nature portfolio

Peer Review File

When and where could rising seas cross thresholds for initiating wetland drowning?

Corresponding Author: Dr Michael Osland

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
Review of COMMSENV-24-0416-T “When and where could…” by Osland et al.

This manuscript takes advantage of recent studies of the wetland drowning thresholds and future sea-level projections from the latest NOAA sea-level report and performs a sensitivity test for different thresholds for wetland drowning. By comparing the projected future relative sea-level rise (RSLR) rate and three defined thresholds, Osland et al. show when and where the coastal wetlands will start to drown across the conterminous United States. They conclude the widespread drowning of coastal wetlands along the Gulf of Mexico and Atlantic coasts could begin within decades, whereas the coastal wetlands along the Pacific coasts are relatively safe. As they suggested, the conclusion of this manuscript underscores the need to prepare for future fast coastal changes. I do appreciate the whole work of this study, but more necessary revisions are needed before considering the publication of this work. Some main comments are shown below:

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1. The first concern that jumped out of my mind when I read the manuscript was how the ‘drowning’ is defined. In lines 128-129, they mentioned different definitions of ‘drowning’ in different regions, but in the present manuscript, ‘drowning’ is defined as the RSLR rates in two consecutive decades or more above the specified threshold, which is pretty arbitrary. All ‘thresholds’ literature cited in this manuscript suggests an elevation deficit rather than the wetland drowning if the RSLR rate exceeds the ‘threshold’ rate. Other aspects should be taken into consideration, especially the current wetland surface elevation. It is true the ‘drowning’ will start in 20 years or less if the relative sea-level rise rate crosses the threshold in the microtidal wetlands where the elevation of coastal wetlands is super low, which is close to the mean sea level. But how about the coastal wetlands that have high elevation and large tidal ranges? For example, a coastal wetland has a 1 m elevation, and in the worst case of this study, the threshold is 4 mm/yr, which means the maximum rate of wetland build-up is less than 4 mm/yr. Even with a 10 mm/yr RSLR rate, it will cost ~160 years for this wetland to be drowned with a 6 mm/yr elevation deficit. Apparently, 20 years is not a decent period for this scenario where the wetland is ‘projected to be drowned in the future’ if the deficit keeps existing. It would be appreciated if at least the elevation of coastal wetlands is considered, and a clearer and quantitative definition of ‘drowning’ is provided. One suggestion for the definition of drowning initialization is when the wetland surface elevation is close to the mean sea level and the RSLR rate crosses the threshold. The definition of fully drowned can be the wetland surface elevation is lower than the mean low tide, etc. A recent study by Li et al., (2024) might provide a direction about how the drowning phase of coastal wetlands can be determined based on deficit and elevation differences.

2. The second concern is the projection of future sea-level rise. I understand why the sea-level projection used in this

manuscript is from the latest NOAA report since the study area is in the conterminous United States. However, more efforts are needed to explain the sea-level projection difference between the NOAA report and the latest IPCC report. I don't think the explanation in lines 98-100 is really helpful.

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4. The whole manuscript is about coastal wetlands, but as the author stated, the tidal freshwater wetlands were excluded from the analysis. More discussion is needed here, or at least provides some estimation about the percentage of coastal wetlands that were not included (tidal freshwater wetlands) in the present manuscript.

5. Uncertainty analysis should be carried out this study, especially for the future sea-level projections, which might advance or delay the drowning time of coastal wetlands.

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Li, G., Törnqvist, T.E. & Dangendorf, S. Real-world time-travel experiment shows ecosystem collapse due to anthropogenic climate change. Nat Commun 15, 1226 (2024). https://doi.org/10.1038/s41467-024-45487-6

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Reviewer #2

(Remarks to the Author)
This is a useful and timely manuscript and the research issue is well identified towards the start of the paper. Of course it is only for the USA. I think it would be helpful to just add a qualifying statement that these thresholds may be very different in systems that are characterized by different mixes of organic / inorganic sediments, vegetation assemblages and, perhaps crucially, sit at different elevation in the tidal frame from the systems described here.

The paper is well written and well argued but there is considerable repetition of information between the main text and the methods section. It should be possible to slim down the main text such that there is less repetition (I know this problem is partly a function of the style of submission asked for).

Please see the comments on the attached PDF. These do need a response in each case.

Reviewer #3

(Remarks to the Author)
This paper gives spatially explicit estimates of the onset of tidal wetland drowning in the conterminous United States. The onset of drowning begins when the rate of sea-level rise exceeds a threshold, defined as the maximum rate of wetland elevation gain or threshold. The factors included in NOAA's sea level scenarios are comprehensive. The authors chose three sea-level rise scenarios, 0.5, 1.0 and 1.5 m global mean SLR by 2100. To calculate the time remaining before wetlands begin to lose relative elevation, they permutated these sea level scenarios with three possible rates of wetland vertical change (thresholds) ranging from 4 to 10 mm/yr. A threshold is the maximum absolute rate of positive vertical change a tidal wetland can generate. "Wetland drowning begins when sea-level rise rates exceed the upper bounds for plant growth and wetland vertical adjustment". The choice of thresholds was based on paleoecological records, contemporary instrumental records, and numerical models. They are reasonable. From NOAA's SLR projections from 2020 to 2150 (Table 2.1 in Sweet et al. 2022 I think), they divided the decadal sea level increase by 10. Take for example the increase of 0.33 to 0.46 m from 2040 to 2050 in the intermediate high scenario. That gives a rate of 13 mm/yr during that decade, which exceeds all thresholds for the onset of downing. This analysis does not predict when drowning will actually occur. That depends on the current elevation capital. The authors state that "Our findings show that the timing and extent of wetland drowning are highly sensitive to relative sea-level rise rates and wetland drowning thresholds" This is self-evident. The simplicity of this method is an advantage, enabling regulators and managers to assess wetland assets at risk of submergence, contingent on their understanding of local threshold rates. Despite potential challenges due to lack of local threshold knowledge, the study's contribution provides a valuable addition to current risk assessment tools for wetland conservation and management.

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 Dr Osland,

Your manuscript titled "When and where could rising seas cross thresholds for initiating wetland drowning?" has now been seen by 3 reviewers, and we include their comments and a review attachment at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

Specifically, please ensure that all terminology is clearly defined, consider and discuss the variability of thresholds across different settings, and quantify and communicate uncertainty in the analysis in your revision.

We are committed to providing a fair and constructive peer-review process. Please don't 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 referees' comments (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and the completed checklist:
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We hope to receive your revised paper within six weeks; please let us know if you aren't able to submit it within this time so that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still 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.

Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Olusegun Dada, PhD
Editorial Board Member
Communications Earth & Environment
orcid.org/0000-0001-8020-3323

Clare Davis, PhD
Senior Editor
Communications Earth & Environment

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Please refer to our data policies at http://www.nature.com/authors/policies/availability.html.

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Author Rebuttal letter:

RESPONSE TO REVIEWER COMMENTS

Manuscript Identification #: COMMSENV-24-0416-T
Manuscript Title: When and where could rising seas cross thresholds for initiating wetland drowning?
Manuscript Authors: Michael J. Osland, Bogdan Chivoiu, James B. Grace, Nicholas M. Enwright, Glenn R. Guntenspergen, Kevin J. Buffington, Karen M. Thorne, Joel A. Carr, William V. Sweet, Brady R. Couvillion

RESPONSE TO REVIEWER #1 COMMENTS

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Response: Thank you for your time and review.

Comment: The first concern that jumped out of my mind when I read the manuscript was how the âdrowningâ is defined. In lines 128-129, they mentioned different definitions of âdrowningâ in different regions, but in the present manuscript, âdrowningâ is defined as the RSLR rates in two consecutive decades or more above the specified threshold, which is pretty arbitrary.
Response: Our manuscript does not predict when drowning will be complete. Rather, the focus is on when wetland drowning will begin. The title of the manuscript is âWhen and where could rising seas cross thresholds for initiating wetland drowning?â. We have attempted to make this clear throughout the manuscript. One examples is in the figure captions, which include statements like this one from Figure 1. âThe loss and submergence of wetlands does not occur immediately once a drowning threshold has been crossed. While some wetlands may drown within decades of crossing a threshold, others may persist longer.â Please note that the word initiating is used 10 times (including in the title and abstract); the word initiation is used 8 times; the word start is used three times; the word onset is used 4 times; and the word begin is used 16 times.

Comment: All âthresholdsâ literature cited in this manuscript suggests an elevation deficit rather than the wetland drowning if the RSLR rate exceeds the âthresholdâ rate.

Response: While some of those papers cited in the manuscript focus on thresholds for an elevation deficit, other papers use paleoecological data or models to identify thresholds for wetland submergence and conversion to open water. To increase clarity, we have revised that section as follows:
âA recent global synthesis of paleo-stratigraphic and contemporary in situ data from marshes and mangrove forests concludes that: (1) a deficit between coastal wetland vertical adjustment and relative sea-level rise is likely at 4 mm yr-1 and highly likely at 7 mm yr-1 1; and (2) coastal wetland drowning and conversion to open water is likely when these rates are sustained. Regional analyses identify drowning thresholds as 5 mm yr-1 for eastern USA marshes2, 6-9 mm yr-1 for Mississippi River Delta marshes3, 7 mm yr-1 for marshes in San Francisco Bay4, and 4.6-7.1 mm yr-1 for UK marshes5,6. While some of these thresholds are derived from paleoecological records, others are derived from contemporary instrumental records and/or numerical models. Here, we evaluated three sea-level rise thresholds for wetland drowning (4, 7, and 10 mm yr-1), which were selected to bracket the rates identified in these global and regional studies.â

Comment: Other aspects should be taken into consideration, especially the current wetland surface elevation. It is true the âdrowningâ will start in 20 years or less if the relative sea-level rise rate crosses the threshold in the microtidal wetlands where the elevation of coastal wetlands is super low, which is close to the mean sea level. But how about the coastal wetlands that have high elevation and large tidal ranges? For example, a coastal wetland has a 1 m elevation, and in the worst case of this study, the threshold is 4 mm/yr, which means the maximum rate of wetland build-up is less than 4 mm/yr. Even with a 10 mm/yr RSLR rate, it will cost ~160 years for this wetland to be drowned with a 6 mm/yr elevation deficit. Apparently, 20 years is not a decent period for this scenario where the wetland is âprojected to be drowned in the futureâ if the deficit keeps existing. It would be appreciated if at least the elevation of coastal wetlands is considered, and a clearer and quantitative definition of âdrowningâ is provided. One suggestion for the definition of drowning initialization is when the wetland surface elevation is close to the mean sea level and the RSLR rate crosses the threshold. The definition of fully drowned can be the wetland surface elevation is lower than the mean low tide, etc.
Response: Please note that our manuscript does not predict when drowning will be complete. Rather, the focus is on when wetland drowning will begin, which is critical information needed to help prioritize future scientific and management actions. Here is some related text from the manuscript:

âWetland drowning begins when sea-level rise rates exceed the upper bounds for plant growth and wetland vertical adjustment, ultimately resulting in plant mortality, wetland erosion, wetland fragmentation, and the conversion of wetlands to open water. However, the loss and complete submergence of wetlands does not occur immediately once a drowning threshold has been crossed. While some wetlands may drown within decades of crossing a threshold, others may persist for longer3,7-9, due to factors that can prolong drowning, including tidal range, elevation capital, sediment inputs, landscape position, and the rate of relative sea-level rise.â

