, the authors have not investigated more scenarios. For example, wave attenuation highly depends on the ratio of plant height and water depth. So what are the results under a scenario of a storm surge of 4 m (feasible for the US)? In my opinion, the input oceanic conditions of the model should be based on joint statistical analysis to obtain return periods associated with water levels and wave heights. Otherwise, the BCA is only valid for one condition.

In summary, I think that the paper as is now, is not suitable for publication in this journal. In my opinion, besides developing and presenting the tool, it would be more interesting to apply this tool to specific implementation sites in the US. This way, decision-makers can more easily follow the procedure to compute the BCA, contributing to its implementation nationwide.

<u>Minor comments</u>

Update reference 2.

L38. Ad reference

Update reference 9

L49. Replace do little by are not efficient.

L52. Add sandy beaches

L52-61:Missing important reference: Future of our coasts: The potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems

L67: add reference Field-based numerical model investigation of wave propagation across marshes in the Chesapeake Bay under storm conditions.

L 70. Add reference: Modelling wave attenuation by saltmarsh using satellite-derived vegetation properties and discuss it in this context.

L84. Please indicate the equation number of the Eurotop 2018.

L86. Please add this equation somewhere: The overtopping rate is also a function of freeboard, which is the distance between the 2% wave run-up height and the highest point of the seawall (Fig. 1).

L122. Area density means stem density? Please clarify.

Figure 2. Replace actual by measured. The change in the intensity in the green colors are hard to see. Why you didn't show the Bath site?

Ref: 49 is not very appropriate since in this work you are dealing with muddy sediment. I suggest either expanding this discussion or cut it. As it is, it seems weak.

L154: area density must be defined earlier on in the document.

L176: This statement "calibrated drag coefficients cannot be transferred to new sites" is not true as this is a common practice when data is not available.

L193: ht = 3 m? please clarify.

L201: the choice of discount rate (USACE 2.5% versus federal 7%). What is this?

Other references to include:

10.1016/j.oceaneng.2022.110974

10.1111/1365-2664.14413

Response to Reviewers:

Article title: Wave attenuation and economic benefit of marsh-fronted seawall for nature-based coastal protection.

Manuscript No.: COMMSENV-23-1938-T

We thank the three Reviewers for providing useful comments that have improved the strength and clarity of the paper. The comments are repeated here in black font, followed by a response in red font. Within the revised manuscript, the revised sections are shown in red font.

Reviewer #1:

This manuscript presents a new approach for determining wave dissipation by marsh plants that accounts for vegetation characteristics within a one-dimensional wave model. A benefit-cost analysis tool that accounts for avoided seawall heightening, marsh environmental services, and marsh creation and maintenance costs is used to determine the economic benefit of a marsh-fronted seawall. The primary finding is that marsh-fronted seawalls can be cost effective, but the discount rate used can affect a project's eligibility for federal funding. Overall, the manuscript is well-written, clearly organized, and addresses a topic of current interest to academics and practitioners working on designing and implementing nature-based and hybrid shoreline infrastructure. The use of vegetation-specific characteristics can provide a more refined and location-specific understanding of wave reduction for marsh systems and is an advantage over current approaches. However, there are a few gaps in the presentation of the results and the discussion that should be addressed before recommending the article for publication.

The authors thank Reviewer 1 for their positive comments on the writing style and topic relevance to academics and coastal protection practitioners. To strengthen the manuscript, a sensitivity analysis of the benefit-cost ratio (BCR) is now presented, facilitating a discussion of the sensitivity of BCR to different storm conditions (water depth and offshore wave height), vegetation characteristics, and choice of discount rate. As recommended by the reviewer, the BCR framework is applied to a real-world example at Juniper Cove to demonstrate its application and sensitivity to site specific hydrodynamic and vegetation conditions.

Major comments:

• The abstract includes very little information on the results of the study. I suggest expanding on the results to provide better clarity about the level of benefits provided and how benefits vary based on different factors (e.g., discount rate, vegetation species, etc.).

Thank you and we agree that the major results should be included in the abstract. Please find the edits in:

- Lines 23-24: “The wave attenuation varies by a factor of two across different vegetation species.”; and
- Line 27-29: “While sensitive to discount rate, many cases have benefit-cost ratios (BCR) greater than 1.0, indicating that marsh-fronted seawalls are economically-justified nature-based solution.”

• The manuscript presents modeling results based on a number of assumed parameter values. While there is some comparison of results across feasible ranges for certain model parameters, such as for the benefits and costs, others are explored in less detail (e.g., water depth) or not at all (e.g., the parameters given in Figure 1b). The paper would benefit from a more complete sensitivity analysis that explores how changes in the choice of model parameter values influence the reported BCAs.

This is an excellent suggestion, which has re-shaped the way we present the results. Please see the new Fig. 4, which presents a detailed sensitivity analysis on the BCA, including a range of marsh width, different storm conditions (water depth, offshore wave height), different vegetation species characteristics and their seasonality characteristics, and different economic discount rates applied. These changes were added in:

- Lines 215-294: Under *Results* subheading “Benefit-Cost Ratio for seawall fronted with marsh with Sensitivity Analysis”.
- Lines 217-220: “The benefit-cost ratio was estimated for the marsh-fronted seawall configuration (Fig. 1) with vegetation widths of 0 to 100 m. The base case was defined with offshore wave height $H_0 = 1.5$ m, water depth $h_t = 3$ m, plant species *Spartina alterniflora*, 50 years useful project life, and 2.5% discount rate, which is the rate given in the 2023 US Water Resource Development Act[77].”
- Lines 230-248: The first sensitivity considered three different water depths to examine the effects of plant submergence ratio to the wave attenuation performances (Fig. 4a, Fig. 4b, Fig. 4c).
- Lines 250-261: The second sensitivity varied both water depth and offshore wave height to compare 4 different storm conditions (Fig. 4d).
- Lines 263-270: The third sensitivity explored the impact of 4 different vegetation species and the seasonality effects of one particular species (Fig. 4e).
- Lines 272-284: The fourth sensitivity explore the choice of discount rate at 5 different levels ranging from 0% to 11% (Fig. 4f).

• The manuscript mentions that vegetation characteristics such as structural stiffness, plant morphology, and stem density vary across seasons and can affect wave attenuation. However, the likely variability across seasons was not considered in the analysis. Were the values used for a specific season? How would the results be affected considering the inter-seasonal variability?

