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Title: Global coastal wetland change under sea-level rise and related stresses: the DIVA Wetland Change Model

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Abstract: The Dynamic Interactive Vulnerability Assessment Wetland Change Model (DIVA_WCM) comprises a dataset of contemporary global coastal wetland stocks (estimated at 756 x103 km2 (in 2011)), mapped to a one-dimensional global database, and a model of the macro-scale controls on wetland response to sea-level rise. Three key drivers of wetland response to sea-level rise are considered: 1) rate of sea-level rise relative to tidal range; 2) lateral accommodation space; and 3) sediment supply. The model is tuned by expert knowledge, parameterised with quantitative data where possible, and validated against mapping associated with two large-scale mangrove and saltmarsh vulnerability studies. It is applied across 12,148 coastal segments (mean length 85 km) to the year 2100. The model provides better-informed macro-scale projections of likely patterns of future coastal wetland losses across a range of sea-level rise scenarios and varying assumptions about the construction of coastal dikes to prevent sea flooding (as dikes limit lateral accommodation space and cause coastal squeeze). With 50 cm of sea-level rise by 2100, the model predicts a loss of 46 - 59% of global coastal wetland stocks. A global coastal wetland loss of 78% is estimated under high sea-level rise (110 cm by 2100) accompanied by maximum dike construction. The primary driver for high vulnerability of coastal wetlands to sea-level rise is coastal squeeze, a consequence of long-term coastal protection strategies. Under low sea-level rise (29 cm by 2100) losses do not exceed ca. 50% of the total stock, even for the same adverse dike construction assumptions. The model results confirm that the widespread paradigm that wetlands subject to a micro-tidal regime are likely to be more vulnerable to loss than macro-tidal environments. Countering these potential losses will require both climate mitigation (a global response) to minimise sea-level rise and maximisation of accommodation space and sediment supply (a regional response) on low-lying coasts.

Cover Letter

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21 December 2015

To Whom It May Concern

We have extensively revised the manuscript ‘**Global coastal wetland change under sea-level rise and related stresses: the DIVA Wetland Change Model’** by Spencer and co-authors, for further consideration for publication in Global and Planetary Change. We believe that we have addressed all the comments and queries raised by the reviewers in detail and in full. Our ‘response to referees’ indicates where on a manuscript the responses have been made. We believe that these responses have resulted in a significantly improved paper and we thank the referees and the editorial team for the opportunity to respond to the criticism of the original submission. We maintain the separation of the general narrative from a more specific set of technical issues raised in the supplementary material; we believe that this decision helps meet the journal’s concern to present problems and results in a way that is suitable for a broad readership. However, for ease of review we include the Supplementary Material at the end of the revised manuscript.

The manuscript has been prepared to conform to the instructions for contributors. This material has not been previously published elsewhere, nor is it under consideration for publication elsewhere. All the authors have approved this submission. There are no closely related manuscripts that have been submitted or are in press. As far as I am aware, there are no actual or potential conflicts of interest, of a financial, personal or other kind, with other people or organizations that could inappropriately influence, or be perceived to influence, this work. No funding source has had any involvement in the study design, collection, analysis and interpretation of the data, in the writing of the manuscript and in the decision to submit the paper for publication.

Yours sincerely,

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Global coastal wetland change under sea-level rise and related stresses: the DIVA Wetland Change Model

Spencer et al.

Response to Referees

Reviewer #1: This manuscript describes the results of a model that was calibrated and applied to the global distribution of wetlands. Its primary drivers include the rate of sea-level rise versus tidal range, the presence of lateral accommodation space, and sediment supply. As these drivers are altered over time, and applied to different coastal wetland areas, the authors conclude that there is basically little future for coastal wetlands beyond the year 2100. This is truly depressing.

Authors' response: we provide a range of estimates of future wetland loss which show that whilst wetland loss is potentially significant under all scenarios (combinations of sea level rise, sediment supply and availability of lateral accommodation space), it is only under the more extreme combinations that coastal wetlands have 'little future'. Further we have emphasised the policy responses that would help to avoid these worst-case losses.

Indeed, I think that there is value to these assessments, and I believe strongly that these authors are among the best in the world at framing these results appropriately. They have certainly nailed down the important drivers lauded widely in the literature.

Authors' response: these comments noted, with thanks.

This paper can provide important context for policy experts and scientists alike; however, I wonder how accurate these types of "doom and gloom" predictions will be in actuality. This is not the first model to report such findings, but the scale is certainly unique. It is just very difficult to accept these outcomes given the Holocene record of what wetlands have done in the past. This model is basically predicting the collapse of most wetlands globally within the next 85 years. Will scientists be chastised at the end of this century because we were wrong? I fear so, specifically because the recognized need among the scientific community for more complexity in these models (e.g., biological feedbacks) is dismissed (as the authors do on lines 110-119), even though we know that revised simulations will give different, and more conservative predictions of loss.

Authors' response:

i) the Holocene record indicates that coastal wetlands have shown high levels of persistence when rates of sea level rise have been low to moderate, but significant wetland loss at high rates of sea level rise. There are locations where mangroves have persisted even under high rates of sea level rise, but these have been in settings of high sediment supply. Thus the Holocene record does in fact support the modelling approach adopted here of identifying sea level rise, sediment supply and accommodation space as the primary determinants of wetland vulnerability. But the Holocene record is not a good analogue for the future because, as we show, human influence has made wetlands more vulnerable. This view is supported by recent assessments of historical and recent losses of natural coastal wetlands; Davidson (2014) estimates that natural coastal wetlands have declined by 46–50% since the beginning of the 18th century and by 62–63% over the course of the 20th century and Leadley et al.'s (2014) Wetland Global Extent Index estimates an almost 50% decline between 1970 and 2008. In addition to human influence on sea level rise, human agency has caused reductions in sediment supply and, critically, the reduction of future accommodation space through the building of sea defences. This has significantly changed the reference frame of wetland response, both vertical and lateral, to sea level change. We have modified both the abstract to the paper and the main text (revised manuscript lines 77-79, 705-715) to better reflect this argument.

ii) see our first response above on the 'collapse of most wetlands globally within the next 85 years';

iii) we accept that this global-scale model lacks a consideration of more complex internal feedbacks that influence rates and styles of wetland loss. We now explicitly add this caveat and referenced new text (lines 644-651 and lines 716-718 in revised text). Our intention in this submission of a first global coastal wetland loos and change model is to encourage debate on the issue of large–scale wetland loss within the scientific community to feed into future model development.

I enjoyed reading this paper. The authors are very familiar with the literature, including the important drivers of surface elevation deficit and techniques used to assess deficit. Also, this is an incredibly well-written paper. I learned a lot from reading this!

Authors'response: Comments noted, with thanks.