âBy focusing on wetland drowning thresholds and relative sea-level rise rates that exceed these thresholds, we provide an approach for rapidly gauging when and where rising sea levels could cross tipping points for initiating wetland drowning at large spatial scales. Where data are available, this simple approach can be applied at national or regional scales to quickly quantify and compare differences in the timing and extent of the onset of wetland drowning and thereby help prioritize future scientific and management actions. Customized and often estuary-specific local models of wetland responses to sea-level rise are costly, time consuming, and not feasible at large (for example, regional or national) spatial scales. Our results can be used by scientists to prioritize vulnerable coastal areas where customized local models and improved understanding of local relative sea-level rise rates and local drowning thresholds would be valuable. Local models will also be needed to determine the duration of drowning to account for factors that can prolong drowning, including elevation capital, landscape position, plant community, tidal range, sediment inputs, and the rate of relative sea-level rise14,31-33,50.â

Comment: A recent study by Li et al., (2024) might provide a direction about how the drowning phase of coastal wetlands can be determined based on deficit and elevation differences.
Response: Good point. This is a highly relevant study. We have added the following sentence related to that study: âA recent analysis of 253 surface elevation change monitoring stations in Louisiana indicated that 87% of wetlands were unable to keep up with rising water levels over a 13-year period of unusually rapid sea-level rise greater than 10 mm yr-1 10.â

Comment: The second concern is the projection of future sea-level rise. I understand why the sea-level projection used in this manuscript is from the latest NOAA report since the study area is in the conterminous United States. However, more efforts are needed to explain the sea-level projection difference between the NOAA report and the latest IPCC report. I donât think the explanation in lines 98-100 is really helpful.
Response: We have modified that section as follows to more clearly describe the relationships

between the projections and scenarios in the IPCC report and the Sweet et al. 2022 report.

âThe relationships between these scenarios and the Intergovernmental Panel on Climate Change (IPCC) emissions scenario-based and warming-level based projections11, including sea-level rise exceedance probabilities under alternative global warming levels can be found in Sweet et al. 202212. The IPCCâs Sixth Assessment Report on Climate Change projects a global mean sea-level rise by 2100 of 0.44 m (0.32-0.61 m) for the SSP2-4.5 scenario and 0.77 (0.63-1.01 m) for the SSP5-8.5 scenario11. The SSP2-4.5 and SSP5-8.5 scenarios represent Intermediate and Very High future greenhouse gas emissions scenarios, respectively, and those scenarios are based upon processes for which projections can be made with at least medium confidence11. Higher amounts of sea-level rise could be caused be low-confidence processes (for example, ice sheet dynamics) whose quantification is highly uncertain11,12. Those low-confidence processes are not included in the IPCC medium-confidence projections11,12.â

Comment: How about sea-level rise acceleration or deceleration affect the drowning time? Recent studies identify the acceleration of sea-level rise along the Gulf of Mexico and the U.S. southeast coast, where a more than 10 mm/yr geocentric sea-level (GSL) rise rate was identified over the past decade or so (Yin, 2023 & Dangendorf et al., 2023). This high rate of GSL rise might last for the next couple of years when the period of high GSL rise rate (10 mm/yr) reaches to 2 decades. Based on the âtwo-decade criteria of drowningâ in the present manuscript, the whole Gulf Coast and Southeast Coast might be identified as the initiating of wetland drowning in 2020 with all defined thresholds. It is highly possible that this high GSL rise rate might decrease in the next few decades, and how could the wetland condition be defined then if the RSLR rate is lower than the defined threshold? It would be helpful to have some discussion about this, especially since the cyclic pattern of sea-level rise may be superposed to the internal climate-driven sea-level rise, which might advance the drowning time in the future.
Response: These are interesting studies. We agree that decadal-scale accelerations and decelerations would affect wetland drowning. However, that is not the scope of our work. Our analyses use the projection data associated with the Sweet et al. 2022 report. But our approach does require the targeted rates to be sustained. Please note the following related text in the methods section: âThere were some instances where the decadal-scale relative sea-level rise rates would rise above a drowning initiation threshold but then drop below the threshold at the next decade. To determine the decade of wetland drowning initiation, we only used decades where the subsequent rate was also above the specified threshold.â

Comment: The whole manuscript is about coastal wetlands, but as the author stated, the tidal freshwater wetlands were excluded from the analysis. More discussion is needed here, or at least provides some estimation about the percentage of coastal wetlands that were not included (tidal freshwater wetlands) in the present manuscript.
Response: This is a good point and request. Unfortunately, the NOAA CCAP and NLCD data do not include a class that corresponds with the tidal freshwater wetlands. The Palustrine wetland class includes both tidal and non-tidal freshwater wetlands. The following text is relevant: âNote that these CCAP categories include vegetated tidal saline wetlands (i.e., the vegetated âestuarine wetlandâ classes), but they do not include the adjacent tidal freshwater wetlands, which are also vulnerable to the same drowning thresholds. National land cover products like CCAP and NLCD do not contain a category that identifies tidal freshwater marshes and tidal freshwater forests. Thus, our areal estimates reflect the abundance of tidal saline wetlands within a cell. The inclusion of the tidal freshwater wetlands would increase the total area of vulnerable coastal wetlands, especially in wetland-rich states like Louisiana, Florida, North Carolina, Texas, South Carolina, Georgia, Alabama, and Mississippi.â

Comment: Uncertainty analysis should be carried out this study, especially for the future sea-level projections, which might advance or delay the drowning time of coastal wetlands.
Response: The current combination of three median sea-level rise scenarios and three thresholds results in 9 combinations, which is already lot of information for the reader to digest. We could include the lower and higher percentiles for each of the three sea-level rise scenarios. However, that would result in an additional 18 combinations (27 total). For example, Figure 1 currently includes nine panels. Including uncertainty would produce 27 total panels. We are willing to include those additional 18 panels in a supporting file if deemed helpful. However, we think that including those lower and higher percentiles in the current figures would be an overwhelming amount of information for the reader to comprehend.

RESPONSE TO REVIEWER #2 COMMENTS

Comment: This is a useful and timely manuscript and the research issue is well identified towards the start of the paper.
Response: Thank you. We appreciate your time and helpful comments.

Comment: Of course it is only for the USA. I think it would be helpful to just add a qualifying statement that these thresholds may be very different in systems that are characterized by different mixes of organic / inorganic sediments, vegetation assemblages and, perhaps crucially, sit at different elevation in the tidal frame from the systems described here.
Response: In response to this comment, we have added the following text: âThese analyses highlight the importance of refining understanding of wetland drowning thresholds and the factors that control these thresholds (for example, soil properties, sediment inputs, tidal range, plant community composition). Our findings also highlight the importance of utilizing the best available relative sea-level rise projections to gauge exposure to inundation levels that exceed these thresholds.â

Comment: The paper is well written and well argued but there is considerable repetition of information between the main text and the methods section. It should be possible to slim down the main text such that there is less repetition (I know this problem is partly a function of the style of submission asked for).
Response: We have moved some of the sentences that were in the main text to the methods section. There is still some repetition due to the format (i.e., methods separated from main text).

Comment: Please see the comments on the attached PDF. These do need a response in each case.
Response: Thank you those more detail comments. We have inserted each of those comments into this document. The subsequent comments in this Reviewer #2 section are the comments that were in the attached PDF.

Comment: odd heading...
Response: Main replaced with Introduction.

Comment: 'landward encroachment of oceanic salts' odd wording...
Response: Rephrased to: âthe inland movement of oceanic salts into freshwater systems.â

Comment: Who says so? Needs a reference
Response: References added.

Comment: only if sufficient sediment is available - a crucial caveat
Response: Sediment is important for many wetlands, but some coastal wetlands can build soil elevation due to biogenic accretion and without regular sediment inputs. For example, within mangrove forests along karst coasts, belowground root accumulation can lead to surface elevation gains (biogenic accretion) in the absence of regular allochthonous sediment inputs.

Comment: it seems odd to refer to UK marshes here when the rest of the manuscript is so strongly USA - focussed. I would omit.
Response: The references in this section include several studies that are outside of the US. For example, the first example is a global synthesis. We think that including these threshold from the USA and other regions is important for justifying the selection of the three thresholds.

Comment: The comparison will be important to non US-readers. As a result, I don't think that the reader should have to go to Sweet et al (2022) to get this information. The comparison should be reported here- or at least in Supplementary Material
Response: We have modified that text as follows to more clearly describe the relationships between the IPCC and Sweet et al. 2022 scenarios and projections.

âThe relationships between these scenarios and the Intergovernmental Panel on Climate Change (IPCC) emissions scenario-based and warming-level based projections11, including sea-level rise exceedance probabilities under alternative global warming levels can be found in Sweet et al. 202212. The IPCCâs Sixth Assessment Report on Climate Change projects a global mean sea-level rise by 2100 of 0.44 m (0.32-0.61 m) for the SSP2-4.5 scenario and 0.77 (0.63-1.01 m) for the SSP5-8.5 scenario11. The SSP2-4.5 and SSP5-8.5 scenarios represent Intermediate and Very High future greenhouse gas emissions scenarios, respectively, and those scenarios are based upon processes for which projections can be made with at least medium confidence11. Higher amounts of sea-level rise could be caused be low-confidence processes (for example, ice sheet dynamics) whose quantification is highly uncertain11,12. Those low-confidence processes are not included in the IPCC medium-confidence projections11,12.â

Comment: do we really need the value judgement 'iconic'?
Response: Good point. âIconicâ has been removed from that sentence and the rest of the manuscript.

Comment: what is the definition of 'large' here? Areas in excess of what?
Response: The next sentence indicates the scale meant by large (i.e., national or regional).

Comment: similar problem with 'local'. At what scale do you move from 'local' to 'large'?
Response: We have added âestuary-specificâ to the sentence

Comment: really important that 'large' is defined
Response: We have added â(for example, regional or national)â to the sentence.

Comment: This is repetition of lines 78-81. Better here? Certianly don't need it x2
Response: These sentences are similar but different. We think that this is important information that is needed in both places. However, we can modify if needed.

Comment: that's a rather different set of arguments from the focus of this paper. Omit?
Response: In addition to comparing the impacts of alternative thresholds, our analyses also compare the impacts of alternative sea-level rise scenarios. Our results show that the initiation of wetland drowning is expected to be earlier under higher sea-level rise. This is a result that highlights the value of minimizing sea-level rise acceleration.

Comment: does the cell have to be 100% vegetated wetland or is there some cut off percentage?
Response: The intent of this step was to limit the study area to include areas that contained estuarine vegetated wetlands, regardless of the size of those wetlands. So, the included cells did not have to be 100% vegetated. We included all 1-degree cells that contained any amount of estuarine vegetated wetlands.

Comment: what is the resolution (pixel size) of the coverage data? How is fragmented wetland dealt with?
Response: The resolution of the C-CAP data is 30 m. In a fragmented marsh, some of the cells would be deemed Open Water and some of the cells would be deemed Estuarine Emergent Wetland.