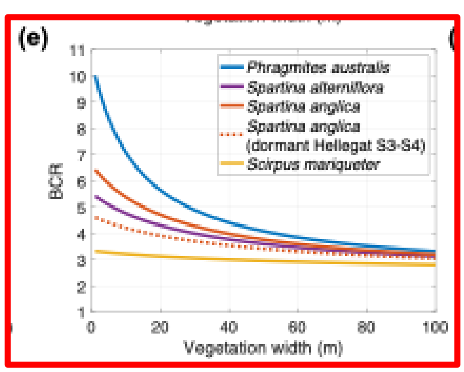
Yes, the seasonality is important, and we agree that this point should be clarified. The vegetation characteristic are shown in Table 3a, Table 3b, Table 4, and Table 9. Each table specifies the source of the values and the justifications in the notes below each table. Most of these values were adopted from Zhang et al., 2021, where a range of plant parameters were reported for each species. The mean values of each value range were used as representative values of the average plant condition, and the lowest values for number of leaves per stem and height were considered representative of winter (dormant) conditions. The choice for winter conditions was validated in the wave height comparison with data from Vuik et al., 2016, which is summarized in Fig. 2. Specifically, in Fig. 2a, the 1-D wave model uses lower bound plant parameters adopted from Zhang et al., 2021 and some reported plant characteristics in Vuik et al., 2016 to represent the winter field conditions described in Vuik et al., 2016. With this assumption, the model was able to match the measured winter wave heights reported in Vuik et al., 2016. Having this confirmation, we similarly used the lower bound reported values from Zhang et al., 2021 to represent the dormant plant conditions (dormant season) and the mean values were used to represent the healthy plant conditions (growing season). This allowed us to consider the inter-seasonal variability for both the site-specific case study (new Fig. 5e) and also for the hypothetical marsh-fronted seawall configuration in Fig. 4e (orange solid line vs dotted line). Both figures show that inter-seasonality variability of plant conditions influence BCR by roughly a factor of two.

The seasonality sensitivity analysis is now highlighted in the new Fig. 4 and Fig. 5 and associated text, and the summary comment is given here:

- Lines 269-270: “This demonstrated that the seasonality of plant conditions influenced the BCR by roughly a factor of two (Fig. 4e). However, both plant conditions achieved BCR above 1.0.”

• The effect of vegetation type on the BCA should be presented in the Results section. Currently, Figures 4e and f are only mentioned in the Discussion section. In addition, I suggest including the results for Phragmites australis since its wave reduction performance is different from Spartina alterniflora.

Thank you and we agree with the suggestion. In addition to Fig. 3, compares the wave attenuation abilities of different vegetation types, the effects of vegetation type on BCR is now also included in Fig. 4e in the *Results* section. The results for *Phragmites australis* is also included in Fig. 4e and copied below. The new text highlighting these points within the results can be found in lines 263 to 270.



- Lines 263-270: "The third sensitivity test explored the impact of vegetation species and seasonality (Fig. 4e). As shown in Fig. 3, the larger and more rigid *Phragmites australis* produces the greatest wave attenuation, which is reflected in the highest BCR (blue line and circle). Variation in plant characteristics over a growing season was explored by comparing the average reported stem height and number of leaves per stem for *Spartina anglica* (solid orange line) with the validated dormant plant parameters from Hellegat between locations S3 and S4 (dotted orange line)[51,67]. This demonstrated that the seasonality of plant conditions influenced the BCR by roughly a factor of two (Fig. 4e). However, both plant conditions achieved BCR above 1.0."

• The BCA calculation uses a 100-year evaluation period, during which the marsh would presumably be exposed to consistent hydrodynamic conditions and experience no shift in vegetation. However, this is unlikely to be the case in many areas due to sea level rise. There is currently no consideration of how sea level rise or other climate-change related impacts would affect the resilience of the marsh and the subsequent economic evaluation of the marsh-fronted seawall. I understand that a full analysis might be beyond the scope of the current manuscript, but the potential impacts on the findings and the implications for project evaluation should be discussed.

Thank you for pointing out the project evaluation period. The useful project life is now changed from 100 years to 50 years to stay in-line with common practices evaluating for coastal wetlands, which are also used in Federal Emergency Management Agency (FEMA) 2022. We agree that using a shorter period of 50 years would be appropriate in view of expected climate change impacts on future hydrodynamic conditions. This update is noted here:

- Lines 218-220: "The base case was defined with offshore wave height $H_0 = 1.5$ m, water depth $h_t = 3$ m, plant species *Spartina alterniflora*, 50 years useful project life, and 2.5% discount rate, which is the rate given in the 2023 US Water Resource Development Act[77]."

We have also expanded our consideration of how sea level rise impacts wave attenuation and BCR in lines 389-403. Although a complete analysis of sea level rise impacts on the BCR sensitivity is beyond the scope of the current manuscript, we have added an explicit analysis of BCR sensitivity to water depth and storm conditions in Fig. 4a. These can be interpreted from the sea level rise point of view. For example, in the discussion we have added the following:

- Lines 389-394: "Sea level rise would both increase the water depth and decrease the available marsh width due to coastal squeeze, where the seawall acts as a physical barrier that prevents the marshes from migrating inland as the intertidal elevations shift upwards[91]. In Fig. 4a, the effects of sea level rise can be interpreted as a reduced marsh width (leftward shift along the horizontal axis) and an increase in water depth (upward shift along the vertical axis). Designs that consider time horizons associated with significant sea level rise should consider both effects."

Minor comments:

• Line 269 and Line 511: “Disadvantage communities” should be “disadvantaged communities.”

Since the discussion on “disadvantaged communities” is removed, this comment is resolved.

• Line 206-210: The text switches between two citation formats. Please be consistent.

Thank you for noticing. This section has been removed but all the other citations in the manuscript have been corrected for consistency.

• Line 233-234: Is this true for all vegetation types?

Since Fig. 4 is updated with a new figure, this comment is resolved. To answer your original question, the BCR $\geq$ 1 at all vegetation width were true for all vegetation types. In the updated manuscript, the BCR sensitivity analysis by varying vegetation species (Fig. 4e) demonstrates BCR $>$ 1 for all the different vegetation species. However, for some dormant vegetation conditions, BCR < 1 were calculated when a higher discount rate of $\geq$ 6% was applied, which is mentioned within the new case study. Please see:

- Lines 335-337: “The BCR for dormant plants drop below 1.0 for discount rates greater than or equal to 6%, which echoes the strong influence of discount rate on investment decisions based on BCR, and the need to consider seasonal variation in vegetation.”
- Lines 406-407: “The BCR for dormant plants under all three storm return periods is below 1.0 for discount rates greater or equal to 6%.”

• Line 243-244: I am not sure if this statement is accurate. It appears to me that the BCR values are higher for the USACE discount rate for Figures 4c and 4d.

Thank you for noticing and apologies for the typo. Since Fig. 4 is updated with a new figure, this comment is resolved.

• Line 193: Why was a water depth of 3m chosen? Please provide justification.

The water depth of 3 m was originally chosen because this was the model parameter used in Vuik et al., 2016. Fig. 4 has now been updated with a new figure in which multiple water depths (2, 3, 4, 5 m) at the toe of the seawall were explored. The range of water depths were chosen to represent different storm conditions in the hypothetical marsh-fronted seawall configuration in Fig. 1.

Reviewer #2:

In this manuscript, the authors present a benefit-cost analysis (BCA) of a marsh-fronted seawall design. The benefit-cost analysis was constructed to compare whether placing a marsh in front of a seawall would be more economically beneficial than heightening the seawall to deliver the same overtopping rate. The analysis includes a sophisticated 1D numerical model to simulate wave energy propagation within a vegetation field. This model was validated against field measurements resulting in very good agreement with that data. Then, the model was used to analyze the sensitivity of the wave attenuation to plant species. In my opinion, the methodology presented here has great potential to assess if a marsh restoration project is economically viable or not. However, some issues need to be further developed and investigated.

Thank you for noting the great potential in the 1-D wave model and benefit-cost analysis (BCA) framework. We appreciate your suggestions for further development.