Comments:

(1) DIVA_WCM is a "doom and gloom" model having many, if not all, of the same assumptions used by SLAMM. I caution the author's validation procedures against SLAMM, which may be among the worst of all sea-level models in the world in terms of prediction. Whether SLAMM provides an appropriate hypothesis testing platform is a different matter. It seems that SLAMM is being used because it is an easy model with little complexity (e.g., no biological feedbacks), widely available, and useful for comparison at the scales that DIVA_WCM is being applied. I.e., all the reasons why SLAMM is not an accurate model. That is OK, but it is important that the authors also compare their model output from specific sections of coast against a suite a models (which can include SLAMM) so that the readers can at least know the predictive ability of DIVA_WCM against more than just that one model. I know it is not feasible to apply a suite approach to the entire world, but how about selecting four locations, partnering with people running different models, and give it a try? For example, you could select: (1) mesotidal, low sediment; (2) mesotidal, high sediment; (3)

microtidal, low sediment; and (4) microtidal, high sediment locations. Why would you not want to know this yourself?

Authors' response: SLAMM is used for model calibration not validation. The calibration was largely undertaken against the SLAMM model for precisely the reasons that the reviewer notes – the SLAMM model is really the only landscape-scale wetland change model that has been applied widely enough over the timescale of interest to provide the necessary datasets for calibration. We do, however, provide one use of the WARMER model as part of the calibration exercise. This is a numerical model which does include biophysical feedbacks; we discuss the relations between DIVA, WARMER and SLAMM in response to comment (8) below. Other landscape-scale models have been calibrated, but against relatively short historical datasets of wetland loss. We now add to Table 2 information on the tidal range at each of the six calibration sites – and information on suspended sediment concentrations where available. These show that the calibration datasets do encompass the site types referred to above: (1) (San Francisco Bay); (2) (Georgia coast, USA); (3) (Gulf coast, Florida); (4) (some locations in SE Louisiana and during resuspension events, Moreton Bay, Queensland).

(2) L. 98. I realize that the lead author has been using SETs for many years and is a world expert on its use, but note that it was re-named to "Surface-Elevation Table" over a decade ago to better reflect what the "table" actually measures.

Authors' response: terminology changed (line 105 in revised text)

Also, (L. 98-103) the authors are correct about the limitations of this technique, but there are SET-MH data sets now available of sufficient length to verify model runs. The lead author has some of these data. The scale of DIVA_WCM may preclude comparisons with SET data from the large areas simulated in this assessment, but if you had side-by-side comparisons for specific locations on a smaller scale, those comparisons would translate up-scale and would strengthen this paper considerably.

Authors' response: we have modified the text (lines 108-114 in revised text) to acknowledge that the network of SET sites is now becoming sufficiently geographically widespread to enable ideas of regional variations in coastal wetland vulnerability to be tested. We make reference to Lovelock et al. (2015) - which was not available when the paper was first submitted – which uses the Indo-Pacific SET network to assess the vulnerability of Indo-Pacific mangroves to sea-level rise. We discuss in full a validation using the output of the Lovelock et al. model further below. Of the six calibration studies used to calibrate the DIVA_WCM model, two use SET outputs to directly calibrate surface accretion rates. So there is in fact incorporation of SET findings into the DIVA_WCM model to the maximum degree possible at the present time.

(3) L. 110-115. These statements are problematic for me. So, in summary, you know that the simplified, open-access model is probably incorrect because there is a suite of papers saying that not incorporating complexity and feedbacks is bad, but the scale of application should overcome that issue? Can you please explain to the reader then what you are calibrating? Calibrating your output against the output of SLAMM applied to different locations? What is

the benefit then to science? Calibrating your output against real scenarios or a suite of models using different assumptions would be much stronger.

Authors' response: we feel that this is an honest statement of the challenges faced by this type of analysis. We now qualitatively validate the DIVA model against a model with a different structure, that of Lovelock et al., in a new Figure 5. The Lovelock model is a binary model of wetland survival versus wetland loss at 2100 and it is, therefore, difficult to make a quantitative comparison to DIVA outputs arranged by coastal segment. Nevertheless, the comparison of the two models is encouraging and addresses the wider point of assessing DIVA_WCM outputs against other models.

(4) The scale of DIVA_WCM model application is outstanding, and represents a real strength of this assessment. That is why I REALLY want it all to be correct, or at least know to what degree I can consider it correct.

Authors' response: we share the reviewer's sentiments.

(5) Line 228. Please delete this line. I think I know what you are saying, though maybe not, but this entire modeling exercise is not reconcilable against the Holocene record if humans are not included in the change to some degree. The IPCC SLR scenarios alone include human influences, but there are many other inherent influences that are part of this DIVA_WCM modeling, including the current distribution of wetlands, ability to migrate, sediment supply, etc.

Authors' response: This line now deleted.

(6) I like the inclusion and discussion of "lateral accommodation space".

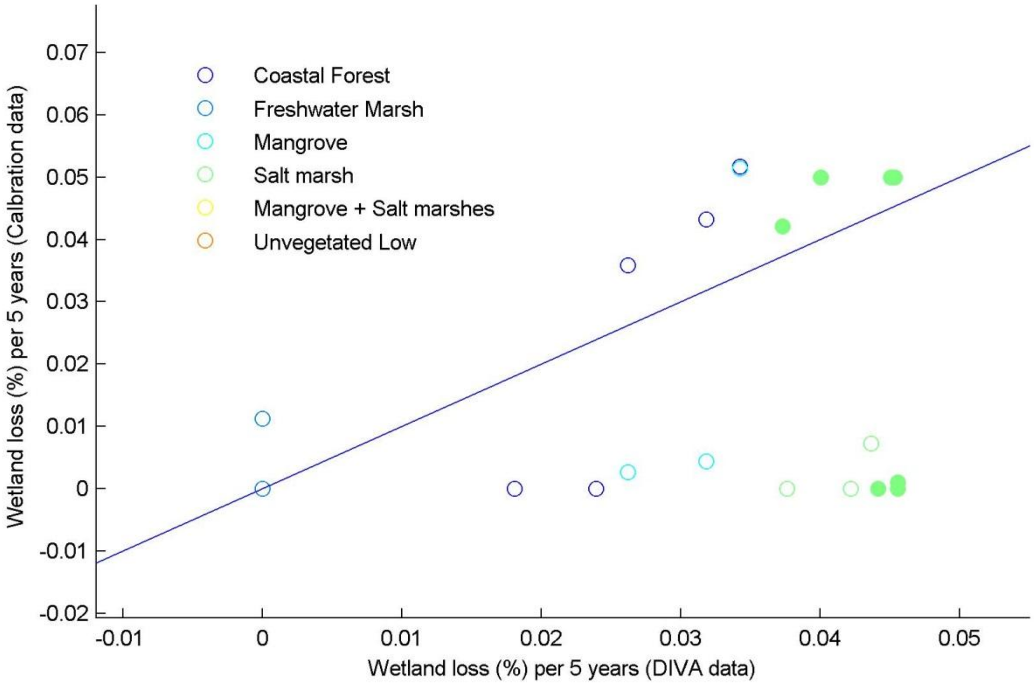
Authors' response: noted

(7) Lines 533. I think this should read "…sea-level rise / tidal datum, rslr_d, (Table 6(b)) with higher loss rates where this term is high." Right? If not, I do not understand it. High SLR and low tidal range (high value) should equate to greater losses compared with Low SLR and high tidal range (low value).