RESPONSE TO REVIEWER #3 COMMENTS

Comment: This paper gives spatially explicit estimates of the onset of tidal wetland drowning in the conterminous United States. The onset of drowning begins when the rate of sea-level rise exceeds a threshold, defined as the maximum rate of wetland elevation gain or threshold. The factors included in NOAAâs sea level scenarios are comprehensive. The authors chose three sea-level rise scenarios, 0.5, 1.0 and 1.5 m global mean SLR by 2100. To calculate the time remaining before wetlands begin to lose relative elevation, they permutated these sea level scenarios with three possible rates of wetland vertical change (thresholds) ranging from 4 to 10 mm/yr. A threshold is the maximum absolute rate of positive vertical change a tidal wetland can generate. âWetland drowning begins when sea-level rise rates exceed the upper bounds for plant growth and wetland vertical adjustmentâ. The choice of thresholds was based on paleoecological records, contemporary instrumental records, and numerical models. They are reasonable.
Response: Thank you for your review and comments.

Comment: From NOAAâs SLR projections from 2020 to 2150 (Table 2.1 in Sweet et al. 2022 I think), they divided the decadal sea level increase by 10. Take for example the increase of 0.33 to 0.46 m from 2040 to 2050 in the intermediate high scenario. That gives a rate of 13 mm/yr during that decade, which exceeds all thresholds for the onset of downing. This analysis does not predict when drowning will actually occur. That depends on the current elevation capital. The authors state that âOur findings show that the timing and extent of wetland drowning are highly sensitive to relative sea-level rise rates and wetland drowning thresholdsâ This is self-evident. The simplicity of this method is an advantage, enabling regulators and managers to assess wetland assets at risk of submergence, contingent on their understanding of local threshold rates.
Response: We agree that the simplicity is an advantage that enables the approach to be applied at larges spatial scales (e.g., regional or national). Our results can be used by scientists to prioritize vulnerable coastal areas where customized local models and improved understanding of local relative sea-level rise rates and local drowning thresholds would be valuable.

Comment: Despite potential challenges due to lack of local threshold knowledge, the study's contribution provides a valuable addition to current risk assessment tools for wetland conservation and management.
Response: Thank you for your review.
References mentioned in this document.

1 Saintilan, N. et al. Widespread retreat of coastal habitat is likely at warming levels above 1.5Â° C. Nature 621, 112-119 (2023).
2 Morris, J. T. et al. Contributions of organic and inorganic matter to sediment volume and

accretion in tidal wetlands at steady state. Earth's Future 4, 110-121 (2016).
3 TÃ¶rnqvist, T. E., Jankowski, K. L., Li, Y.-X. & GonzÃ¡lez, J. L. Tipping points of Mississippi Delta marshes due to accelerated sea-level rise. Science Advances 6, eaaz5512 (2020).
4 Buffington, K. J. et al. Incorporation of uncertainty to improve projections of tidal wetland elevation and carbon accumulation with sea-level rise. Plos one 16, e0256707 (2021).
5 Horton, B. P. et al. Predicting marsh vulnerability to sea-level rise using Holocene relative sea-level data. Nature Communications 9, 2687 (2018).
6 Saintilan, N. et al. Constraints on the adjustment of tidal marshes to accelerating sea level rise. Science 377, 523-527 (2022).
7 Lovelock, C. E. et al. The vulnerability of Indo-Pacific mangrove forests to sea-level rise. Nature 526, 559-563 (2015).
8 Haaf, L. et al. Sediment accumulation, elevation change, and the vulnerability of tidal marshes in the Delaware Estuary and Barnegat Bay to accelerated sea level rise. Estuaries and Coasts 45, 413-427 (2022).
9 Langston, A. K., Alexander, C. R., Alber, M. & Kirwan, M. L. Beyond 2100: Elevation capital disguises salt marsh vulnerability to sea-level rise in Georgia, USA. Estuarine, Coastal and Shelf Science 249, 107093 (2021).
10 Li, G., TÃ¶rnqvist, T. E. & Dangendorf, S. Real-world time-travel experiment shows ecosystem collapse due to anthropogenic climate change. Nature Communications 15, 1226 (2024).
11 Fox-Kemper, B. et al. in Climate change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (eds V Masson-Delmotte et al.) 1211â1362 (Cambridge University Press, 2021).
12 Sweet, W. V. et al. Global and regional sea level rise scenarios for the United States: updated mean projections and extreme water level probabilities along U.S. coastlines. NOAA Technical Report NOS 01. (National Oceanic and Atmospheric Administration, National Ocean Service, 2022).

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
I have re-read the manuscript by Osland et al., and most my concerns are solved. It is well-written and in good shape for publication if the following minor revisions are made.
1. On page 2, lines 43-44. Need a reference.
2. On page 4, line 88. I agree with the other reviewer that the reference for the UK marshes is not necessary, especially since the global synthesis study has already been included.
3. On pages 4-5, lines 93-106. “Our study area spans … fossil fuel withdrawals, and other factors”. This part is repeated in the method section.
4. On page 10, line 230. “ could be caused by low-confidence processes ...”
5. On page 10, line 226. “0.44 m (0.32-0.61)” should be the SSP1-1.9 scenario, SSP2-4.5 scenario should be 0.56 m (0.44–0.76). This change is relative to a baseline of 1995-2014 in the IPCC report, while in the NOAA sea level report, the rising sea level for 2100 is relative to a 2000 baseline, line 216.
6. On page 10, line 237, relative to 2000 sea levels (Table 2.2 in NOAA sea level report, 2022)?
7. On page 11, line 254. This is not clear to me. Are you referring to the onset of the drowning if the rate of next decade was above the threshold or the rates for all the following decades were above the threshold? For example, if the drowning initiated on 2030, does that mean the sea-level rise rate for all the following decades (2040-2150) are above the threshold as well?
8. On page 20, line 474, caption for Figure 4, "These are wetlands flooded at relative ..." this sounds like the wetlands are flooded once the drowning initiated, whereas the tidal wetlands are flooded regularly during high tide no matter whether the threshold is crossed or not.
9. Lots of repetition among captions and legends in Figure 2, 3, and 4, Supplementary Figure 1, 2, and 3

Reviewer #2

(Remarks to the Author)
The changes made in response to a very full set of reviewer comments are generally good, although there are a couple in Reviewer 2 that are not answered. I see no harm in more clearly stating that the analytical component is USA only. It is important that the distinction between the initiation of wetland drowning v. the completion of wetland drowning is clearly made. This is an important point. Certainly in the meso-tidal wetlands of NW Europe, where marshes sit high in the tidal frame, drowning may initiate a change into a different system but one which might still support a vegetated platform. In such systems, there is no simple evolution from vegetated marsh to open water. I think that point about uncertainty analysis is pertinent and I would have the extended number of panels in Supplementary Material.

Reviewer #3

(Remarks to the Author)
Authors did a nice job with the revisions and answers to reviewers questions. After rereading this I am left with the feeling that we already know that drowning begins when rates of SLR exceed rates of marsh elevation gain. Don't we? But the novelty I think is mapping relative SLR corrected for local subsidence rates (or rise) to assess when the tipping point would be reached.

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 Dr Osland,

Your manuscript titled "When and where could rising seas cross thresholds for initiating wetland drowning?" 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 provided you comprehensively address the remaining discussion points from reviewers #1 and #2 in the manuscript and include the data uncertainty analysis within the Supplementary Material. If appropriate, we will publish your manuscript under the open access CC BY license (Creative Commons Attribution v4.0 International License)

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.

If you have any questions or concerns about any of our requests, please do not hesitate to contact me.

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

Best regards,

Carolina Ortiz Guerrero, Ph.D.

Associate Editor
Communications Earth & Environment

REVIEWERS' COMMENTS:

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I have re-read the manuscript by Osland et al., and most my concerns are solved. It is well-written and in good shape for publication if the following minor revisions are made.
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8. On page 20, line 474, caption for Figure 4, "These are wetlands flooded at relative ..." this sounds like the wetlands are flooded once the drowning initiated, whereas the tidal wetlands are flooded regularly during high tide no matter whether the threshold is crossed or not.
9. Lots of repetition among captions and legends in Figure 2, 3, and 4, Supplementary Figure 1, 2, and 3

Reviewer #2 (Remarks to the Author):

The changes made in response to a very full set of reviewer comments are generally good, although there are a couple in Reviewer 2 that are not answered. I see no harm in more clearly stating that the analytical component is USA only. It is important that the distinction between the initiation of wetland drowning v. the completion of wetland drowning is clearly made. This is an important point. Certainly in the meso-tidal wetlands of NW Europe, where marshes sit high in the tidal frame, drowning may initiate a change into a different system but one which might still support a vegetated platform. In such systems, there is no simple evolution from vegetated marsh to open water. I think that point about uncertainty analysis is pertinent and I would have the extended number of panels in Supplementary Material.

Reviewer #3 (Remarks to the Author):

Authors did a nice job with the revisions and answers to reviewers questions. After rereading this I am left with the feeling that we already know that drowning begins when rates of SLR exceed rates of marsh elevation gain. Don't we? But the novelty I think is mapping relative SLR corrected for local subsidence rates (or rise) to assess when the tipping point would be reached.

Author Rebuttal letter:

RESPONSE TO REVIEWER COMMENTS

Manuscript Identification #: COMMSENV-24-0416A
Manuscript Title: When and where could rising seas cross thresholds for initiating wetland drowning?
Manuscript Authors: Michael J. Osland, Bogdan Chivoiu, James B. Grace, Nicholas M. Enwright, Glenn R. Guntenspergen, Kevin J. Buffington, Karen M. Thorne, Joel A. Carr, William V. Sweet, Brady R. Couvillion

RESPONSE TO REVIEWER #1 COMMENTS

Comment: I have re-read the manuscript by Osland et al., and most my concerns are solved. It is well-written and in good shape for publication if the following minor revisions are made.
Response: Thank you for your review.

Comment: 1. On page 2, lines 43-44. Need a reference.
Response: We have added two references to support that statement (1,2 below).
ï· May, C. L. et al. in Fifth National Climate Assessment (eds A.R. Crimmins et al.) (U.S. Global Change Research Program, 2023).
ï· Couvillion, B. R., Beck, H., Schoolmaster, D. & Fischer, M. Land area change in coastal Louisiana 1932 to 2016: U.S. Geological Survey Scientific Investigations Map 3381, 16 p. pamphlet, https://doi.org/10.3133/sim3381. (2017).

Comment: 2. On page 4, line 88. I agree with the other reviewer that the reference for the UK marshes is not necessary, especially since the global synthesis study has already been included.
Response: We have removed the reference to UK marshes.

Comment: 3. On pages 4-5, lines 93-106. âOur study area spans â¦ fossil fuel withdrawals, and other factorsâ. This part is repeated in the method section.
Response: We have deleted the repetitive text from the methods section.

Comment: 4. On page 10, line 230. â could be caused by low-confidence processes ...â
Response: Thanks for catching that. We have changed the âbeâ to âbyâ in that sentence.

Comment: 5. On page 10, line 226. â0.44 m (0.32-0.61)â should be the SSP1-1.9 scenario, SSP2-4.5 scenario should be 0.56 m (0.44â0.76). This change is relative to a baseline of 1995-2014 in the IPCC report, while in the NOAA sea level report, the rising sea level for 2100 is relative to a 2000 baseline, line 216.
Response: Thanks for catching this too. We have changed that sentence as follows: âThe IPCCâs Sixth Assessment Report on Climate Change projects a global mean sea-level rise by 2100 of 0.56 m (0.44-0.76 m) for the SSP2-4.5 scenario and 0.77 (0.63-1.01 m) for the SSP5-8.5 scenario3, relative to a baseline of 1995-2014.â
Comment: 6. On page 10, line 237, relative to 2000 sea levels (Table 2.2 in NOAA sea level report, 2022)?
Response: We have added ârelative to a 2000 baselineâ in the sentence that introduces the scenarios from the USA interagency report.