While some of the findings of the paper can be helpful in other regions, the methods and the conceptualization of the manuscript are mainly devoted to American readers. Thus, the target audience is not global, but regional (one country). For readers outside of the US is difficult to understand some terms such as USACE, Federal, FEMA, etc. In the conclusions, the authors state: "The present study provides a quantitative example of how ecosystems services can be quantified within the framework required by federal funding." It seems that the ONLY audience of this journal is from the US (other readers might think of other federal states such as Argentina, Australia, Belgium, Bosnia and Herzegovina, Brazil, Canada, Germany, India, Iraq, Malaysia, Mexico, Micronesia, Nepal, Nigeria, Pakistan, Russia, Switzerland, the United Arab Emirates, and the United States).

Thank you and we agree that the manuscript should orientate to a global audiences. The sections and details that relate specifically about the US policies were removed and replaced with a more global context. Firstly, the manuscript introduces a global interest for ecosystem across the US, Europe and Asia, shown in:

- Lines 61-64: "Globally, there is growing interest for ecosystem restoration, such as the Federal Emergency Management Agency (FEMA) Hazard Mitigation Assistance (HMA) grant program in the United States[36], the Natural Restoration Law (NRL) in the European union[37], and Nature-based Solutions Asian Hub in Asia[38]."

Secondly, the range of discount rates applied in the BCR sensitivity analysis in Fig. 4 encompasses discount rates that were used in the US and Europe. This is shown in:

- Lines 272-276: "The fourth sensitivity test explored the influence of discount rate (Fig. 4f), considering values from 0% to 11%, which spans typical values applied globally for long term project evaluations. This includes the United States historical Water Resources Development Act (WRDA) from 1971 to 2024 range between 2.25% and

8.875%[78,79], European Commission Impact Assessment Guidelines at 4%[80,81], and discount rates for natural assets in land-use planning at 0% to 11%[82]."

Thirdly, the specific details about project eligibility for US federal funding are removed. At the end of the *Discussion*, the manuscript concludes how the coastal protection benefits of marshes from can be monetized in the benefit-cost analysis framework in addition to ecosystem services. This is shown in lines 428-432:

- Lines 426-429: "The present study provides an example of how ecosystems services can be quantified in the BCA framework. Specifically, the coastal protection benefit of marsh was framed in terms of the reduction in construction costs associated with a reduced seawall height."

In the BCA a project lifetime of 100 years was considered. At this time, the sea level is expected to rise considerably (depending on the scenario), but the authors have not even mentioned that or discussed the impact of this in their analysis. An important handicap of the marsh-seawall design is that the migration length of the marsh to adapt to the SLR can be very limited. Thus, the marsh width could be reduced. It is still not very clear if the marsh elevation can maintain the same path of the sea level rise. Thus, this brings some uncertainty but the authors have completely neglected that.

Thank you for the suggestion to incorporate the effects of sea level rise, and we agree that the problem of coastal squeeze should also be considered. First, the useful project life is changed from 100 years to 50 years to be in-line with common practices evaluating for coastal wetlands, which are also used in Federal Emergency Management Agency (FEMA) 2022. We agree that using a shorter period of 50 years is more appropriate in view of drastic climate change impacts to influencing future hydrodynamic conditions. The changes are made in lines 218-220:

- Lines 218-220: "The base case was defined with offshore wave height $H_0 = 1.5$ m, water depth $h_t = 3$ m, plant species *Spartina alterniflora*, 50 years useful project life, and 2.5% discount rate, which is the rate given in the 2023 US Water Resource Development Act[77]."

Second, the uncertainties related to the effects of sea level rise on the salt marshes wave attenuation performance are discussed in lines 388-403. Although a complete analysis of sea level rise impacts on the BCR sensitivity is beyond the scope of the current manuscript, the BCR sensitivities can be indirectly interpreted using Fig. 4a. In the following new text in the discussion, we consider sea level rise and coastal squeeze:

- Lines 388-403: "Both the seasonality of plants (Fig. 4e) and changes in water depth (Fig. 4a) impacted the BCR by roughly a factor of two. Sea level rise would both increase the water depth and decrease the available marsh width due to coastal squeeze, where the seawall acts as a physical barrier that prevents the marshes from migrating inland as the intertidal elevations shift upwards[91]. In Fig. 4a, the effects of sea level rise can be interpreted as a reduced marsh width (leftward shift along the horizontal axis) and an increase in water depth (upward shift along the vertical axis). Designs that consider time horizons associated with significant sea level rise should consider both effects. Recall that wave attenuation follows a decreasing marginal influence with increasing marsh width, which results in the highest BCR approaching zero marsh width (Fig 4). This limit is obviously infeasible, as a marsh of negligible width is unlikely to survive. Marsh restoration guidelines recommend a minimum marsh width of 5 m[92], and sufficient sediment availability[93] for a marsh to be sustainable. Although the marginal benefits from wave damping decreases with wider marshes, it is desirable to maximize the marshland size at any site for greater magnitude of benefits, mostly driven by ecosystem services benefits, while achieving BCR>1.0. In reality, the spatial extent of the marshland is usually not a design choice, but it is constrained by the bathymetry and tidal elevations, which sets the intertidal range within which the marsh lives[83]."

The authors claim that the model can be used to assess the variation of coastal protection due to the vegetation seasonality. However, it is not then included in the BCA. They could have added another line in the Figure 4 plots representing dormant and healthy conditions. Previous authors have found that marshes provide more protection against hurricanes than winter storms in the Chesapeake Bay because of the growth cycle of the Spartina Alterniflora.

Thank you for this suggestion. We have added the vegetation seasonality effects on the BCR in Fig. 4e by comparing the healthy *Spartina anglica* (orange dashed line) to the dormant *Spartina anglica* (orange dotted line). The sensitivity analysis on plant seasonality is added in:

- Lines 263-270: "The third sensitivity test explored the impact of vegetation species and seasonality (Fig. 4e). As shown in Fig. 3, the larger and more rigid *Phragmites australis* produces the greatest wave attenuation, which is reflected in the highest BCR (blue line and circle). Variation in plant characteristics over a growing season was explored by comparing the average reported stem height and number of leaves per stem for *Spartina anglica* (solid orange line) with the validated dormant plant parameters from Hellegat between locations S3 and S4 (dotted orange line)[51,67]. This demonstrated that the seasonality of plant conditions influenced the BCR by roughly a factor of two (Fig. 4e). However, both plant conditions achieved BCR above 1.0."

In addition, the vegetation seasonality impacts are also examined in a new real-world case study shown in Fig. 3 and Fig. 5e. The healthy plant parameters are observed to provide stronger wave attenuation performances than dormant plant parameters, which are consistent to the reference Garzon et al., 2019 from the Reviewer about the coastal protection against hurricanes in Chesapeake Bay is stronger in the fall than winter due to the growth cycle of Spartina Alterniflora:

- Lines 196-201: "Moreover, our model predicts healthy plants provide 8% to 17% more wave attenuation than dormant plants (compare solid and dotted lines of black and orange lines in Fig. 3a), which is due to higher number of leaves per stem, as well as higher stem stiffness $E_S I_S$ of healthy plants (black and orange circles in Fig. 3b) than dormant plants (black and orange triangles in Fig. 3b). This is consistent with seasonal variation discussed in Garzon et al., 2019[52] who showed that marshes provided 15% to 30% more reduction in wave height during fall than in winter."