Authors' response: the text as written is correct as is the reviewer's interpretation

(8) Table 1. Is the WARMER model a derivation of SLAMM? If not, how did this model compare for the overlaid areas with DIVA_WCM?

Authors' response: The comment refers to Table 2 not Table 1. WARMER is not a derivative of SLAMM. It is a numerical saltmarsh model which does include biophysical feedbacks (the lack of which within SLAMM is commented upon above by the reviewer). Interestingly, the WARMER model (solid dots below) performs in a very similar manner to the SLAMM model (open dots) when it comes to comparisons with the DIVA model (see modified version of Figure 4 below)



(9) Discussion. Line 576 - "higher sensitivity to sea-level rise". Maybe because there are no feedbacks in the model? So, perhaps remind the reader that this SLR sensitivity may be reduced significantly if appropriate feedbacks by hydrology and vegetation type are to be included in the future.

Authors' response: we revise the text (641-651 lines in revised text) as follows 'In its current form the DIVA_WCM model shows higher sensitivity to sea-level rise than these earlier analyses, and losses two or more times higher than these earlier estimates appear possible. However, this sensitivity may be reduced in future iterations if appropriate feedbacks from changing plant physiology and tidal hydrodynamics can be included in the model structure. Thus, for example, increased atmospheric CO_2 and warmer temperatures, allied to mid-range rates of sea level rise, may lead to increases in the rates of plant productivity and wetland accretion (Langley et al., 2009; Cherry et al., 2009; Kirwan and Gutenspergen, 2012; Kirwan and Mudd, 2012), These dynamics might be further reinforced by increased sediment supply to wetland surfaces with greater tidal energetics under higher sea levels, albeit with limits to 'ecogeomorphic' adaptability at higher rates of sea level rise (Kirwan et al., 2010).'

(10) Line 580-581. Conservative rate of loss? This is a very bold statement given that up to 78% of global wetlands have been killed in your simulations under what may actually become a reasonable SLR scenario by 2100? Do you really believe that? Even at 50%, it is a stretch.

Authors' response: We understand the reviewer's comments at this point and remove the reference to 'conservative losses'. We do think that these magnitude of losses are possible and important to raise for climate policy and coastal management. They are not unrealistic figures when compared against the historical and recent record: Davidson (2014) estimates that natural coastal wetlands have declined by 46–50% since the beginning of the 18th century and by 62–63% over the course of the 20th century and Leadley et al.'s (2014) Wetland Global Extent Index estimates an almost 50% decline between 1970 and 2008.

(11) Lines 595-622. These are great paragraphs, although I do not understand Line 610. What does the "fertilizing effect of regional scale assessments" mean?

Authors' response: we amend the text here (lines 679-681 in revised text) to 'calibration of these curves provides an important focus for the linking of regional scale assessments to global scale wetland modelling.'

(12) Lines 612-613. Except that your regional-scale models used for comparison are all the same model type, with wonderful potential to be incorrect.

Authors' response: please see response to comments (1) and (8) above.

(13) Discussion. You need to add a well-thought-out, dedicated section to this discussion explaining the possibility that this model may over predict losses in comparison to other modeling assessments, and why. Consult Kirwin and/or Guntenspergen papers for insight on this. You have to provide all the potential caveats to the reader. Past SLAMM model applications have taken heat because they chose to ignore addressing or assessing these issues in the write-up. What is the error associated with these predictions? We need a measure of accuracy because some of these projected losses, even at 46-59%, are really high.

Authors' response: we add a new paragraph (lines 644-651 in revised text) to flag up the reviewer's concerns 'However, this sensitivity may be reduced in future iterations if appropriate feedbacks from changing plant physiology and tidal hydrodynamics can be included in the model structure. Thus, for example, increased atmospheric CO2 and warmer temperatures, allied to mid-range rates of sea level rise, may lead to increases in the rates of plant productivity and wetland accretion (Langley et al., 2009; Cherry et al., 2009; Kirwan and Gutenspergen, 2012; Kirwan and Mudd, 2012), These dynamics might be further reinforced by increased sediment supply to wetland surfaces with greater tidal energetics under higher sea levels, albeit with limits to 'ecogeomorphic' adaptability at higher rates of sea level rise (Kirwan et al., 2010). '

In summary, I made a lot of comments that I hope are helpful. I like this paper. We just need to know something more about the potential inaccuracies of this application of DIVA_WCM as applied to global wetland losses. All models are inaccurate, but to different degrees. This paper will be impactful when published, and I think the authors should consider a reasonable defense of these predictions when it is published. You need to be able to stand behind these predictions.

Authors’ response: We appreciate these comments. We now add a new qualifier (lines 716-718 in revised text) to the final set of conclusions: ‘Further development of the model is now needed to better assess the role of ecogeomorphic feedbacks to see if the incorporation of these terms fundamentally affects model outcomes.’

Reviewer #3: This is an extensive and impressive study of the potential losses to coastal wetland stocks with sea level rise. It is global in scope, working with a revamped DIVA model. This paper will make a valuable contribution to the literature when published.
The inclusion of the "dikes" modifier is very interesting. The attempt to reconcile models from smaller scales (e.g. SLAMM) to the larger scale of the DIVA model is important and points the way to new research paths to bridge gaps for management.
The maps (Fig. 8) are very compelling.

Authors’ response: comments noted, with thanks.

Specific comments
Line 68 - extend citation and statement to include mangroves e.g. "and aquaculture (Murdiyarso et al. 2015 Nature Climate Change)"

Authors’ response: Murdiyarso et al. 2015 added (line 70 in revised text) – this was not available at time of submission.

Line 69 - again, extend to beyond tidal marsh refs

Authors’ response: reference to Alongi (2008) review paper added (lines 71-72 in revised text)

Line 102-103 - I thought these authors say that RSETs are not focussed on areas with anticipated high rates of losses, but that they should be.

Authors’ response: this text now revised (see response to reviewer #1 comment above)

Line 179 - is there a web link to the model and the databases?