Comment: 7. On page 11, line 254. This is not clear to me. Are you referring to the onset of the drowning if the rate of next decade was above the threshold or the rates for all the following decades were above the threshold? For example, if the drowning initiated on 2030, does that mean the sea-level rise rate for all the following decades (2040-2150) are above the threshold as well?
Response: Our calculations required two consecutive decades, but do not necessarily refer to the entire period through 2150. See Supplementary Figure 1 for more detail and examples from four cells. Supplementary Figure 1 is also pasted below. To increase clarity, we have revised that section as follows: âThere were some instances where the decadal-scale relative sea-level rise rates would rise above a drowning initiation threshold but then drop below the threshold at the next decade. To determine the decade of wetland drowning initiation, we only used decades where the rate for the following decade was also above the specified threshold. The decade for the onset of drowning was identified by the last year of the first decade (for example, 2030 for the 2020-2030 decade where the 2030-2040 decade was also above the specified threshold).â

Supplementary Figure 1. Relative sea-level rise (SLR) rates for three alternative SLR scenarios for 4 of the 168 1-degree cells included in this study. The three horizontal lines show the 4, 7, and 10 mm yr-1 thresholds for initiating wetland drowning. Intermediate-Low corresponds with a 0.5 m GMSLR by 2100, Intermediate corresponds with a 1.0 m GMSLR by 2100, and Intermediate-High corresponds with a 1.5 GMSLR by 2100. GMSLR = global mean SLR.
Comment: 8. On page 20, line 474, caption for Figure 4, "These are wetlands flooded at relative ..." this sounds like the wetlands are flooded once the drowning initiated, whereas the tidal wetlands are flooded regularly during high tide no matter whether the threshold is crossed or not.
Response: We have replaced âflooded atâ with âexposed toâ in the captions for Figures 3, 4, Supplementary Figure 2, and Supplementary Figure 3.

Comment: 9. Lots of repetition among captions and legends in Figure 2, 3, and 4, Supplementary Figure 1, 2, and 3
Response: We wanted to make sure that the readers could interpret an individual figure without having to refer to other figures. Please let us know if any of the repeated text in those figure captions should be removed.

RESPONSE TO REVIEWER #2 COMMENTS

Comment: The changes made in response to a very full set of reviewer comments are generally good, although there are a couple in Reviewer 2 that are not answered.
Response: Thank you. We have made additional revisions to respond to these comments.

Comment: I see no harm in more clearly stating that the analytical component is USA only.
Response: In response to this comment, we have added the following sentences in the Results and Discussion section: âOur analyses utilize thresholds and relative sea-level rise rates for the conterminous United States. However, this approach may need to be customized for other parts of the world where thresholds are different or coastal wetland responses to sea-level rise are governed by additional factors.â

Comment: It is important that the distinction between the initiation of wetland drowning v. the completion of wetland drowning is clearly made. This is an important point.
Response: Thank you. We have attempted to make this distinction clear throughout the manuscript.

Comment: Certainly in the meso-tidal wetlands of NW Europe, where marshes sit high in the tidal frame, drowning may initiate a change into a different system but one which might still support a vegetated platform. In such systems, there is no simple evolution from vegetated marsh to open water.
Response: We agree. In some wetlands, rising sea levels are expected to induce shifts in plant community composition prior to conversion to open water. That is the case for some wetlands in the United States too, where high elevation capital can allow shifts in plant communities (e.g., from high marsh to low marsh) prior to conversion to open water in response to rising sea levels.

Comment: I think that point about uncertainty analysis is pertinent and I would have the extended number of panels in Supplementary Material.
Response: In response to this request, we have added two supplementary figures (Supplementary Figures 3 and 4). These two figures each include nine panels and show the lower (17%) and higher (83%) percentiles for each of the three sea-level rise scenario projections.
RESPONSE TO REVIEWER #3 COMMENTS

Comment: Authors did a nice job with the revisions and answers to reviewers questions. After rereading this I am left with the feeling that we already know that drowning begins when rates of SLR exceed rates of marsh elevation gain. Don't we? But the novelty I think is mapping relative SLR corrected for local subsidence rates (or rise) to assess when the tipping point would be reached.
Response: Thank you for your review and helpful comments.

References include in this response to reviewer comment document
1 May, C. L. et al. in Fifth National Climate Assessment (eds A.R. Crimmins et al.) (U.S. Global Change Research Program, 2023).
2 Couvillion, B. R., Beck, H., Schoolmaster, D. & Fischer, M. Land area change in coastal Louisiana 1932 to 2016: U.S. Geological Survey Scientific Investigations Map 3381, 16 p. pamphlet, https://doi.org/10.3133/sim3381. (2017).
3 Fox-Kemper, B. et al. in Climate change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (eds V Masson-Delmotte et al.) 1211â1362 (Cambridge University Press, 2021).

Title: When and where could rising seas cross thresholds for initiating wetland drowning?

Authors: Michael J. Osland[1], Bogdan Chivoiu[2], James B. Grace[1], Nicholas M. Enwright[1], Glenn R. Guntenspergen[3], Kevin J. Buffington[4], Karen M. Thorne[4], Joel A. Carr[3], William V. Sweet[5], Brady R. Couvillion[6]

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[5]National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring MD, USA

[6]U.S. Geological Survey, Wetland and Aquatic Research Center, Baton Rouge, LA, USA

Corresponding author: Michael J. Osland (mosland@usgs.gov)

Content type: Article

by reviewers. Because the manuscript has not yet been approved for publication by the U.S. Geological Survey (USGS), it does not represent any official USGS finding or policy.

Abstract: Accelerated sea-level rise is an existential threat for coastal wetlands, but the timing and extent of wetland drowning are debated. Recent data syntheses have clarified future relative sea-level rise exposure and sensitivity thresholds for drowning. We integrated these advances to estimate when and where rising sea levels could cross thresholds for initiating wetland drowning across the conterminous United States. Our results show that there is much spatial variation in relative sea-level rise rates, which impacts the potential timing and extent of wetlands crossing thresholds. High rates of relative sea-level rise along wetland-rich parts of the Gulf of Mexico and Atlantic coasts highlight areas where wetlands are already drowning or could begin to drown within decades, including the iconic wetland complexes within the Mississippi River Delta, Greater Everglades, Chesapeake Bay, Texas, Georgia, and the Carolinas. Collectively, our results underscore the need to prepare for transformative coastal change.

Main

Sea-level rise is expected to be among the most costly and far-reaching consequences of climate change[1-5]. Coastal cities and ecosystems are already being transformed by more frequent flooding and the landward encroachment of oceanic salts. Coastal wetlands, including marshes, mangrove forests, and freshwater swamps, are among the most threatened ecosystems. These wetlands are increasingly recognized for their ecosystem services and their ability to mitigate the impacts of climate change[6-8]. In addition to improving water quality and supporting critical fish and wildlife habitat, coastal wetlands protect coastal communities from storms, support fisheries, and sequester carbon from the atmosphere. Yet for decades, there has been debate regarding the future of these valuable ecosystems in the face of rapidly rising seas[9].

While some studies have indicated that catastrophic wetland loss is imminent[9-15], others have argued that wetlands are resilient ecosystems that can readily adapt to future change[16-21]. The ensuing uncertainty from this debate has hindered decisions regarding how and when to prepare for transformative coastal change. For example, should managers use limited resources to: (1) resist change and help current coastal wetlands adapt where they are now; or (2) acknowledge transformative coastal change and facilitate the retreat and migration of wetlands into new positions in the coastal landscape? To better inform future-focused coastal conservation and restoration decisions, there is a pressing need to advance understanding regarding the potential timing of coastal wetland drowning under rapidly rising seas. Here, we use emerging knowledge regarding coastal wetland drowning thresholds and future relative sea-level rise rates to elucidate when and where coastal wetland drowning could begin across the conterminous United States. We show how the best available data concerning these two critical components can bring clarity to this debate and provide powerful information at large spatial scales regarding the initiation of coastal wetland drowning under accelerated sea-level rise.

Growing consensus regarding thresholds

In the past decade, there has been growing consensus – from paleoecological records, contemporary instrumental records, and numerical models – regarding critical thresholds for wetland drowning[10,13,22-26]. Coastal wetland responses to sea-level rise are greatly influenced by biogeomorphic feedbacks that enable wetlands to build surface elevation to avoid drowning and adjust to rising seas[17,27,28]. These feedbacks involve nonlinear interactions between flooding regimes, root growth, sedimentation, and other factors, which can collectively lead to the vertical accumulation of organic matter and sediments under the right conditions. While these feedbacks can enable wetlands to gain elevation to adjust alongside small increases in sea level, there are submergence limits,[13] or drowning thresholds, beyond which coastal wetlands cannot adjust to rising seas and begin to drown[10,13,22-25,29]. Wetland drowning begins when sea-level rise rates exceed the upper bounds for plant growth and wetland vertical adjustment, ultimately resulting in plant mortality, wetland erosion, wetland fragmentation, and the conversion of wetlands to open water. However, the loss and complete submergence of wetlands does not occur immediately once a drowning threshold has been crossed. While some wetlands may drown within decades of crossing a threshold, others may persist for longer[13,30-32], due to factors that can prolong drowning, including tidal range, elevation capital, sediment inputs, landscape position, and the rate of relative sea-level rise.

A recent global synthesis of paleo-stratigraphic and contemporary in situ data from marshes and mangrove forests concludes that a deficit between coastal wetland vertical adjustment and relative sea-level rise is likely at 4 mm yr^{-1} and highly likely at 7 mm yr^{-1} [10]. Regional analyses identify drowning thresholds as 5 mm yr^{-1} for eastern USA marshes[22], 6-9 mm yr^{-1} for Mississippi River Delta marshes[13], 7 mm yr^{-1} for marshes in San Francisco Bay[26], and 4.6-7.1 mm yr^{-1} for UK marshes[23,24]. Here, we evaluated three sea-level rise thresholds for wetland drowning (4, 7, and 10 mm yr^{-1}), which were selected to bracket the rates identified in these global and regional studies.

Relative sea-level rise data and projections

Our study area spans the coastal conterminous United States (CONUS), which includes Washington, D.C. and 22 coastal states along the Pacific Ocean, Gulf of Mexico, and Atlantic Ocean (Fig. 1). Within the study area, we created a grid of 168 1-degree resolution cells for data acquisition and analyses. We examined three alternative sea-level rise scenarios, the Intermediate-Low, Intermediate, and Intermediate-High relative sea-level rise scenarios identified by the most recent United States interagency sea-level rise technical report[3]. These three scenarios correspond to 0.5, 1.0, and 1.5-m global mean sea-level rise levels by 2100, respectively. The relationships between these scenarios and the Intergovernmental Panel on Climate Change (IPCC) warming-level based projections[2], including sea-level rise exceedance probabilities under alternative global warming levels can be found in Sweet et al. 2022[3].