- Lines 330-333: “As expected, Fig. 5e shows that the BCR of healthy plants (dashed lines) are significantly higher than dormant plants (dotted lines). The healthy plants provided 16% to 50% more wave attenuation than dormant plants, which is consistent with the 15% to 30% protection difference between fall and winter plants reported in Garzon et al., 2019[52].”

The authors claim that “A novel design tool was developed for decision makers to visualize the Benefit Cost-Ratio (BCR) over a range of marsh width (measured in the direction perpendicular to the seawall) and avoided seawall heightening, considering different discount rates.” This is only partially true because the decision makers can only assess the data shown in Figure 4. With other oceanic conditions or plant characteristics, this figure is no longer valid. It would be more beneficial if a comprehensive scenario of oceanic and plant conditions were considered and then the results summarised in one/more figures. All the analysis is based on one oceanic condition based on a previous paper and based on that, the authors present some conclusions supported by the BCA. Nevertheless, the authors have not investigated more scenarios. For example, wave attenuation highly depends on the ratio of plant height and water depth. So what are the results under a scenario of a storm surge of 4 m (feasible for the US)? In my opinion, the input oceanic conditions of the model should be based on joint statistical analysis to obtain return periods associated with water levels and wave heights. Otherwise, the BCA is only valid for one condition.

Thank you for this excellent suggestion to consider more hydrodynamic and plant conditions and to discuss the sensitivity of each of these parameters on the BCR. An updated sensitivity analysis is now given in Fig. 4, which considers different storm conditions (different water depth and offshore wave height), different vegetation species and seasonality, and different economic discount rates applied. We agree that this makes the conclusion much broader and more useful. This new analysis is discussed in a new section called “Benefit-Cost Ratio for seawall fronted with marsh with Sensitivity Analysis” which begins at line 215.

Further, to improve the audience’s accessibility to conduct their own BCA analysis, we provided an example in Table 7 using the unit benefits and costs from Table 6 to formulate the BCR computation.

In summary, I think that the paper as is now, is not suitable for publication in this journal. In my opinion, besides developing and presenting the tool, it would be more interesting to apply this tool to specific implementation sites in the US. This way, decision-makers can more easily follow the procedure to compute the BCA, contributing to its implementation nationwide.

Thank you for your suggestion to apply the BCA tool to a specific site, which we have added. A BCA case study based on a real seawall reconstruction project at Juniper Cove, Massachusetts, United States is now included in lines 297-346 under the *Results* subheading “Benefit-Cost Analysis Case Study Example”. In this case study we were able to use specific cost values for this site. Table 10 is the BCA breakdown for the Juniper Cove case study to demonstrate how site-specific cost values can be adapted in the BCA framework so that decision-makers can more easily follow the BCA computation procedure. The Juniper Cove case study (new Fig. 5) also explored the same sensitivity factors considered in the hypothetical marsh-fronted seawall (new Fig 4), which validates that the sensitivity responses of the hypothetical case are consistent with observations for the real-world example.

Minor comments

Update reference 2.

- Added a new reference (3) Kunze & Strobl 2024, in line 36, next to the original reference 2. "Each year, coastal storms threaten hundreds of millions of people[1–3], disrupt transportation networks[4,5], and produce billions of dollars in damage[6,7]."

L38. Add reference

- Added reference (8) NOAA 2024, in line 38: "In 2022 in the United States alone, coastal storms have resulted in economic losses over USD$165 billion[8]."

Update reference 9

- Added references (12) Pycroft et al., 2015 and (13) Asuncion & Lee 2017, in lines 42-43: "Without adaptation to the climate, humanity would experience annual economic losses of 0.3% to 9.3% global GDP[11–13]."

L49. Replace do little by are not efficient.

- Corrected in line 50: "However, these hard structures are not efficient in dissipating wave energy..."

L52. Add sandy beaches

- Added in line 55: "In contrast, natural shorelines, including marsh[20–22], mangrove[21,23], seagrass[22,24], kelp beds[22], coral reef[21,22], oyster reef[25,26], and sandy beach[22,27], attenuate wave energy[21,22]."

L52-61: Missing important reference: Future of our coasts: The potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems

- Added as reference (39), in line 66: "Marsh-fronted seawalls might deliver the same level of desired coastal protection more economically, with lower construction and maintenance cost than gray infrastructure alone[39]."

L67: add reference Field-based numerical model investigation of wave propagation across marshes in the Chesapeake Bay under storm conditions.

- Added as reference (52), in line 74: "The effect of vegetation drag on wave propagation has been primarily modeled by calibrating an empirical drag coefficient that is fitted with observations of wave attenuation by real[51,52] and artificial model plants[53]."

L 70. Add reference: Modelling wave attenuation by saltmarsh using satellite-derived vegetation properties and discuss it in this context.

- Thank you for the great suggestion and it is added as reference (87). The reference of satellite-derived vegetation properties is added as part of the discussion for the use of remote sensing techniques to quantify vegetation characteristics needed as inputs into vegetation drag models.
- Lines 357-365: "Since it can be labor intensive to collect in-situ vegetation characteristics that are necessary as inputs into the vegetation drag model, there is a need for efficient methods to characterize vegetation species type, plant height, and shoot density. Studies demonstrated the power of machine learning on remote sensing data collected by satellites, airborne planes, and unmanned aircraft systems (drones) for visual, multispectral, hyperspectral imageries, and Light Detection and Ranging (LiDAR) data can efficiently classify and map the spatial distribution of different salt marsh species over large areas[85,86]. Vegetation indices derived from satellite imagery, such as leaf area index, can also be used to estimate vegetation frontal surface area for inputting into wave modeling[87]."

L84. Please indicate the equation number of the Eurotop 2018.

- Added in line 89: "With the predicted wave height at the toe of the seawall, empirical equations in EurOtop, 2018[54] were used to compute the overtopping rate (Eq. 5.12, 5.16, 5.17, 5.20)."

L86. Please add this equation somewhere: The overtopping rate is also a function of freeboard, which is the distance between the 2% wave run-up height and the highest point of the seawall (Fig. 1).

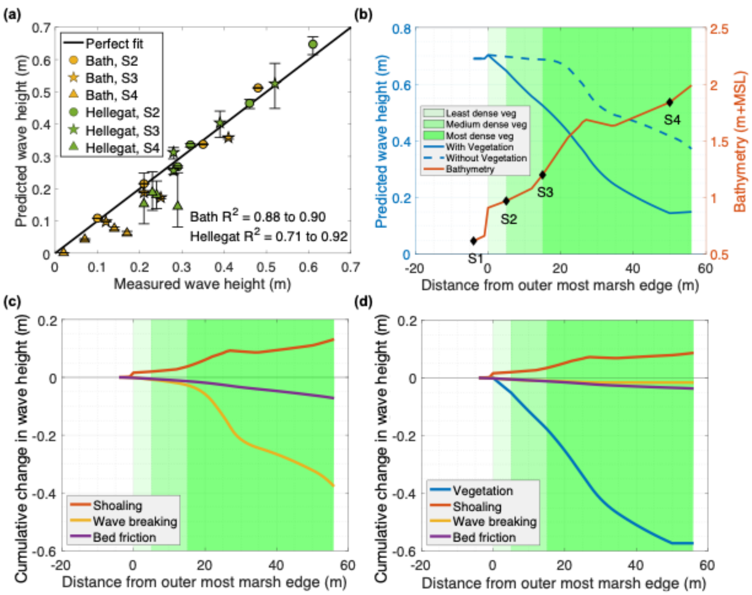
- There was a mistake in this line and is corrected in lines 89-91: "The overtopping rate is also a function of freeboard R_c, which is the distance between the still water level and the highest point of the seawall (Fig. 1)."
- The overtopping rate equation reference is added in line 89: "With the predicted wave height at the toe of the seawall, empirical equations in EurOtop, 2018[54] were used to compute the overtopping rate (Eq. 5.12, 5.16, 5.17, 5.20)."