Authors’ response: Not at present. However, we now provide a weblink which includes contact details for the head of model development (line 192 in revised text)

Line 193 - from where is the elevation data derived?

Authors’ response: derived from the ETOPO2 (NGDC, 2001) dataset. Previously this was only referenced, with weblink, in relation to slope calculation, in the Supplementary Material. We now add this information in the main text also (lines 206-207 in revised text)

Line 205. I am not certain agree with slower response times for forests, particularly during loss phases, although I can see that above ground biomass takes longer than tidal marsh to re-establish. Please clarify statement of reduced sensitivity. Perhaps additional references to Allen are needed.

Authors' response: We remove the existing ambiguous reference to 'ecological sensitivity' and the general reference of Allen (1974) with a more specific argument, supported by a reference on the ecophysiology on mangroves. New text (lines 219-222 in revised text): 'Mangroves and coastal forests respond more robustly to environmental change than the other wetland types because slower growth rates across a wide range of environmental tolerance allows for survival under moderate levels of stress (Ball, 1988). '

Line 206 - Is ecological sensitivity scored as response times in years? More information on this is needed. Perhaps provide range or typical response time for each veg type?

Authors' response: This comment is covered at lines 353-367 in substantially revised text. We have extensively revised the text at this point to cover the question on timescales. It should be noted, however, that whilst there is a considerable literature on the response of mangrove seedlings to changes in flooding regime there is almost no literature that we know of on the response of mature mangrove trees to these effects.

Paragraph starting line 242. This is a confusing group of sentences. It considers sediment accretion, tidal range and tidal prism, but it is unclear how these are linked. There are studies that show that sediment accretion is proportional to inundation depth (i.e. greater volumes of water flooding a site give rise to higher rates of surface accretion), but it is not clear that this is the point of this early part of the paragraph. Clarify the aims of this paragraph. Perhaps it should be expanded to two paragraphs.

Authors' response: we adjust the preceding paragraph (lines 248-258 in revised text) to make the relationships between tidal flooding, sediment supply and wetland surface elevation clearer. 'If sediment supply is sufficient, marsh surfaces will accrete vertically, rapidly at first but then slowing over time as fewer tides inundate the progressively higher surface (Allen, 1990). Conversely, in sediment-poor wetlands, subject to a rise in relative sea level without equal increases in wetland surface elevation from sediment accretion, the duration and depth of tidal flooding will increase over time. In this situation, wetland vegetation may revert to a community composition more typical of lower elevations in the tidal frame (Huiskes, 1990; Mendelssohn and Morris, 2000).'

Line 260 - where is the segment specific uplift rate derived from? Provide link to data set.

Authors' response: we add the link in revised text (lines 277-278) '(obtained from http://www.atmosp.physics.utoronto.ca/~peltier/data.php),'

Line 315. Perhaps bring A4 into the main paper because of the complexity of this section and because it is important to understanding the outputs. "Furthermore, each factor is multiplied by an internal weighting to reflect their relative significance within the sedsup parameter (Equation 3, Supplementary Material). The respective weights are based on expert judgement, derived from field experience and the published literature."

Authors’ response: we are concerned about the length of the paper and so feel that it is acceptable to leave the detail in the Supplementary Material, with proper signposting in the main text.

L366 - 368. I don't understand this sentence

Authors’ response: we accept that the original text was not as clear as might have been the case. We now provide a shortened text which we believe makes the use of beta distribution curves clearer (revised text lines 389-391).

Highlights:

- database identifies estimated (in 2011) 756 x10^3 km^2 global coastal wetland stock
- with 50 cm of sea-level rise by 2100, losses of 46 – 59% of global coastal wetlands
- under high sea-level rise (110 cm by 2100), global wetland losses may reach 78%
- under low sea-level rise, micro-tidal wetlands more vulnerable to loss
- wetland loss likely to be exacerbated by non-climate related, anthropogenic impacts

Global coastal wetland change under sea-level rise and related stresses: the DIVA Wetland Change Model

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Abstract

The Dynamic Interactive Vulnerability Assessment Wetland Change Model (DIVA_WCM) comprises a dataset of contemporary global coastal wetland stocks (estimated at 756 $x10^3$ km^2 (in 2011)), mapped to a one-dimensional global database, and a model of the macro-scale controls on wetland response to sea-level rise. Three key drivers of wetland response to sea-level rise are considered: 1) rate of sea-level rise relative to tidal range; 2) lateral accommodation space; and 3) sediment supply. The model is tuned by expert knowledge, parameterised with quantitative data where possible, and validated against mapping associated with two large-scale mangrove and saltmarsh vulnerability studies. It is applied across 12,148 coastal segments (mean length 85 km) to the year 2100. The model provides better-informed macro-scale projections of likely patterns of future coastal wetland losses across a range of sea-level rise scenarios and varying assumptions about the construction of coastal dikes to prevent sea flooding (as dikes limit lateral accommodation space and cause coastal squeeze). With 50 cm of sea-level rise by 2100, the model predicts a loss of 46 – 59% of global coastal wetland stocks. A global coastal wetland loss of 78% is estimated under high sea-level rise (110 cm by 2100) accompanied by maximum dike construction. The primary driver for high vulnerability of coastal wetlands to sea-level rise is coastal squeeze, a consequence of long-term coastal protection strategies. Under low sea-level rise (29 cm by 2100) losses do not exceed ca. 50% of the total stock, even for the same adverse dike construction assumptions. The model results confirm that the widespread paradigm that wetlands subject to a micro-tidal regime are likely to be more vulnerable to loss than macro-tidal environments. Countering these potential losses will require both climate mitigation (a global response) to minimise sea-level rise and maximisation of accommodation space and sediment supply (a regional response) on low-lying coasts.

Keywords: tidal wetlands, wetland vulnerability, wetland transitions, wetland loss, accommodation space, sea-level rise

1. Introduction

Millennial, centennial and decadal records of changing patterns of coastal wetlands, including mangrove forests, saltmarshes, mudflats and associated habitats, show that they are particularly sensitive to environmental change (e.g. Morris et al., 2002; French, 2006; Fitzgerald et al., 2008; Mudd et al., 2009). More recent system changes also reflect the impacts of human activities superimposed on these natural dynamics, such as drainage and conversion to agriculture (e.g. Gedan et al., 2009) and aquaculture (e.g. Murdiyarso et al., 2015). There is concern, therefore, as to how near-future global environmental change will further modify these systems **(**e.g. Alongi, 2008; Kirwan et al., 2010; Fagherazzi et al., 2012).