For each of the three global mean sea-level rise scenarios, our analyses incorporate decadal regional relative sea-level rise projections[3], which account for critical processes that influence local sea-level rise rates, such as: (1) changes in gravitational field and rotation; (2) shifts in oceanographic factors; and (3) vertical land movement (for example, subsidence or uplift) due to sediment compaction, glacial isostatic adjustment, groundwater withdrawals, fossil fuel withdrawals, and other factors. These relative sea-level rise projections are critical in the United States because there is much spatiotemporal variation, with some regions affected by rates that are much higher (for example, the western Gulf of Mexico) or much lower (for example, the Northwest region's Pacific coast) than global mean sea-level rise rates. We used the three relative sea-level rise scenario projections to determine when the selected drowning thresholds would be crossed. For each grid cell, we used the decadal-scale data associated with the regional relative sea-level rise scenarios[3] to identify the decade of coastal wetland drowning initiation, which was defined as the decade in which relative sea-level rise rates are projected to be at rates greater than or equal to 4, 7, or 10 mm yr^{-1} (see Extended Data Fig. 1 for examples from 4 of the 168 cells). To determine the wetland area that could be affected, the extent of potential drowning initiation within each grid cell was determined using current estuarine wetland coverage data[33].

On a regional basis, the three scenarios closely align with the regional trajectories that sea-level rise is currently on and expected to maintain for at least the next several decades[3]. For example, the trajectory along the Southeast region's Atlantic coast by 2050 falls between the Intermediate and Intermediate High Scenarios (0.36 and 0.43 m rise by 2050, respectively, relative to 2005 sea levels)[3]. The trajectory along the western Gulf of Mexico coast is even higher, falling between the Intermediate and Intermediate High Scenarios (0.57 and 0.63 m rise by 2050, respectively)[3]. In contrast, the trajectory along the Northwest region's Pacific coast is lower, falling between the Intermediate and Intermediate-Low Scenarios (0.15 and 0.18 m rise by 2050, respectively)[3].

Coastal wetlands are not the same across CONUS

Coastal wetlands in the United States are diverse. Thus, coastal wetland drowning means different things in different regions (Fig. 2a and 2b). For example, in the iconic Everglades ecosystems of tropical south Florida, coastal wetland drowning often refers to the submergence of mangrove forests and freshwater marshes as they are converted to mudflats and open water[34,35]. In the Mississippi River Delta and Chesapeake Bay, coastal wetland drowning often refers to the submergence of temperate coastal marshes and freshwater forests[13,36]. In arid parts of California and south Texas, coastal wetland drowning may refer to the submergence of hypersaline, succulent plant-dominated marshes[37]. Here, our use of the term coastal wetland drowning encompasses all these regional variations of vegetated coastal wetland conversions to tidal flats or open water due to submergence, wetland erosion, and wetland fragmentation.

When will wetland drowning begin?

Our results show that there is substantial spatial variation across CONUS in wetland abundance and exposure to high rates of relative sea-level rise, which produces much variability in the potential timing and extent of wetlands crossing thresholds for initiating drowning (Figs. 1, 3, 4; Extended Data Fig. 2). We present these results at state-specific (Fig. 3; Extended Data Fig. 2) and CONUS scales (Fig. 4). In general, low-lying regions that currently have a high areal coverage of coastal wetlands[38] are also among the most vulnerable to wetland drowning (Fig. 3; Extended Data Fig. 3). The most prominent wetland drowning hotspot is within Louisiana’s Mississippi River Delta. From 1932 to 2016, Louisiana lost 4833 km^2 of coastal wetlands due to high rates of subsidence and relative sea-level rise (Fig. 2c)[36]. Louisiana currently accounts for nearly 30% of CONUS’ coastal wetlands[38], and those wetlands are expected to continue to be among the first to drown[13] (Figs. 1, 3, 4; Extended Data Fig. 2). At rates exceeding 6 to 9 mm yr^{-1}, considerable conversion of marsh to open water is expected to occur within 50 years in the Mississippi River Delta[13].

In general, wetland drowning is expected to begin earliest along the wetland-rich northwestern Gulf of Mexico, south-Atlantic, and mid-Atlantic coasts, especially within subsidence hotspots, where relative sea-level rise rates already exceed critical thresholds for drowning. In addition to Louisiana, the Texas coast and Chesapeake Bay are also wetland-rich regions[38] that also contain subsidence hotspots[39-41], where wetland drowning is happening now[42,43]. Although Florida’s coastal wetlands have been comparatively stable over the past thousand years due to minimal subsidence and small rates of relative sea-level rise[44,45], the potential extent of future wetland drowning in Florida is very large[34,35] due to the state’s low-lying topography and because the Florida coast contains roughly 25% of CONUS’ coastal wetlands[38], including the iconic mangrove-marsh mosaic of the Greater Everglades[46]. Conversely, the onset of wetland drowning is expected to be later along the Pacific coast, especially along the Washington and Oregon coasts due to effects of post-glacial rebound, which produces relative sea-level rise rates that are lower than global mean sea-level rise rates[47,48] (Extended Data Fig. 1).

Our findings show that the timing and extent of wetland drowning are highly sensitive to relative sea-level rise rates and wetland drowning thresholds (Figs. 1, 3, 4, Extended Data Fig.

1). For example, wetland drowning is expected to begin on all three coasts by 2040 under the highest sea-level rise scenario and lowest drowning threshold (Fig. 1g; Fig. 3g; Fig. 4c). Conversely, wetland drowning is delayed under the lowest sea-level rise scenario and highest drowning threshold (Fig. 1c; Fig. 3c; Fig. 4a). Under the Intermediate-Low scenario, the timing and extent of wetland drowning vary greatly in response to drowning thresholds (compare Fig. 1a-c; Fig. 3a-c; Fig. 4a). However, under the Intermediate-High scenario, wetland drowning begins between 2020-2060 under all three drowning thresholds (compare Fig. 1g-i; Fig. 3g-i; Fig. 4c). These analyses highlight the importance of refining understanding of wetland drowning thresholds and utilizing the best available relative sea-level rise projections to gauge exposure to inundation levels that exceed these thresholds.

Discussion

By focusing on wetland drowning thresholds and relative sea-level rise rates that exceed these thresholds, we provide an approach for rapidly gauging when and where rising sea levels could cross tipping points for initiating wetland drowning at large spatial scales. Where data are available, this simple approach can be applied at national or regional scales to quickly quantify and compare differences in the timing and extent of the onset of wetland drowning and thereby help prioritize future scientific and management actions. Customized local models of wetland responses to sea-level rise are often costly, time consuming, and not feasible at large spatial scales. Our results can be used by scientists to prioritize vulnerable coastal areas where customized local models and improved understanding of local relative sea-level rise rates and local drowning thresholds would be valuable. Local models will also be needed to determine the duration of drowning to account for factors that can prolong drowning, including elevation capital, landscape position, tidal range, sediment inputs, and the rate of relative sea-level rise[13,30-32,49].

Collectively, our findings underscore the importance of minimizing sea-level rise acceleration to avoid catastrophic wetland losses and transformative coastal change associated with wetland drowning. Our results also show that wetland drowning under many scenarios could begin within decades. Thus, there is an urgent need to better anticipate and prepare for the social and ecological implications of coastal wetland losses and transformations due to rapidly rising seas.

Methods

Study area and study grid

Our study area spanned the coastal conterminous United States (CONUS), which includes Washington, D.C. and 22 coastal states along the Pacific Ocean, Gulf of Mexico, and Atlantic Ocean (Fig. 1). Within this area, we created a grid of 168 1-degree resolution cells for data acquisition and analyses. These cells were created to: (1) match the spatial resolution and registration of the relative sea-level rise data[3]; and (2) include only cells containing estuarine vegetated wetlands, which were identified using estuarine wetland coverage data (that is, the estuarine emergent, scrub shrub, and forested wetland classes) from NOAA’s 2016 Coastal Change Analysis Program [C-CAP] land cover data[33]. Note that these CCAP categories include vegetated tidal saline wetlands (i.e., the vegetated “estuarine wetland” classes), but they do not include the adjacent tidal freshwater wetlands, which are also vulnerable to the same drowning thresholds. National land cover products like CCAP and NLCD do not contain a category that identifies tidal freshwater marshes and tidal freshwater forests. Thus, our areal estimates reflect the abundance of tidal saline wetlands within a cell. The inclusion of the tidal freshwater wetlands would increase the total area of vulnerable coastal wetlands, especially in wetland-rich states like Louisiana, Florida, North Carolina, Texas, South Carolina, Georgia, Alabama, and Mississippi.

Global and regional relative sea-level rise scenarios

We examined the effects of the Intermediate-Low, Intermediate, and Intermediate-High scenarios identified by the most recent United States interagency sea-level rise report[3], which for 2100 correspond to 0.5, 1.0, and 1.5-m global mean sea-level rise scenarios. For each of the three global scenarios, our analyses incorporate regional relative sea-level rise scenarios, which account for critical processes that influence local sea-level rise rates, such as: (1) changes in gravitational field and rotation; (2) shifts in oceanographic factors; and (3) vertical land movement (for example, subsidence or uplift) due to sediment compaction, glacial isostatic adjustment, groundwater withdrawals, fossil fuel withdrawals, and other factors[3].

Data analyses: timing and extent of the start of wetland drowning

We evaluated the following three thresholds for wetland drowning: sea-level rise rates of 4, 7, and 10 mm yr^{-1}. These thresholds were selected to bracket studies indicating that coastal wetland drowning begins when sea-level rates exceed thresholds for vertical adjustment[10,13,22-26]. The relative sea-level rise projection data begin in 2005 and are available for each decade thereafter from 2020-2150. To determine the decadal-scale rate of relative sea-level rise, we divided the sea-level increase by the number of years (that is, 10 for most intervals, 15 for 2005-2020). For example, a relative sea-level increase of 30mm across a decade was converted to a relative sea-level rise rate of 3 mm yr^{-1}. There were some instances where the decadal-scale relative sea-level rise rates would rise above a drowning initiation threshold but then drop below the threshold at the next decade. To determine the decade of wetland drowning initiation, we only used decades where the subsequent rate was also above the specified threshold. See Extended Data Fig. 1 for examples of the relative sea-level rise data relative to thresholds for four individual cells in Washington (Extended Data Fig. 1a), Maine (Extended Data Fig. 1b), Florida (Extended Data Fig. 1a), and Louisiana (Extended Data Fig. 1d).

Data analyses and visualization

We developed maps that show the timing of the onset of wetland drowning under each of the nine threshold-by-sea-level rise combinations (that is, three thresholds by three sea-level rise scenarios). To determine the amount of wetland affected, the extent of potential drowning initiation within each grid cell was determined using estuarine vegetated wetland coverage data (that is, the estuarine emergent, scrub shrub, and forested wetland classes) from NOAA's 2016 C-CAP 30-m land cover data[33]. At the state scale, we developed figures that show the timing, area, and percent of wetlands expected to cross drowning initiation thresholds for each of the 22 coastal states and Washington D.C. At the CONUS scale, we developed figures that show the timing and percent of wetland area expected to cross drowning initiation thresholds.

Data availability

Data will be made publicly available upon acceptance as a USGS Data Release on Sciencebase.gov.

References

1 IPCC. *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. (IPCC, 2023).

2 Fox-Kemper, B. *et al.* in *Climate change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on*

Climate Change (eds V Masson-Delmotte *et al.*) 1211–1362 (Cambridge University Press, 2021).

3 Sweet, W. V. *et al. Global and regional sea level rise scenarios for the United States: updated mean projections and extreme water level probabilities along U.S. coastlines. NOAA Technical Report NOS 01*. (National Oceanic and Atmospheric Administration, National Ocean Service, 2022).

4 Hauer, M. E. *et al.* Sea-level rise and human migration. *Nature Reviews Earth & Environment* **1**, 28-39 (2020).

5 Barnard, P. L. *et al.* Dynamic flood modeling essential to assess the coastal impacts of climate change. *Scientific Reports* **9**, 4309 (2019).