L122. Area density means stem density? Please clarify.

- To clarify the terminology, "area density" is replaced by "shoot density". The clarification is added within the parenthesis in line 139: "Reported plant morphology, rigidity[67], and shoot density (shoots per bed area) were used to predict ..."

Figure 2. Replace actual by measured. The change in the intensity in the green colors are hard to see. Why you didn't show the Bath site?

- Thanks for the suggestion to change Fig. 2a y-axis label to "Measured wave height (m)" and the intensity of green colors have been increased to show greater gradation. Fig. 2:



- Fig. 2b, Fig. 2c, Fig. 2d demonstrate how the components that influence the wave heights can be decomposed using Hellegat as an example. Therefore, showing it for Bath would be a redundant demonstration.

Ref: 49 is not very appropriate since in this work you are dealing with muddy sediment. I suggest either expanding this discussion or cut it. As it is, it seems weak.

- Thank you for noticing. The discussion is modified to strengthen the argument in lines 161-165: "Because wave breaking generates turbulence and sediment resuspension[72,73], a reduction in wave breaking would have the added benefit of reducing resuspension, which should favor sediment retention within the marsh. In addition, because breaking waves generate scouring at coastal infrastructures[74], reducing wave breaking would also reduce scouring maintenance cost." The original reference (49) is now reference (74).

L154: area density must be defined earlier on in the document.

- In addition to the clarification added within the parenthesis in line 139: "Reported plant morphology, rigidity[67], and shoot density (shoots per bed area) were used to predict ...", it is also added in lines 183-184: "The morphology, stiffness, and shoot density (shoots per bed area) are shown Table 4 in *Methods*."

L176: This statement "calibrated drag coefficients cannot be transferred to new sites" is not true as this is a common practice when data is not available.

- The statement is rephrased in lines 201-205: "Because wave attenuation is sensitive to structural stiffness, plant morphology, and shoot density (Fig. 3)[49], calibrated drag coefficients may not be accurate for new sites with different vegetation, or even at different seasons of the same site, even though this is a common practice when in-situ measurements are not available for a given site."

L193: ht = 3 m? please clarify.

- This line is removed and replaced with the sensitivity analysis description in lines 218-220: "The base case was defined with offshore wave height $H_0 = 1.5$ m, water depth $h_t = 3$ m, plant species *Spartina alterniflora*, 50 years useful project life, and 2.5% discount rate, which is the rate given in the 2023 US Water Resource Development Act[77]."
- In particular, the base case description for the sensitivity analysis uses water depth at toe of seawall $h_t = 3$ m because this was the parameterization used in the same marsh-fronted seawall configuration in Vuik et al., 2016.

L201: the choice of discount rate (USACE 2.5% versus federal 7%). What is this?

- This section is removed because instead of comparing two specific discount rates used in the United States, a range of discount rates from 0% to 11% are used in the new sensitivity analysis to represent the different discount rates applied globally. This is discussed in lines 272-276:
- Lines 272-276: "The fourth sensitivity test explored the influence of discount rate (Fig. 4f), considering values from 0% to 11%, which spans typical values applied globally for long term project evaluations. This includes the United States historical Water Resources Development Act (WRDA) from 1971 to 2024 range between 2.25% and 8.875%[78,79], European Commission Impact Assessment Guidelines at 4%[80,81], and discount rates for natural assets in land-use planning at 0% to 11%[82]."

Other references to include:
10.1016/j.oceaneng.2022.110974

- Thanks for the suggestion, it is added as reference (30) in line 57: "… reduced wave load on the seawall[30], and many environmental service benefits[31]."

10.1111/1365-2664.14413

- Thanks for the suggestion, it is added as reference (29) in line 56: "The nature-based hybrid solution of maintaining a marsh in front of a seawall provides flood risk reduction[28,29], …".

Reviewer #3:

This paper analyzes the merit of marsh-fronted seawalls as a coastal protection measure relative to seawalls alone, utilizing a new model of wave attenuation by marsh plants and a benefit-cost analysis. The paper concludes that marsh-fronted seawalls are "a feasible, cost-effective, and nature-based" alternative to traditional hard-structure-only seawalls. The topic is certainly very important; the analysis has been carefully carried out; and the conclusion of the paper is mostly convincing. I do have several questions and comments that, hopefully, will help the paper become stronger.

Thank you for the positive note about the importance of research topic. Your comments were very helpful in improving the paper.

(1) I find the design of the benefit-cost analysis to be rather unconventional; the discussion of the benefit-cost analysis needs to be modified, in my opinion. The authors calculate benefit and cost of marsh-fronted seawalls *** relative to *** traditional seawalls. In conventional benefit-cost analyses of coastal protection (see, for example, D. Min, D. Kim & K. Cho, "Cost-benefit analysis of seawalls in South Korea: A bottom-up assessment," Coastal Management, 2016 and references included there), benefit and cost of a protection measure is calculated relative to the case of no protection.

Thank you for the reference to Min et al., 2016 about a bottom-up cost-benefit analysis of seawalls. However, the concept of benefit-cost analysis (BCA) can also be applied to assess the incremental changes relative to the unchanged base case, which is supported by United States Federal Emergency Management Agency (FEMA) BCA reference guide. This explanation is added in the manuscript:

- Lines 98-100: “Federal Emergency Management Agency (FEMA) guidelines permit formulating an incremental BCA on the inclusion of a marsh relative to the base case of an existing seawall without a fronting marsh[58,59].”

Moreover, the reference (59) Cooper et al., 2016 is an example of using incremental costs and benefits of berm design relative to the baseline of not constructing any infrastructures for coastal flooding hazard mitigation. Similarly in this manuscript, the seawall is assumed to be already present, so the BCA is focused on whether having vegetation in front of the seawall provide more benefits from additional coastal wave attenuation and environmental benefits than the cost of building the marsh area.

Finally, we have added a case study that illustrates how the analysis could be applied in a proposed seawall refurbishment. This is added in the *Results* section under subheading “Benefit-Cost Analysis Case Study Example” in lines 297-346.

Following the authors' calculation, a benefit-cost ratio exceeding 1.0 does not mean that marsh-fronted seawalls can be justified economically. It only means that marsh-fronted seawalls are better than traditional seawalls. In the discussion section (and also in the methodology section), the authors mention the benefit-cost-ratio thresholds of 1.0 and 2.5 that the U.S. government agencies use. I do not believe that the benefit-cost ratios that the authors have calculated can be compared to these thresholds. These thresholds are meant to be applied to the ratio of total benefit to total cost, not to the ratio of incremental benefit to incremental cost. Thus, the authors need to modify their discussion of what could be said from their benefit-cost ratios.