On contemporary timescales, tidal wetlands are biologically productive ecosystems of high biodiversity supplying multiple ecosystem services. At the same time they are subject to significant, and accelerating, rates of global coastal wetland loss due to natural and anthropogenic drivers (e.g. Adam, 2002; Millennium Ecosystem Assessment, 2005; Barbier et al., 2011; Nicholls et al., 2011). Davidson (2014) estimates that natural coastal wetlands have declined by 46–50% since the beginning of the 18th century and by 62–63% over the course of the 20th century and Leadley et al.'s (2014) Wetland Global Extent Index estimates an almost 50% decline between 1970 and 2008.

Ecosystem services and loss rates have become linked over the last decade with the recognition of the role of low-lying wetlands in natural coastal protection (e.g. Shepard et al., 2012), following the interactions between mangrove ecosystems and the wave fields of the 2004 Asian tsunami (e.g. McIvor et al., 2012) and between coastal marshes and 2005 Hurricanes Katrina and Rita on the Gulf coast, USA (e.g. Barbier et al., 2013) amongst others. Much remains to be done, however, on identifying the exact linkages between mosaics of coastal habitat area and habitat fragmentation and the maintenance of a coastal protection function (e.g. Barbier et al., 2008; Koch et al., 2009; Loder et al., 2009; Gedan et al., 2011). Furthermore, these debates are embedded in a context where the knowledge of the general spatial distribution of coastal wetland ecosystems is currently poor, particularly for saltmarshes (e.g. Rebelo et al., 2009, Saintilan et al., 2009; Chmura, 2011). There are serious gaps in the information base and much of the data that has been collected has come from different sources and different time periods and at a range of scales (Friess and Webb, 2014). Indeed, Friess et al. (2012) goes as far as to argue that the under-reporting of saltmarsh from the tropics underpins the presumption that mangrove replaces saltmarsh in the tropical intertidal zone. These shortcomings have hampered the assessment of the extent and condition of wetlands and proper estimations of the rate of loss. Thus one review concludes ‘a number of prognostications have been made regarding the future of the world’s mangrove forests in the face of climate change with local, regional, and global forecasts ranging from extinction to no or little change in areal coverage’ (Alongi, 2008, 8).

Accelerated sea-level rise is a major threat to wetland futures at regional to global scales. However, most detailed studies on wetland vulnerability to accelerated sea-level rise have been over small spatial scales and short timescales and most concentrate on the likelihood of vertical drowning (Webb et al., 2013), when sediment accumulation on the platform cannot keep vertical pace with sea-level rise. There has been less emphasis on rates of horizontal retreat, associated with wave-induced marsh boundary erosion (Mariotti and Carr, 2014). Thus, for example, the Surface Elevation Table – Marker Horizon (SET-MH) methodology has the necessary precision to allow annual surface elevation change to be related to annual rates of sea level change (Cahoon et al., 2002) although inter-site and inter-annual variations in surface response characteristics are high (Cahoon et al., 2006). Historically, the SET-MH global network of sites has been patchy and not focussed on those areas where wetland loss rates are thought to be particularly high (Webb et al., 2013). However, there has been an expansion of sites globally in the last few years and it is becoming possible to use this network to model larger scale patterns in wetland vulnerability, as has been shown for Indo-Pacific mangrove SET sites (Lovelock et al., 2015). Furthermore, SET datasets have been used as calibration datasets in other models of wetland change, most notably the SLAMM model; we return to this usage below.

The generic problems of large-scale analysis have been addressed in part by the development of macro-scale landscape models. These models vary in structure, complexity and the ease with which they can be applied. The more sophisticated landscape models use geomorphic and hydrologic sub-models to distribute fluxes of water, sediments and nutrients across a raster grid (e.g. CELSS model: Sklar et al., 1985) to calculate likely changes in wetland type extent. However, the data and computational requirements of such an approach largely preclude its application as a broad-scale tool for wetland analysis (Martin et al., 2002; Reyes, 2009; Couvillion and Beck, 2013). Simpler models, such as cellular automata (Ross et al., 2009), capture the key characteristics of wetland dynamics empirically, require fewer data, and are easily applied, but the ability to deal with low frequency, high magnitude impacts and the recognition of the interaction and feedback of geo-morphological and ecological processes are missing (Kirwan and Guntenspergen, 2009). Nevertheless, these approaches are useful for calibration purposes, as we demonstrate below. Of this suite of large-scale models, the one that has been most widely applied is the ‘Sea Level Affecting Marshes Model’ (SLAMM) (Clough et al., 2010). SLAMM is open source and has a user-friendly interface for implementation; is based on empirical calculations so that computation times are substantially less than those required for complex numerical models; and implementation has low data demands.

The pioneering Global Vulnerability Assessment (GVA), and its subsequent revision, is a macro-scale model which provided the first worldwide estimates of the impacts of accelerated sea-level rise on coastal systems (Hoozemans et al., 1993; Nicholls et al., 1999). This included a first-order perspective on coastal wetland loss. Subsequently, the data on coastal wetland stocks has improved (e.g. Vafeidis et al., 2008; Spalding et al., 2010; Giri et al., 2011), and the understanding of the main drivers of change, including sea-level rise, has increased (Nicholls, 2004; McFadden et al., 2007; Nicholls et al., 2007). Hence, a re-evaluation of these earlier assessments of wetland vulnerability is timely. This paper discusses the further development and application of a broad-scale wetland change model: the Dynamic Interactive Vulnerability Assessment Wetland Change Model (DIVA_WCM), originally developed within, and subsequently to, the European Community DINAS-COAST Project. In this paper we show how a newly constituted database of contemporary global coastal wetland extent can be linked to a revised conceptual model of the controls on wetland health and resilience. In comparison to its previous version (McFadden et al., 2007), the revised model has been parameterised with quantitative data where possible, calibrated by SLAMM and other model outputs and validated by expert knowledge, including map-based approaches. Thus, in its current form the model provides better-informed macro-scale projections of likely future wetland extents than have been available previously.

2. Methods

2.1 The DIVA modelling framework

DIVA is an integrated, global modelling framework of coastal systems that assesses biophysical and socio-economic consequences of sea-level rise and socio-economic development, taking into account coastal erosion, coastal flooding, wetland change and salinity intrusion (http://www.diva-model.net; Hinkel, 2005; Hinkel and Klein, 2009; Hinkel et al., 2010, 2013, 2014). The DIVA data modelling framework divides the world's coast (excluding Antarctica) into 12,148 variable length coastal segments (mean length: 85 km; range: 0.009 km to 5,213 km) and associates up to 100 data values with each segment (Vafeidis et al., 2008). Each segment represents a relatively homogenous unit based on geomorphology, population density and administrative boundaries; there are a greater number of segments in the more populated areas. Only the DIVA data associated with wetland change are considered in this paper.