6 Barbier, E. B. *et al.* The value of estuarine and coastal ecosystem services. *Ecological Monographs* **81**, 169-193 (2011).

7 Temmerman, S. *et al.* Marshes and mangroves as nature-based coastal storm buffers. *Annual Review of Marine Science* **15**, 95-118 (2023).

8 Macreadie, P. I. *et al.* Blue carbon as a natural climate solution. *Nature Reviews Earth & Environment* **2**, 826-839 (2021).

9 Törnqvist, T. E., Cahoon, D. R., Morris, J. T. & Day, J. W. Coastal wetland resilience, accelerated sea-level rise, and the importance of timescale. *AGU Advances* **2**, e2020AV000334 (2021).

10 Saintilan, N. *et al.* Widespread retreat of coastal habitat is likely at warming levels above 1.5° C. *Nature* **621**, 112-119 (2023).

11 Park, R. A., Trehan, M. S., Mausel, P. W. & Howe, R. C. in *The potential effects of global climate change on the United States. Appendix B- Sea level rise* (eds J.B. Smith & D.A. Tirpak) (Office of Policy, Planning, and Evaluation, U.S. Environmental Protection Agency, 1989).

12 Parkinson, R. W., DeLaune, R. D. & White, J. R. Holocene sea-level rise and the fate of mangrove forests within the wider caribbean region. *Journal of Coastal Research* **10**, 1077-1086 (1994).

13 Törnqvist, T. E., Jankowski, K. L., Li, Y.-X. & González, J. L. Tipping points of Mississippi Delta marshes due to accelerated sea-level rise. *Science Advances* **6**, eaaz5512 (2020).

14 Saintilan, N. *et al.* Constraints on the adjustment of tidal marshes to accelerating sea level rise. *Science* **377**, 523-527 (2022).

15 Blum, M. D. & Roberts, H. H. Drowning of the Mississippi Delta due to insufficient sediment supply and global sea-level rise. *Nature Geoscience* **2**, 488-491 (2009).

16 French, J. R. Numerical simulation of vertical marsh growth and adjustment to accelerated sea-level rise, North Norfolk, UK. *Earth Surface Processes and Landforms* **18**, 63-81 (1993).

17 Morris, J. T., Sundareshwar, P. V., Nietch, C. T., Kjerfve, B. & Cahoon, D. R. Responses of coastal wetlands to rising sea level. *Ecology* **83**, 2869-2877 (2002).

18 Kirwan, M. L. & Megonigal, J. P. Tidal wetland stability in the face of human impacts and sea-level rise. *Nature* **504**, 53-60 (2013).

19 Kirwan, M. L., Temmerman, S., Skeehan, E. E., Guntenspergen, G. R. & Fagherazzi, S. Overestimation of marsh vulnerability to sea level rise. *Nature Climate Change* **6**, 253-260 (2016).

20 Schuerch, M. *et al.* Future response of global coastal wetlands to sea-level rise. *Nature* **561**, 231-234 (2018).

21 Buchanan, M. K., Kulp, S. & Strauss, B. Resilience of US coastal wetlands to accelerating sea level rise. *Environmental Research Communications* **4**, 061001 (2022).
22 Morris, J. T. *et al.* Contributions of organic and inorganic matter to sediment volume and accretion in tidal wetlands at steady state. *Earth's Future* **4**, 110-121 (2016).
23 Horton, B. P. *et al.* Predicting marsh vulnerability to sea-level rise using Holocene relative sea-level data. *Nature Communications* **9**, 2687 (2018).
24 Saintilan, N. *et al.* Constraints on the adjustment of tidal marshes to accelerating sea level rise. *Science* **377**, 523-527 (2022).
25 Saintilan, N. *et al.* Thresholds of mangrove survival under rapid sea level rise. *Science* **368**, 1118-1121 (2020).
26 Buffington, K. J. *et al.* Incorporation of uncertainty to improve projections of tidal wetland elevation and carbon accumulation with sea-level rise. *Plos one* **16**, e0256707 (2021).
27 Cahoon, D. R., McKee, K. L. & Morris, J. T. How plants influence resilience of salt marsh and mangrove wetlands to sea-level rise. *Estuaries and Coasts* **44**, 883–898 (2020).
28 Woodroffe, C. D. *et al.* Mangrove sedimentation and response to relative sea-level rise. *Annual Review of Marine Science* **8**, 243-266 (2016).
29 Kirwan, M. L. *et al.* Limits on the adaptability of coastal marshes to rising sea level. *Geophysical Research Letters* **37**, L23401 (2010).
30 Lovelock, C. E. *et al.* The vulnerability of Indo-Pacific mangrove forests to sea-level rise. *Nature* **526**, 559-563 (2015).
31 Haaf, L. *et al.* Sediment accumulation, elevation change, and the vulnerability of tidal marshes in the Delaware Estuary and Barnegat Bay to accelerated sea level rise. *Estuaries and Coasts* **45**, 413-427 (2022).
32 Langston, A. K., Alexander, C. R., Alber, M. & Kirwan, M. L. Beyond 2100: Elevation capital disguises salt marsh vulnerability to sea-level rise in Georgia, USA. *Estuarine, Coastal and Shelf Science* **249**, 107093 (2021).
33 NOAA. *NOAA's Coastal Change Analysis Program (C-CAP) 2016 Regional Land Cover Data - Coastal United States, https://www.fisheries.noaa.gov/inport/item/48336*. (NOAA Office for Coastal Management, 2021).
34 Wanless, H. R. & Vlaswinkel, B. M. *Coastal landscape and channel evolution affecting critical habitats at Cape Sable, Everglades National Park, Florida. Final Report to Everglades National Park.* (University of Miami, 2005).
35 Parkinson, R. W. & Wdowinski, S. Accelerating sea-level rise and the fate of mangrove plant communities in South Florida, USA. *Geomorphology* **412**, 108329 (2022).
36 Couvillion, B. R., Beck, H., Schoolmaster, D. & Fischer, M. *Land area change in coastal Louisiana 1932 to 2016: U.S. Geological Survey Scientific Investigations Map 3381, 16 p. pamphlet, https://doi.org/10.3133/sim3381*. (2017).
37 Osland, M. J. *et al.* Climatic controls on the distribution of foundation plant species in coastal wetlands of the conterminous United States: knowledge gaps and emerging research needs. *Estuaries and Coasts* **42**, 1991-2003 (2019).
38 Osland, M. J. *et al.* Migration and transformation of coastal wetlands in response to rising seas. *Science Advances* **8**, eabo5174 (2022).
39 Zhou, X. *et al.* Rates of natural subsidence along the Texas coast derived from GPS and tide gauge measurements (1904–2020). *Journal of Surveying Engineering* **147**, 04021020 (2021).

40 Haley, M., Ahmed, M., Gebremichael, E., Murgulet, D. & Starek, M. Land subsidence in the Texas coastal bend: Locations, rates, triggers, and consequences. *Remote Sensing* **14**, 192 (2022).
41 Sherpa, S. F., Shirzaei, M. & Ojha, C. Disruptive role of vertical land motion in future assessments of climate change-driven sea level rise and coastal flooding hazards in the Chesapeake Bay. *Journal of Geophysical Research: Solid Earth* **128**, e2022JB025993 (2023).
42 Stagg, C. L. *et al.* Quantifying hydrologic controls on local- and landscape-scale indicators of coastal wetland loss. *Annals of Botany* **125**, 365-376 (2020).
43 Ganju, N. K., Defne, Z. & Fagherazzi, S. Are elevation and open-water conversion of salt marshes connected? *Geophysical Research Letters* **47**, e2019GL086703 (2020).
44 Feher, L. C. *et al.* Soil elevation change in mangrove forests and marshes of the Greater Everglades: a regional synthesis of surface elevation table-marker horizon (SET-MH) data. *Estuaries and Coasts* **https://doi.org/10.1007/s12237-022-01141-2** (2023).
45 Breithaupt, J. L. *et al.* Increasing rates of carbon burial in southwest Florida coastal wetlands. *Journal of Geophysical Research: Biogeosciences* **125**, e2019JG005349 (2020).
46 Davis, S. M. & Ogden, J. C. *Everglades: the ecosystem and its restoration*. (St. Lucie Press, 1994).
47 He, X. *et al.* Sea level rise estimation on the Pacific coast from Southern California to Vancouver Island. *Remote Sensing* **14**, 4339 (2022).
48 Engelhart, S. E., Vacchi, M., Horton, B. P., Nelson, A. R. & Kopp, R. E. A sea-level database for the Pacific coast of central North America. *Quaternary Science Reviews* **113**, 78-92 (2015).
49 Coleman, D. J. *et al.* Reconciling models and measurements of marsh vulnerability to sea level rise. *Limnology and Oceanography Letters* **7**, 140-149 (2022).

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Fig. 1. Maps showing when coastal wetland drowning is expected to begin under alternative sensitivity thresholds for wetland drowning and sea-level rise (SLR) scenarios across the conterminous USA. Colors indicate the year in which wetland drowning is expected to begin. This is when rising sea levels are expected to cross thresholds for coastal wetland drowning. The loss and submergence of wetlands does not occur immediately once a drowning threshold has been crossed. While some wetlands may drown within decades of crossing a threshold, others may persist longer. Intermediate-Low corresponds with a 0.5 m Global Mean SLR (GMSLR) by 2100, Intermediate corresponds with a 1.0 m GMSLR by 2100, and Intermediate-High corresponds with a 1.5 GMSLR by 2100. GMSLR = global mean SLR. Note that the earliest possible date in our analysis is 2020. However, there are some areas, like Louisiana's Mississippi River Delta, where wetland drowning has already begun.