Following with the preceding discussion, FEMA permits the use of incremental BCA to evaluate whether it is economically justified to act on an additional element on top of a base case. Therefore, a benefit-cost ratio (BCR) above 1.0 would mean it is economically justified to construct and restore the marshes in front of the seawall because there are more monetary benefits than costs for this action.

In the *Discussion* section, the BCR thresholds used in the United States government agencies were removed to make the findings of the paper relevant to a wider range of audiences. The revised manuscript now focuses only on the process of developing the BCR values, but does not discuss which thresholds of BCR would be acceptable for decision making. The *Discussion* section was modified accordingly. In particular, the following phrases are relevant to the change:

- Lines 375-379: "The BCR was shown to be sensitive to several factors, including design storm condition (water depth and offshore wave height), vegetation species and seasonality, and choice of discount rates, but in most cases BCR > 1 supported the conclusion that marsh-fronted seawall is a viable nature-based solution, even in locations for which only a narrow width of marsh is possible."

The concluding phrase of the *Discussion* section ends by emphasizing one of the novel contributions of the manuscript is to propose a methodology to monetize the coastal protection benefits of marsh in terms of avoided seawall heightening. This is shown in:

- Lines 426-429: "The present study provides an example of how ecosystems services can be quantified in the BCA framework. Specifically, the coastal protection benefit of marsh was framed in terms of the reduction in construction costs associated with a reduced seawall height."

The usefulness of the benefit-cost ratios reported in Figure 4 is limited for practitioners evaluating alternative coastal protection measures unless they know the benefit and cost of traditional seawalls as well.

We agree that the previous Fig. 4 can only provide limited insights for practitioners to conduct BCA. Therefore, Fig. 4 has been replaced with a sensitivity analysis on the variables that affect BCR, including water depth, offshore wave heights, vegetation characteristics and choice of discount rate scenarios. In addition, the newly added Juniper Cove case study is an example to demonstrate to practitioners how site-specific cost and benefit values (Table 10) can be used in the proposed BCA framework. Since the BCA is focused on evaluating whether construction the marsh area in front of an existing seawall is economically justified or not, it does not need to serve the purpose of evaluating alternative coastal protection measures. However, the cost components discussed in the BCA can be incorporate into a larger BCA is the practitioner wishes to decide between building a whole new seawall, or build a shorter seawall with marshes in front of it on a bare coastline without any engineered coastal defense structures.

(2) Figure 4 seems to show that benefit-cost ratios are higher when discount rates are lower. But the text following Figure 4 seems to say the opposite.

The following text seems not correct: "The value of environmental services … occur in the future time. Therefore, lower BCR values are present in low and medium estimates at USACE 2.25% discount rate than at federal 7% discount rate." If benefit occurs later, BCR values must be higher, not lower, with a lower discount rate.

Thank you for noticing and apologies for the typo. Since Fig. 4 is updated with a new figure, so that this comment is no longer relevant.

Also, it is unclear whether the authors are saying the benefits of marsh-fronted seawalls occur earlier or later compared to traditional seawalls.

Thank you for pointing out the confusion in the phrasing. As mentioned in the preceding responses, it is assumed that there is an existing seawall, so the BCA focuses on comparing whether placing a marsh in front of that existing seawall is economically justified. Therefore, it does not compare the options between constructing the marsh-fronted seawall versus constructing a traditional seawall.

(3) Benefit-cost ratios reported in Figure 4 are based on a specific set of assumptions. So some discussion of where these numbers can be applied would be useful. Are they applicable to highly nonlinear coastlines as well as near-straight coastlines? Are they applicable to urban coastlines as well as rural coastlines?

First, rather than only present BCR for a specific set of conditions, we now present a sensitivity analysis of the factors that influences BCR. The new Fig. 4 presents BCR for a wider range of conditions, and also discusses how the variables of water depth, wave height, marsh width, vegetation type and discount rate influence the BCR. We hope that this expanded discussion will be a guide for considering different sites. Second, the 1-D wave model used in the manuscript is most appropriate for straight coastline sections. More complicated coastline shapes would necessitate a more detailed wave modeling, such as using 2-D SWAN numerical spectral models, but it would not change the BCR analysis because monetizing the wave attenuation contributions from vegetation drag is only one component of the BCR. This is now noted in lines 304-310:

- Lines 304-310: “Since the Juniper Cove site has a mildly curving coastline, 1-D wave model is appropriate. The 1-D wave model assumes that linear wave theory is valid, and all the wave energy is transferred in the cross-shore direction. In the Juniper Cove case study, the wave propagation towards a mildly curved shoreline was analyzed by subdividing it into 10 transects (Fig. 5d), along which the 1-D wave model was applied between the breakwater and the seawall (see *Methods*), with assumptions that the marsh is fully established."

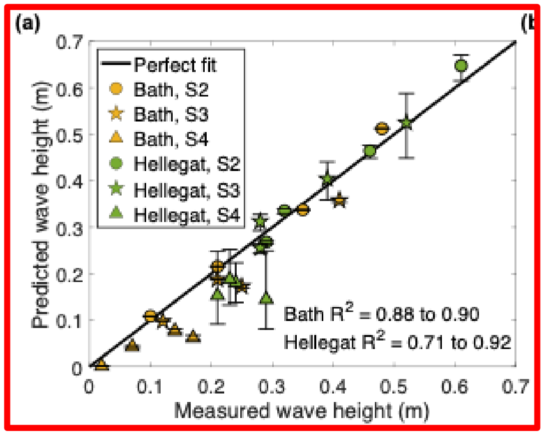
More discussion of how to interpret high vs. low estimates in Figure 4 would be useful. Do they mostly reflect urban vs rural differences?

Thank you for pointing out the need to clarify what low, medium, and high estimates represent. For the construction cost savings related to the avoided seawall heightening, the high versus low estimates are indeed referring to the urban versus rural cost differences. However, for ecosystem services, the high versus low estimates are simply the variation of values found from different sources. To clarify these interpretations, the following text has been added:

- Lines 114-120: "Based on the range of values collected from literature (See *Supplementary Material 1*), each monetized benefit and cost was organized into low, medium, and high estimates[56,57]. For the seawall construction costs (used to evaluate benefit of avoided seawall heightening), low and high estimates represent values in rural and urban settings respectively, with a medium value computed as the median representative values found in literature[60]. The low, medium, and high estimates for all other categories were the lowest, median, and highest representative values found in literature[21,31,60,62,64–66]."

(4) Figure 2 (a) seems to be the main evidence showing the validity of the wave attenuation model. Given this figure is based on two specific sites, I wonder whether the data are used for model calibration as well as validation. That is, have certain features of the model been selected to achieve greater fit? Some discussion on this may be useful.

Thank you for pointing out the need to greater detail. We did not do any model calibration. The vegetation drag model was adopted from Zhang et al., 2019, which was previously validated with a much wider set of field data. In this manuscript, we simply took the vegetation characteristics reported in Vuik et al., 2016 and Zhang et al., 2019 (summarized in Table 3a and Table 3b) and applied them into the 1-D wave model. Since Vuik et al., 2016 did not report the number of leaves per stem parameter, a range of values chosen from the low end of reported values from Zhang et al., 2019 was used to capture the uncertainty of this value. The lower end of reported values was used to correspond to the dormant winter conditions reported in Vuik et al., 2016. To clarify this point, we now show the error bars in the prediction, reflected the uncertainty in the number of leaves per stem (updated Fig. 2a):



- Lines 141-145: "Since the number of leaves per stem (N_l) was not reported, a range of values was chosen to represent winter conditions, $N_l = 0{,}2{,}4$ for Bath and $N_l = 0{,}2{,}5$ for Hellegat, with the maximum corresponding to species-specific low values reported in Zhang et al., 2021[67], since leaf count is lower under winter conditions."