DIVA is driven by climate and socio-economic scenarios. Using the HadGEM2-ES Earth System model from Phase 5 of the Coupled Model Intercomparison Project (CMIP5), three sea-level rise scenarios have been investigated in this paper, representing a subset of the scenarios described by Hinkel et al. (2014). These scenarios consider three Representative Concentration Pathways (RCP) - RCP2.6, RCP4.5, and RCP8.5. The RCPs correspond to different levels of greenhouse gas concentration trajectories, ranging from a world of strong climate mitigation to one of increasing emissions. A major uncertainty in projecting future sea-level rise is the contribution of land-based ice. In Hinkel et al. (2014), each RCP scenario is associated with three levels of ice melt (low, median and high) to create a 'very likely' range. The scenarios represent patterns of change (representing thermal expansion and changes in ocean circulation, plus gravitational changes from ice sheets (the contribution from ice caps is assumed to be uniform)) where some parts of the world have higher or lower sea-level rise compared with the global mean. Projected global mean sea-level rise to the year 2100 with respect to 1995 (mean sea level during 1985-2005 baseline period) for each of the scenarios is given in Table 1 (median values, with 5% and 95% quantiles in parentheses; after Hinkel et al., 2014). In this demonstration paper, we cover the widest range of sea-level rise scenarios, from the lowest (5%) quantile of RCP2.6 (29 cm by 2100), through the median rate of sea-level rise for RCP4.5 (50 cm), to the 95% quantile of RCP8.5 (110 cm). Finally, the sea-level rise scenarios are downscaled to each DIVA database segment, including local land level change, following Peltier (2000a, 2000b), and a 2 mm a^{-1} subsidence in deltas, reflecting natural sediment compaction. Hence relative sea-level change varies from DIVA segment to segment.

For socio-economic scenarios, the Shared Socioeconomic Pathways (SSPs) are used. DIVA considers population and gross domestic product (GDP) growth from the SSP2 scenario which sees the trends typical of recent decades continuing, with moderate global population growth, some progress toward achieving development goals and a slow decrease in the world's dependency on fossil fuels (IIASA, 2012). The socio-economic scenarios can influence the construction of dikes, and hence the availability of accommodation space for wetlands, as explained below.

Table 1 near here

2.2. The Wetland Change Model (DIVA_WCM)

The DIVA_WCM is one module in the DIVA modelling framework (Version 5.1 (http://www.diva-model.net/)). DIVA_WCM comprises i) a newly constituted global database of coastal wetlands built on the basis of the original DIVA database (Vafeidis et al., 2008) and ii) an impacts algorithm for coastal wetlands. It improves upon the existing DIVA-WCM (McFadden et al. 2007) by extensive new parameterisation and calibration.

The coastal wetland database employed in this paper was derived, under licence, from datasets held by the United Nations Environment Programme's World Conservation Monitoring Centre (UNEP-WCMC), the specialist biodiversity assessment arm of UNEP. A global layer of mangrove forest data, revised after Giri et al. (2011), was augmented with a recently improved saltmarsh data layer; both layers were imported into the DIVA database and assigned to the appropriate coastal segment. Sub-sets of the data were checked to ensure that there was no corruption of data in the transfer from the original files to the database. In the database, six wetland types associated with coastline segments are considered: 1) coastal forest; 2) mangrove forest; 3) freshwater marsh (of limited extent); 4) saltmarsh; and unvegetated sediments, which are divided into 5) sabka and saline tidal flats (of very limited extent); and 6) mudflat/sand flat. The distinction between these latter two types is based on climatic setting and elevation (derived from the ETOPO2 (NGDC, 2001) dataset): type 5 is above (‘unvegetated high’) and type 6 is below (‘unvegetated low’) Mean High Water Springs (MHWS), respectively. Data on unvegetated sediments, freshwater marshes and coastal forested originate from the above mentioned GVA (Hoozeman et al., 1993).

French (2006, 120) states that ‘… the existence and ecological function of tidally-dominated saltmarshes are ultimately contingent upon the operation of hydrodynamic and sedimentary processes within constraints imposed by the intertidal accommodation space and the sediment supply’. The DIVA_WCM algorithm considers three key drivers that control wetland response to sea-level rise: 1) local sea-level rise relative to tidal range; 2) lateral accommodation space; and 3) sediment supply, following McFadden et al. (2007). A score of one to five is adopted to represent present and future forcing levels for each of these drivers: one corresponds to the lowest forcing and *vice versa*.

Wetlands respond to sea-level rise over different time horizons. Mangroves and coastal forests respond more robustly to environmental change than the other wetland types because slower growth rates across a wide range of environmental tolerance allows for survival under moderate levels of stress (Ball, 1988). This is represented in the model by different response times for these wetland types. Macro-scale landscape models, and specifically output derived from the WARMER and SLAMM model applications, were used to characterise wetland resilience to sea-level rise and other stresses where possible. Expert judgment, from peer-reviewed literature and research project reports, was applied where necessary.

Figure 1 outlines the primary components of the DIVA_WCM, comprising four sets of calculations:

(1) Assessment of the vulnerability of all wetlands to sea-level rise. This vulnerability score (*VS*) depends upon sea-level rise, lateral accommodation space and sediment supply and is universal. As the score is calculated segment-by-segment, it is described as the Coastal Segment Vulnerability Score (*CSVS*);

(2) Conversion of the Coastal Segment Vulnerability Score into a wetland-specific Ecological Sensitivity Score (*ESS*);

(3) Calculation of the proportion of wetland loss/change that is expected for each wetland type based on the ESS score; and

(4) Calculation of wetland habitat successional changes and wetland loss to open water, generating new wetland areas, through a habitat translation model.

Figure 1 near here

It is important to note that the DIVA-WCM is a wetland loss model for sea-level rise; we acknowledge that near-future environmental change may also produce new areas of wetland in particular landscape settings, but the generation of new wetland is not considered further in this paper. The following sections detail each of these methodological steps. Further information is given in the Supplementary Material.

2.2.1. Relative sea-level rise / tidal range

When relative sea-level rise is sudden and of high magnitude, as might result from tectonic activity, the wetland surface may be abruptly submerged (e.g. Atwater, 1987). More frequently, and the subject of concern here, coastal wetlands are subjected to slow, progressive relative sea-level rise caused by the combination of eustatic factors and regional to local subsidence. This process is reflected in the changing pattern of tidal submergence, or hydroperiod (Reed, 1995). If sediment supply is sufficient, marsh surfaces will accrete vertically, rapidly at first but then slowing over time as fewer tides inundate the progressively higher surface (Allen, 1990). Conversely, in sediment-poor wetlands, subject to a rise in relative sea level without equal increases in wetland surface elevation from sediment accretion, the duration and depth of tidal flooding will increase over time. In this situation, wetland vegetation may revert to a community composition more typical of lower elevations in the tidal frame (Huiskes, 1990; Mendelssohn and Morris, 2000).