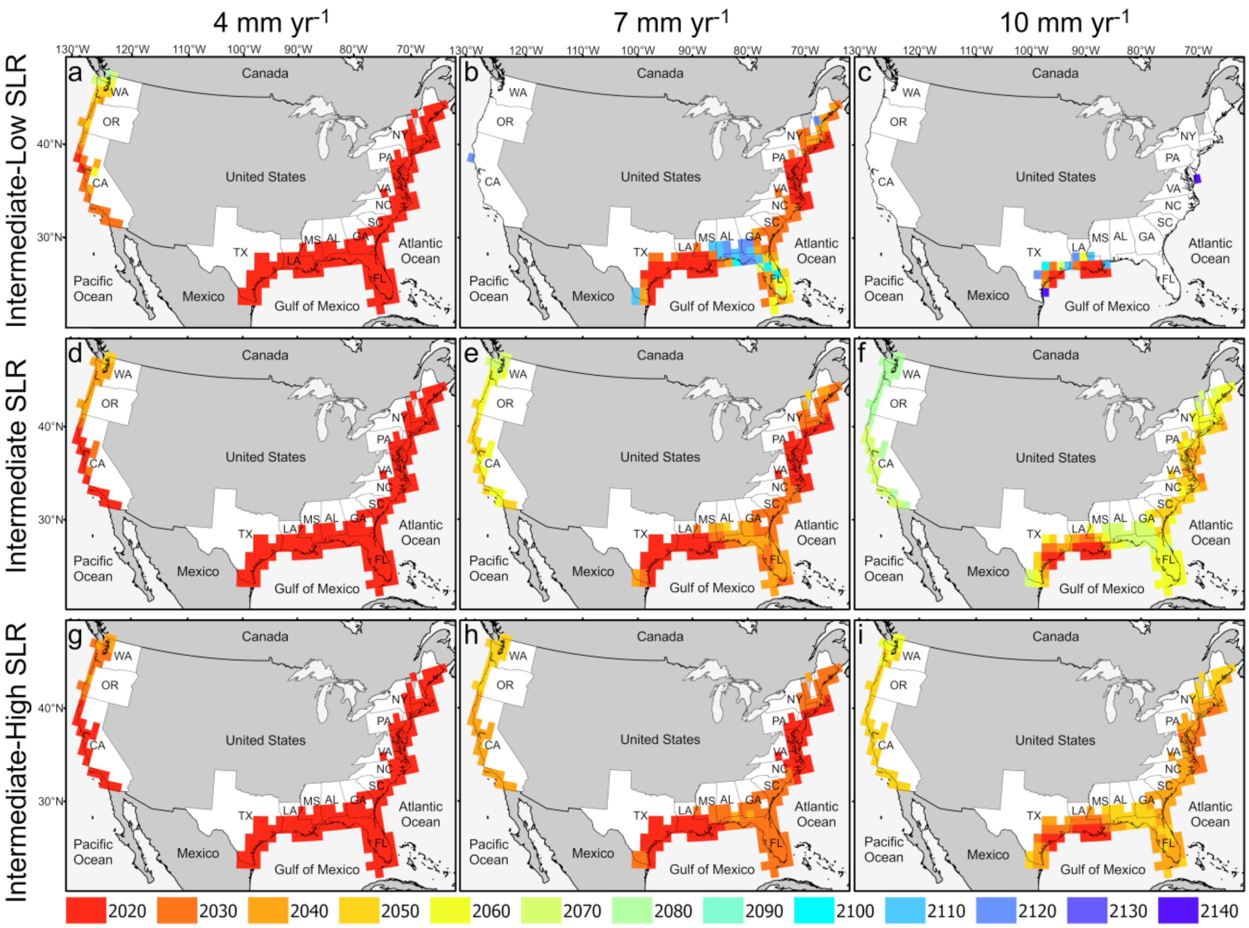


Fig. 2. Coastal wetlands in the United States are diverse. Thus, coastal wetland drowning means different things in different regions. For example, in the Mississippi River Delta and Chesapeake Bay, coastal wetland drowning can refer to the submergence and erosion of coastal marshes (a). In the iconic Everglades ecosystems of south Florida, coastal wetland drowning can refer to the conversion of mangrove forests to mudflats (b). The most prominent wetland drowning hotspot in the United States is within Louisiana's Mississippi River Delta (c; blue shows land loss and green shows land gain, adapted from Couvillion et al. 2017[36]). Louisiana has lost 4833 km^2 of land area between 1932-2016[36], due in part to high rates of subsidence and relative sea-level rise. Photo credits: Karen L. McKee (a) and Michael J. Osland (b).

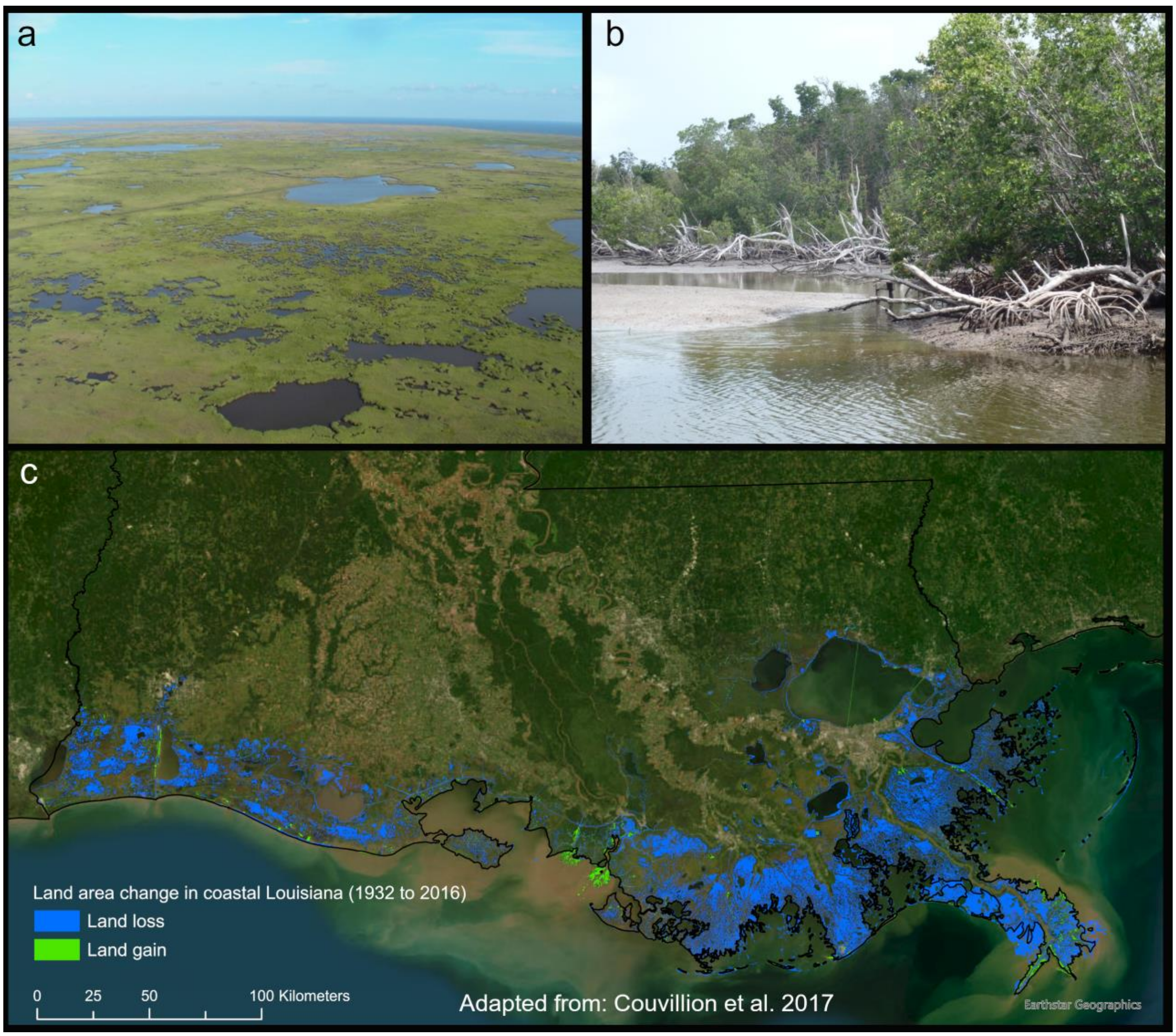


Fig. 3. The potential state-specific timing and extent of the start of coastal wetland drowning under alternative sea-level rise (SLR) scenarios and sensitivity thresholds for wetland drowning across the conterminous USA. Data are presented for 22 coastal states and Washington D.C. The y axes reflect the coastal wetland area that could begin to drown. These are wetlands flooded at relative SLR rates that exceed thresholds for initiating coastal wetland drowning. For each panel, the SLR scenario and sensitivity threshold rates are shown on the right. Inter.-Low = Intermediate-Low (0.5 m GMSLR by 2100), Inter. = Intermediate (1.0 m GMSLR by 2100), Inter.-High = Intermediate-High (1.5 GMSLR by 2100). The loss and submergence of wetlands does not occur immediately once a drowning threshold has been crossed. While some wetlands may drown within decades of crossing a threshold, others may persist longer. The earliest possible date in our analysis is 2020. However, there are some areas, like Louisiana's Mississippi River Delta, where wetland drowning has already begun. For percentage-based analyses, which are helpful for states with small wetlands, see Extended Data Fig. 2. GMSLR = global mean SLR. Note that these figures include tidal saline wetlands but they do not include tidal freshwater wetlands because there is not a national land cover classification that identifies tidal freshwater wetlands.