Also, does each dot in Figure 2(a) represent a specific sensor located at a specific location? Or an observation for a specific period?

Thanks for pointing out the confusing diagram symbology. In the updated Fig. 2a, each symbol and color represent a specific sensor located at a specific site. See the legend in new Fig. 2a, shown above. For both Bath and Hellegat, we selected the two most extreme tide events with the largest wave heights and the two most extreme tide events with largest water depth to validate the 1-D wave model.

(5) In my opinion, choosing a specific site and showing how to apply the analysis of this paper to that site would be very useful. In fact, most of my questions/comments can be addressed via such an example.

Thank you for this suggestion. We have added a site-specific example based on the Columbus Avenue Seawall Reconstruction project at Juniper Cove, in Salem, Massachusetts, United States. The case study is included in:

- Lines 297-346 in the *Results* section under subheading "Benefit-Cost Analysis Case Study Example".
- Lines 702-772 in the *Methods* section under subheading "Methodology for Benefit-Cost Analysis (BCA) Case Study on Juniper Cove".

Response to Reviewers:

Article title: Wave attenuation and economic benefit of marsh-fronted seawall for nature-based coastal protection.

Manuscript No.: COMMSENV-23-1938-T

We thank the three Reviewers for providing additional comments that have further improved the strength and clarity of the paper. The comments are repeated here in black font, followed by a response in red font. Within the revised manuscript, the revised sections are shown in red font.

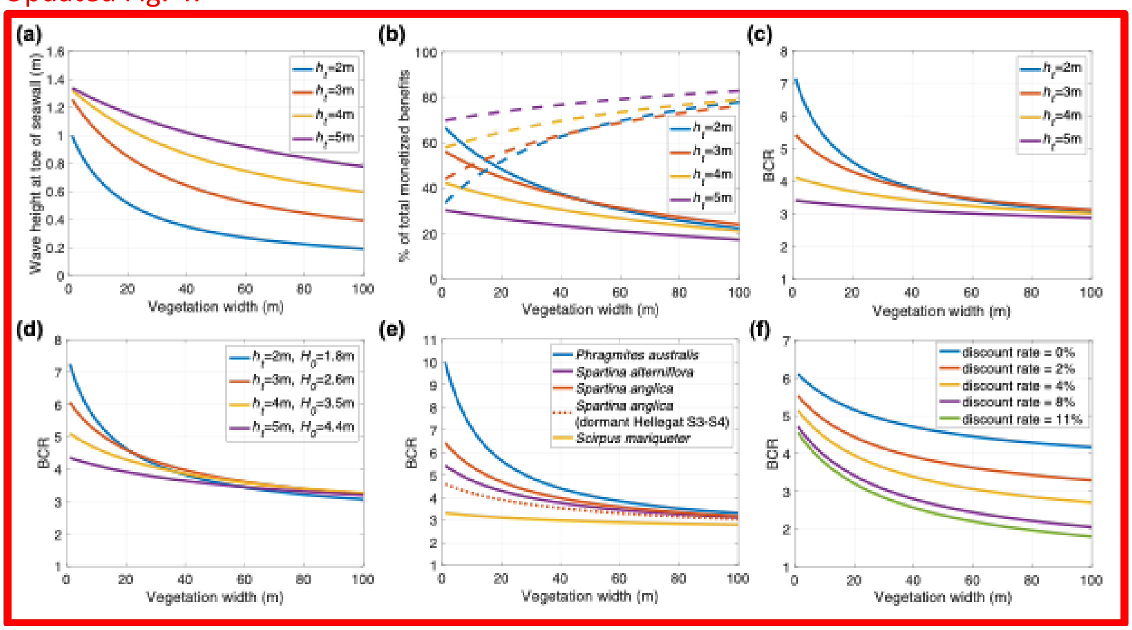
Reviewer #1:

I appreciate the authors' thorough response to the reviews, and I feel that the manuscript has been significantly improved. There are several minor comments that should still be addressed:

- In Lines 254-256, the authors' state "Again, because wave energy loss is proportional to wave height squared, the reduction in wave height is greater for larger waves, resulting in higher BCR for larger storm conditions." However, in Figure 4d, it appears that the BCR is higher for lower water level and wave height combinations for smaller vegetation widths. Please clarify.

Thank you for pointing out the confusion. Here, we intended for the reader to compare the BCR curves in Fig. 4c and Fig. 4d, which have the same water depth, but different wave heights. For example, consider the case with h=3m (orange curve) with near zero vegetation width. The values in Fig. 4c (smaller wave height) and Fig. 4d (larger wave height) are 5.4 and 6.1, respectively, i.e., higher BCR for larger wave. We have reworded several sentences to clarify the intended point of comparison. To make Fig. 4c and Fig. 4d more consistent, the water depth of $h_t = 5$m was also included in Fig. 4a, Fig. 4b, and Fig. 4c.

- Updated Fig. 4:



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- Lines 249-261: "The second sensitivity analysis varied both water depth and offshore wave height to compare storm conditions (Fig. 4d). The offshore wave height H_0 was set at its maximum storm value using the shallow-water wave breaking limit for the water depth at the seawall toe, h_t. Specifically, $H_0 = 0.88h_t$. The offshore wave heights (legend in Fig. 4d) were all larger than the base condition $H_0 = 1.5$ m shown in Fig. 4c. Again, because wave energy loss is proportional to wave height squared, the greater offshore wave height resulted in higher BCR. Specifically, compare the left-side of Fig. 4c and Fig. 4d, in which the blue, orange, yellow, and purple BCR curves ($h_t = 2$, 3, 4, and 5 m, respectively) are each higher in Fig. 4d, for which the offshore wave height is higher. Further, for storm conditions, Fig. 4d again illustrates the decreasing marginal benefit with increasing vegetation width, such that BCR decreases with increasing marsh width. Finally, the BCR lines cross each other at large vegetation width, because given a larger offshore wave height, there is greater overall potential for avoided seawall heightening benefit."

- The discussion of sea level rise that was added is still rather limited, only mentioning the impact on wave height at the toe of the seawall. I believe it would be helpful to include a sample calculation of the BCR with an estimated rate of sea level rise and vertical marsh accretion for the Juniper Cove case study to demonstrate how sea level rise could affect the economic feasibility of the marsh-fronted seawall. As an alternative, the discussion could be expanded to include information on the types of data or additional modeling that would be needed (e.g., vertical accretion rates, vegetation succession, sediment dynamics) to properly evaluate the BCR with sea level rise.