No clear relationships have been found at the large-scale between accretion rates and tidal range (Allen, 1990; French and Reed, 2001; Cahoon et al., 2006; Mossman et al., 2012). However, Stevenson et al. (1986) showed accretion deficits (rate of sea-level rise minus rate of near-surface accretion) to be greater in low tidal range saltmarshes than in higher tidal range marshes along the eastern seaboard of the USA. This has been attributed to the expanded intertidal range that can be occupied by vegetation (e.g. Day et al., 1995) and the increased flood-dominance, and thus enhanced sediment supply (e.g. Friedrichs and Perry, 2001), of macrotidal (> 4 m spring tidal range) marsh systems compared to meso-tidal (2-4 m tidal range) or micro-tidal (< 2 m tidal range) systems (Kirwan et al., 2010; Fagherazzi et al., 2012). Furthermore, in micro-tidal settings the expansion of the tidal prism on sea-level rise is disproportionately large, with increases in tidal channel geometries leading to loss of wetland area (Kirwan and Guntenspergen, 2010).

The first environmental forcing factor captures this process through the dimensionless relative sea-level rise term *rslr_d*, where the annual relative rise in sea level (RSLR) is scaled by the segment-specific tidal range (Equation 1 in Supplementary Material; and see Table A1 for details of the tidal range parameter). Unlike earlier applications of this approach (Nicholls et al., 1999), the dimensionless RSLR is described as a power function with an exponent of 1.4, based on the literature review described above and expert judgement. The scoring of *rslr_d* is based on fixed class boundaries that are initialized before simulation. Assuming a current 3 mm a^{-1} global mean sea-level rise rate (after Church et al., 2013), we subtract the segment-specific uplift (obtained from http://www.atmosp.physics.utoronto.ca/~peltier/data.php), and calculate the 95th, 84th, 50th, and 16th percentiles of the cumulative distribution of the resulting *rslr_d* parameter to derive the class boundaries of *rslr_tidal_score*, while only considering segments where wetlands are present (for exact values see Supplementary Material, Table A2). During simulation, the *rslr_d* forcing factor is updated and scored at every time step and, hence, is driven by the associated sea-level rise scenario (see section 2.1 above and Table 1).

2.2.2. Lateral accommodation space

The notion of 'accommodation space' comprises two components defined by sea-level rise, namely vertical wetland surface adjustment upwards and lateral habitat migration landwards (Phillips, 1986; Allen, 1990). The characterisation of lateral accommodation space within the DIVA_WCM is built on an assessment of the impact of two controlling factors: i) coastal slope (Brinson et al., 1995); and ii) the presence or absence of dikes, which limits lateral accommodation space (Feagin et al., 2010). Lateral accommodation space, *aspace,* is calculated recursively in the model. The *aspace* value is initialised for each segment using the average topographic slope, derived from the ETOPO2 (NGDC, 2001) dataset. Model categorisation of coastal slope, and associated forcing scores, are given in the Supplementary Material Table A3. This initialized *aspace* score is then updated based on the estimated sea-dike height at each time-step. If appropriate, *aspace* is increased by 0.25 at each time step until the highest forcing score is obtained (Equation 2, Supplementary Material). Thus, the loss of lateral accommodation space is a progressive process in terms of stressing wetlands, being maintained at the highest vulnerability for the remainder of the model run once *aspace* reaches the maximum score of five. Importantly, the model does not simulate the impact of creating new lateral accommodation space.

The DIVA model considers dike construction, and dike upgrading, as an adaptation response to coastal flooding (Hinkel et al., 2014). Three scenarios for dike construction are evaluated in this paper. Two bounding cases of 'no dikes' (in which no coastal floodplains are protected) and 'maximum dikes' (in which all coastal floodplains are protected) are considered. In addition, dikes built according to a 'demand-for-safety' function, assuming the SSP2 socio-economic scenario (Hinkel et al., 2014), are also evaluated and termed 'widespread dikes'. The driver *aspace* is not influenced by dikes under 'no dikes'; is most affected under 'maximum dikes'; and is subject to an intermediate effect under 'widespread dikes'.

2.2.3. Sediment supply

It has been strongly argued that sediment starvation at the coast, associated with the human management of river courses, deltas and erodible coastal cliffs, has had profound consequences for the maintenance of coastal sediment systems (e.g. Syvitski et al., 2005, 2009; Stralberg et al., 2011). The DIVA_WCM also characterises the ability of a wetland to keep pace with relative sea-level rise through a third parameter, sediment supply *sedsup*. Following Stevenson et al. (1986), a widely adopted methodological approach has been to compare the rate of vertical accretion to relative sea-level rise and thus to calculate a wetland accretionary surplus or deficit. Such an approach assumes that accretion is equal to wetland surface elevation change. This is now known to be a simplification, as the relative balance between the *in situ* accumulation of organic sediments (Cahoon and Reed, 1995; Middleton and McKee, 2001; Rooth et al., 2003) or external, inorganic inputs (French and Spencer, 1993; Christiansen et al., 2000), or a combination of the two (Saintilan et al., 2013), can affect this balance, as can subsurface processes occurring within the soil column, including compaction, plant growth-decomposition and shrink-swell behaviour related to varying water storage (Cahoon et al., 2011; Krauss et al., 2014). However, given the scale of the DIVA_WCM, these relationships must be simplified for the purposes of modelling, with a distinction between those settings and environmental histories that promote high sediment supply and those that favour low sediment supply. The model therefore considers a combination of six contextual physical and anthropogenic controlling factors – (1) tectonic context; (2) fluvial sediment inputs to the coastal zone; (3) sediment availability from Quaternary glacial sediments; (4) coastal geomorphic setting; (5) degree of coastal protection structures; and (6) timing of sediment supply from historical land use practices – in assessing the impact of varying sediment supply on wetland vulnerability. Each of these factors exhibits a range of values identified by a range in 'forcing score' across different categories (see Supplementary Material, Table A4). Furthermore, each factor is multiplied by an internal weighting to reflect their relative significance within the *sedsup* parameter (Equation 3, Supplementary Material). The respective weights are based on expert judgement, derived from field experience and the published literature. It is recognised that sediment supply is the most difficult forcing factor to understand and parameterise in the model, due both to its localized and highly variable nature and to the lack of wetland datasets that specifically estimate this parameter.