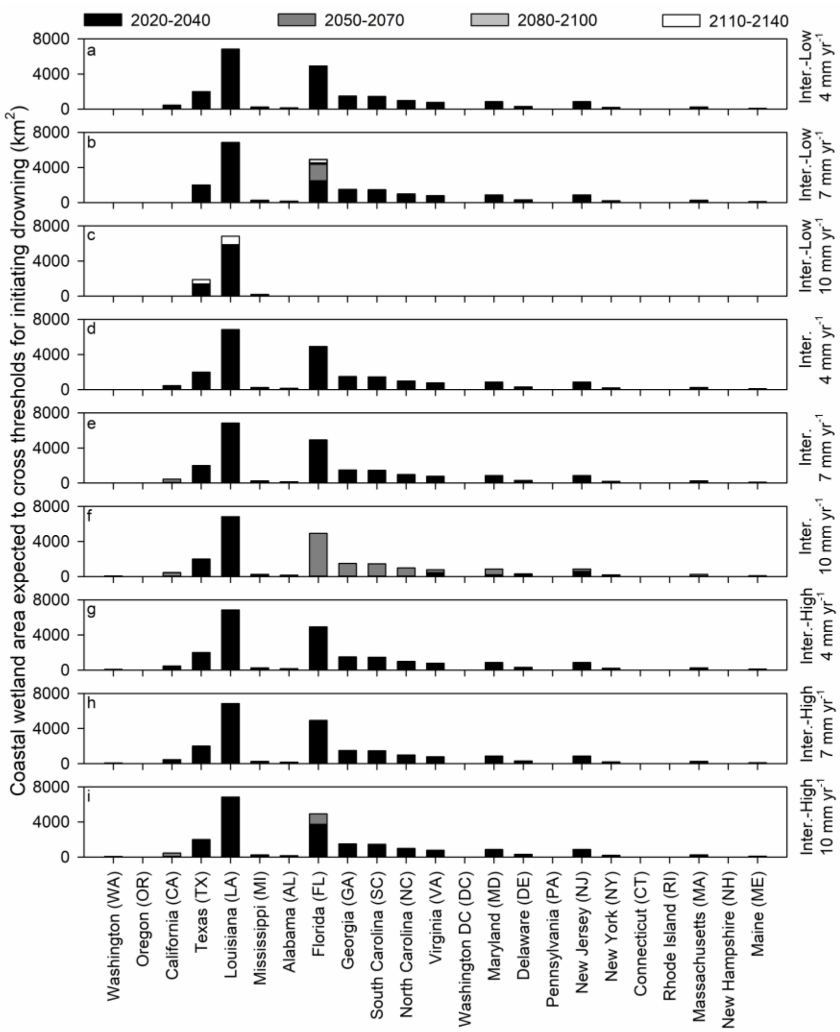
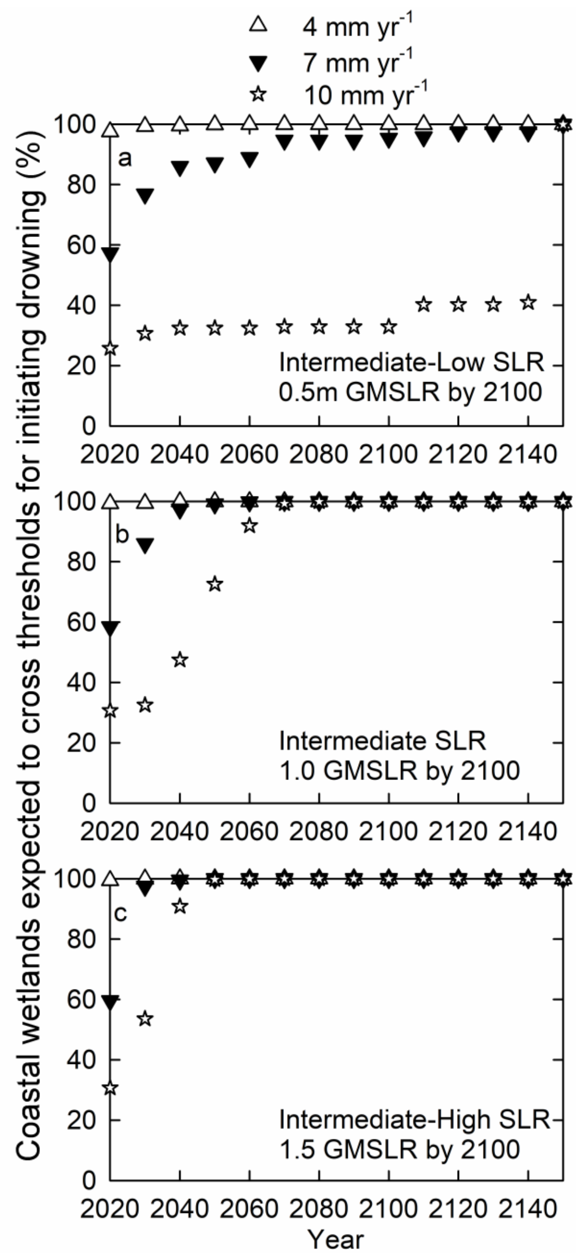
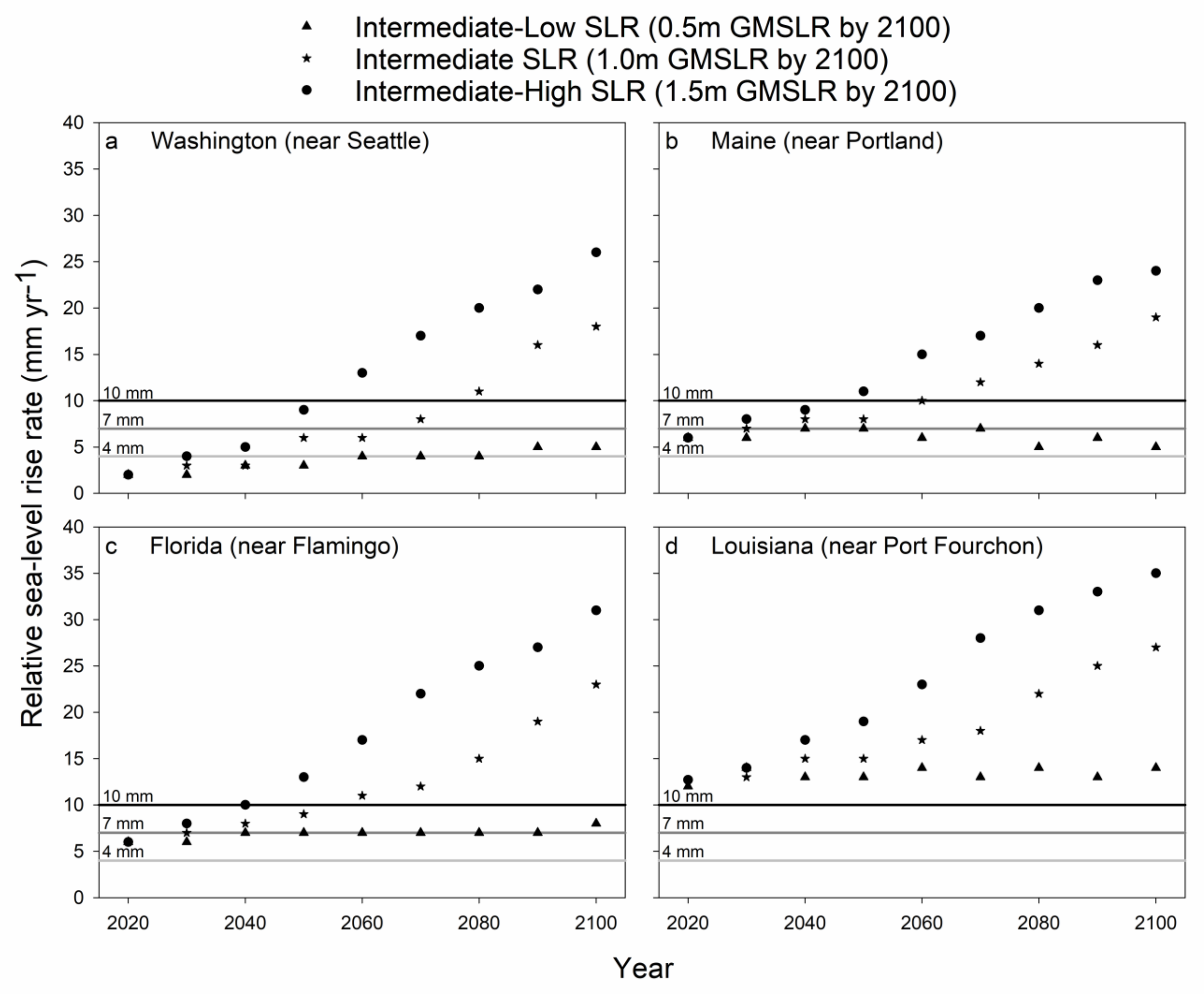


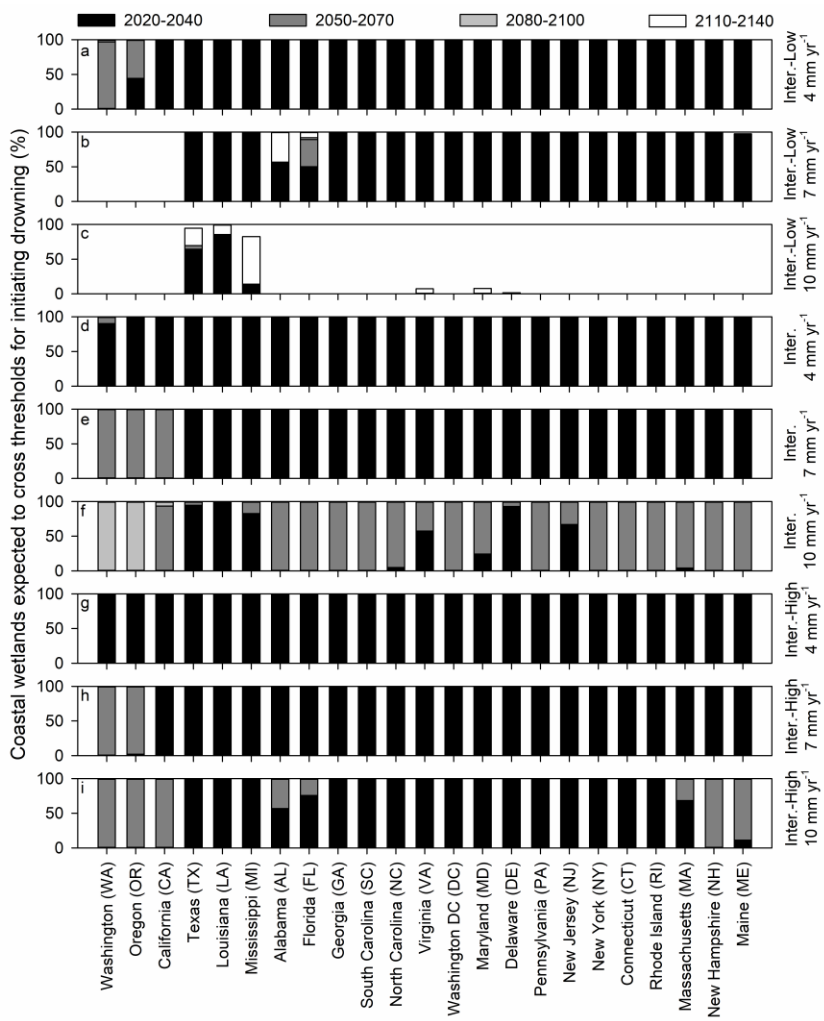
Fig. 4. The potential timing and extent of the onset of coastal wetland drowning under alternative sea-level rise (SLR) scenarios and sensitivity thresholds for wetland drowning (symbols within panels) for the conterminous USA. The y axes reflect the percent of coastal wetlands that could begin to drown on an areal basis. These are wetlands flooded at relative SLR rise rates that exceed thresholds for initiating coastal wetland drowning. The loss and submergence of wetlands does not occur immediately once a drowning threshold has been crossed. While some wetlands may drown within decades of crossing a threshold, others may persist longer. GMSLR = global mean SLR. The earliest possible date in our analysis is 2020. However, there are some areas, like Louisiana's Mississippi River Delta, where wetland drowning has already begun.



Extended Data Fig. 1. Relative sea-level rise (SLR) rates for three alternative SLR scenarios for 4 of the 168 1-degree cells included in this study. The three horizontal lines show the 4, 7, and 10 mm yr^{-1} thresholds for initiating wetland drowning. Intermediate-Low corresponds with a 0.5 m GMSLR by 2100, Intermediate corresponds with a 1.0 m GMSLR by 2100, and Intermediate-High corresponds with a 1.5 GMSLR by 2100. GMSLR = global mean SLR.



Extended Data Fig. 2. The potential state-specific timing and extent of the start of coastal wetland drowning under alternative sea-level rise (SLR) scenarios and sensitivity thresholds for wetland drowning across the conterminous USA. Data are presented for 22 coastal states and Washington D.C. The y axes reflect the percent of coastal wetlands that could begin to drown on an areal basis. These are wetlands flooded at SLR rates that exceed thresholds for initiating coastal wetland drowning. Coastal wetlands in areas without bars (in B and C) are wetlands that have not begun to drown by 2140. For each panel, the SLR scenario and sensitivity threshold rates are shown on the right. Inter.-Low = Intermediate-Low (0.5 m GMSLR by 2100), Inter. = Intermediate (1.0 m GMSLR by 2100), Inter.-High = Intermediate-High (1.5 GMSLR by 2100). The loss and submergence of wetlands does not occur immediately once a drowning threshold has been crossed. While some wetlands may drown within decades of crossing a threshold, others may persist longer. For area based analyses, see Fig. 3. GMSLR = global mean SLR. The earliest possible date in our analysis is 2020. However, there are some areas, like Louisiana's Mississippi River Delta, where wetland drowning has already begun.



Extended Data Fig. 3. The potential timing of coastal wetlands crossing thresholds for initiating wetland drowning under alternative sea-level rise (SLR) scenarios and sensitivity thresholds for the conterminous USA. The y axes reflect the coastal wetland area that could begin to drown. These are wetlands flooded at relative SLR rates that exceed thresholds for initiating coastal wetland drowning. Each of the symbols represents a 1-degree cell, and the plots include 168 1-degree cells distributed across the coastal conterminous United States. For each panel, the SLR scenario and sensitivity threshold rates are shown with text. Inter.-Low = Intermediate-Low (0.5 m GMSLR by 2100), Inter. = Intermediate (1.0 m GMSLR by 2100), Inter.-High = Intermediate-High (1.5 GMSLR by 2100). The loss and submergence of wetlands does not occur immediately once a drowning threshold has been crossed. While some wetlands may drown within decades of crossing a threshold, others may persist longer. GMSLR = global mean SLR.