Thank you for this suggestion. We feel that a detailed evaluation comparing sea level rise with vertical marsh accreditation is beyond the scope of this paper. However, we have expanded the discussion session to include the necessary information needed to comprehensively evaluate the BCR with sea level rise. We have added the following:

- Lines 400-409: "In Fig. 4a, the effects of sea level rise can be interpreted as a reduced marsh width (leftward shift along the horizontal axis) and an increase in water depth (upward shift along the vertical axis). Designs that consider time horizons associated with significant sea level rise should consider both effects. This would require information on both the local sea level rise, as well as the sediment accretion rate, which together determine the change in intertidal zone width[91]. Specifically, sustainable marshes require an accretion rate that keeps pace with the rate of sea level rise[92,93] with adequate room for horizontal landward expansion[93]. Otherwise, additional investment would be needed to build up the land before planting, with earth moving contributing a significant additional cost, which would lower the BCR."

Reviewer #2:

I want to congratulate the authors because they have done an important effort to improve the manuscript. They have managed to provide solid answers to my three most important concerns, namely, targeting for a broader audience (not only in the US), assess the impacts of variations in the vegetation and hydrodynamic conditions and including a case study to show the applicability of this study. Just a minor comment. I noticed that the new text added some times the authors mix the results and discussion, I highlight some examples that should be moved to the discuss section.

Comment 1 at line 75 – suggested addition of Garzon et al., 2019

- Thank you for the suggestion and reference (45) [Garzon et al., 2019], which has been added in line 75: "The effect of vegetation drag on wave propagation has been primarily modeled by calibrating an empirical drag coefficient that is fitted with observations of wave attenuation by real[45,51,52] and artificial model plants[53]."

Comment 2 at line 162 – suggestion to move section to *Discussion*.

- The phrase has been moved into the discussion in lines 370-377: "The wave attenuation model was used to predict the reduction in wave height achieved by a marsh situated in front of a seawall (Fig. 1). The breakdown of each wave dissipation mechanism (Fig. 2) revealed that the loss of wave energy to work against vegetation drag made the waves less likely to reach breaking conditions[69]. Because wave breaking generates turbulence and sediment resuspension[87,88], a reduction in wave breaking would have the added benefit of reducing resuspension, which should favor sediment retention within the marsh. In addition, because breaking waves generate scouring at coastal infrastructures[89], a reduction in wave breaking would also reduce scouring maintenance cost."

Comment 3: Move Line 196 to 205 to the *Discussion*.

- The text has been moved into the discussion in lines 349-359: "A model that captures the morphology and rigidity of marsh plants produced good predictions of wave attenuation. The model demonstrated that wave attenuation is sensitive to structural stiffness, plant morphology, and shoot density (Fig. 3)[49]. While it is a common practice in coastal modeling to describe wave attenuation with drag coefficients calibrated with in-site measurements[45,51,52], these drag coefficients are also sensitive to plant morphology and flexibility, and thus may not be accurate for new sites with different vegetation, or even at different seasons at the same site. In contrast, the new model can predict wave attenuation based on site-specific vegetation morphology and species heterogeneity. This enables a quantitative evaluation of year-round coastal protection, capturing seasonal variation associated with growth patterns, which can be used to determine whether temporary additional flood-response measures are needed during specific seasons of the year."

Comment 4: Move lines 240 to 248 to *Discussion*.

- Thank you for the suggestion. However, we feel this text is needed to help readers to understand the physical principles that produce the trends shown in Fig. 4c. So, we have left this section in the results. For reference, the highlighted reasoning phrase is the second sentence of lines 238-247:
- Lines 238-247: "First, note that the BCR for all water depths declines as vegetation width increases (Fig. 4c). Because wave energy loss is proportional to wave height squared, as wave height declines with distance over the marsh, the marginal decrease in wave height per unit marsh width also declines. This is shown by the reducing slope of wave height versus marsh width in Fig. 4a. As a result, the marginal benefit of seawall height reduction also declines, which is reflected in the decreasing BCR (Fig. 4c). Second, note that the BCR curves for the four water depths (four curves in Fig. 4c) converge at large

marsh width. Since the environmental service benefits and marsh construction costs are constant per unit marsh width and not a function of water depth, the four curves converge as the marginal benefit from reduced seawall heightening per unit marsh width goes to zero."

Comment 5: Move line 282 – 294 to *Discussion* section.

- Thank you for the suggestion. The idea that policies governing the choice of discount rate can influence project investment decisions is already stated in the discussion, and this text was removed from the results.
- Lines 421-430 in *Discussion*: "The BCR outcomes were sensitive to the choice of discount rate, which was especially apparent for the dormant vegetation in the Juniper Cove case study (Fig. 5e). The BCR for dormant plants was less than 1.0 for discount rates greater or equal to 6%. More generally, BCR values vary by more than a factor of two across the range discount rates between 0% and 11% (Fig. 4f). Therefore, policies that govern the choice of discount rate have a strong influence on the BCR outcome, which directly affects project investment decisions[77]. In addition to considering the opportunity costs of alternative investment funds or government bond return rates, the discount rate should also reflect how heavily future ecosystem services are valued. One may consider a lower discount rate knowing that the future ecosystem services are important to hedge against climate challenges of rising sea level and more intensive storms."

Therefore, after these small reviews, I recommend the manuscript for publication.

Reviewer #3:

I am mostly happy with the revised manuscript, and I really appreciate the authors' detailed responses.

I have three minor comments regarding the authors' response to my previous comment (1).
- I still think what the authors do will be clearer (to readers like me) if they emphasize the fact that their BCA analysis is for coastlines with existing seawalls (i.e. not for coastlines with no seawalls at all).

Thank you for the suggestion. We agree, and this point has been emphasized in several locations, explicitly noting that the BCA analysis is for coastlines with existing seawalls:

- Lines 97-102: "A benefit-cost analysis (BCA) was used to evaluate whether the inclusion of a marsh in front of an existing seawall would be an economically-justified alternative to heightening an existing seawall[31,55–58]. The BCA assumed a base case of an existing seawall without a fronting marsh. This illustrated the economic trade-off between restoring a degraded marshland, which reduces wave energy at an existing seawall, or constructing additional seawall height on an existing seawall to achieve the same overtopping rate, i.e., same flood protection."

- Cooper et al. 2016 do not consider adding an extra design to existing seawalls. As written in the very first page of that article, Cooper et al. are comparing building an earthern wall to not building any structure at all. So, I do not believe that Cooper et al. are a good reference for showing wide uses of the "incremental BCA."

Thank you for the comment, and we agree Cooper et al., 2016 is not an appropriate reference, so it has been removed from the manuscript. We appreciate the need to be clear and have included several statements (see above) of the fact that our analysis focused on the benefit of including a marsh in front of an existing seawall as an alternative to heightening an existing seawall.

- If the authors could indicate the relevant page numbers of the URS Group BCA reference guide, that could be useful to some readers. (I couldn't determine which part of that guide corresponds to the authors' statement about incremental BCA.)

The terminology is not defined in the URS Group BCA. We adopted the terminology of “incremental BCA” based on a phrase used in Cooper et al., 2016, “The analysis estimates the incremental costs and benefits of the berm relative to a baseline in which the berm and ancillary components (collectively, “the project”) are not constructed [page 1]”. We understand now that this was confusing, so this terminology has been removed from our paper.

The URS Group BCA reference guide defines BCA as “the method by which the future benefits of a mitigation project are determined and compared to its cost [page 2-5]”. In this study, the mitigation project is the addition or rehabilitation of a marsh in front of an existing seawall. One of the main benefits of this is the cost-savings associated with not having to heighten the seawall, which is used to quantify the monetary coastal protection value of the marshes.