2.3. Coastal Segment Vulnerability Score (CSVS)

The Coastal Segment Vulnerability Score (*CSVS*) reflects the integrated response of a wetland to relative sea level rise / tidal range, lateral accommodation space and sediment supply. The influence of each of these parameters is reflected through the weighted sum of the forcing factors, with the following weights: 0.5 for *rslr d*; 0.2 for *aspace*; and 0.3 for *sedsup* (and see Equation 4, Supplementary Material). These relative weightings indicate the importance of each parameter at the macro-scale, the values being derived from expert judgement, in turn based on field experience and published references. For gaining a better understanding of how these weights influence the model results, we performed a sensitivity analysis, comparing the model output of a series of different weight combinations.

2.4. Ecological Sensitivity Score (ESS)

Ecological systems are characterised by varying reaction and relaxation times to environmental perturbation. Many saltmarsh herbs, shrubs and grasses are very sensitive to landform change. Thus, for example, manipulative experiments in freshwater marsh systems, where inundation frequencies have been changed by transplanting marsh communities to lower (-10 cm) levels have shown responses in plant stem density and biomass over periods as short as a single growing season (McKee and Mendelssohn, 1989). By comparison, coastal forest trees show slower responses to changing environmental conditions. Thus, cypress forests on the Gulf of Mexico, USA have recorded 50% survival rates after 4 years of +120 cm and 18 years of + 60 – 300 cm increases in water levels respectively. Modelling of bottomland forest succession is typically undertaken over 50 year timescales (summarised in Conner and Brody, 1989). However, resilience characteristics are quite different from herbs and shrubs, showing permanence (if not regeneration) until a threshold point is reached when the system collapses catastrophically, as in the case of hurricane-impacted mangrove forest (e.g. Cahoon et al., 2003). Once such a threshold has been crossed, system re-establishment may be difficult and long-delayed (for review see Spencer and Möller, 2013). Lag weights for current and previous 5-year time steps of a model run were applied to parameterize these habitat-specific response lags to changes in the environmental forcing factors (Table A5, Supplementary Material). For ‘freshwater marsh’, ‘salt marsh’, ‘unvegetated low’, and ‘unvegetated high’, a response time of 5 years was assumed and for ‘coastal forest' and 'mangrove forest', a response time of 10 years. The resulting modification of the Coastal Segment Vulnerability Score (*CSVS*) is termed the Ecological Sensitivity Score (*ESS*) (Fig. 1).

2.5. Habitat successional changes and wetland loss to open water

Most existing large-scale models of wetland response to accelerated sea-level rise (e.g. the GVA and its subsequent revisions (Nicholls et al., 1999)) assume the conversion of vegetated surfaces to open water and thus simply generate statistics on total loss of wetland area. Such models are most appropriate where local rates of relative sea-level rise are high, such as in subsiding, sediment-starved deltaic environments. However, under more moderate rates of sea-level rise, and with an adequate sediment supply, ecosystem change may be i) slower than predicted; and ii) involve change stepped across wetland types rather than outright loss, as ecological tolerances of particular plant communities are exceeded in turn. DIVA_WCM assesses both conversion to open water and transitions to other wetland types due to environmental change through i) the construction of a series of wetland response curves, to define the proportion of wetland expected to be lost; and ii) a model of wetland transitions, where losses are distributed between different wetland types and open water.

During the first stage in the development of the habitat transition algorithm, a series of habitat-specific response curves were estimated for total wetland loss as a function of Ecological Sensitivity Score (ESS) (Fig. 1). These curves were approximated using the beta distribution (Fig. 2; and see Equation 6, Supplementary Material) as this distribution can describe a wide range of shapes within a constrained distribution (0% to 100% total wetland loss and 0.0 to 5.0 ESS value). This is particularly useful for constructing habitat-specific response curves, reflecting different resilience characteristics that were then calibrated using WARMER and SLAMM model outputs (described in more detail below).

Figure 2 near here

Where there is wetland change or loss, Figure 3 outlines the model of transition that was used within the DIVA_WCM. Except in the case of coastal forest, with low to moderate environmental forcing (CS*VS* value < 4) wetland types are transformed not only into open water (50%) but also into other wetland types which are found lower in the tidal frame (50%), created as a result of losses of wetland that occupy higher elevations. Thus, 'low unvegetated' wetland (i.e. mudflat-sandflat) can be created where it did not previously exist within a geographical location. Under high levels of environmental forcing (CS*VS* value >= 4) the model converts all wetland types to open water.

Figure 3 near here

2.6. Model calibration

In previous explorations of the DIVA_WCM model structure (McFadden et al., 2007), the model was calibrated qualitatively against model predictions of large-scale wetland type transitions in the Barataria and Terrebonne sub-basins of the Mississippi Delta Plain (Reyes et al., 2000). However, such calibration is problematic because these simulations begin in the period well before the 1985 – 2005 baseline used in this study. More recent scenario modelling in the same region, associated with Louisiana's 2012 Coastal Master Plan (Couvillion et al., 2013) does provide detailed forecasting of wetland loss on a sub-basin by sub-basin basis, but only until 2060. As an alternative way forward in this study, therefore, DIVA_WCM was calibrated against a set of six recent studies of wetland change undertaken using the WARMER, and particularly, the SLAMM model (Table 2).

Table 2 near here

A number of difficulties were encountered in the inter-comparison of the DIVA_WCM with WARMER and SLAMM model outputs. Firstly, in many of the SLAMM studies it was difficult to extract the necessary comparative information required on the sea-level rise scenario that had been applied (i.e. starting year, end year, sea-level rise function used (such as SRES, RCP, linear models), total sea-level rise within the simulation period (with reference to starting year)). Where scenarios referred to a SRES-scenario (IPCC SRES, 2000), but with user-defined amplitude, these were calculated, on a globally uniform basis, with the SRES-scenarios supplied with DIVA. Other scenarios were identified as being driven by a linear rate of sea-level rise and constructed accordingly. Secondly, the definition of wetland habitat types differed between the six calibration studies and introduced some additional wetland types not present in the DIVA typology. It was thus necessary to re-classify the wetland descriptions into their equivalent DIVA categories. Thirdly, the effect of sea-dikes were included in SLAMM – DIVA_WCM model comparisons where the SLAMM studies made explicit reference that wetland loss had been affected by the presence of a dike. However, it was not always very clear as to whether or not this had actually been the case. For calibration, the DIVA_WCM model was run against the relevant WARMER and SLAMM model output for each of the sea-level rise scenarios reported in the respective study, including dikes where applicable. The results were aggregated to allow inter-model comparison, the form of aggregation depending on whether the WARMER / SLAMM study area integrated several DIVA coastal segments or, alternatively, the one DIVA segment integrated several WARMER / SLAMM sites. All loss rates are reported as percent total wetland loss per 5 years. The error measure used to evaluate the model performance with reference to the reported data is the relative mean difference (RMD). The 'Nelder-Mead simplex direct search' algorithm (Lagarias et al., 1998) was applied to search for the RMD closest to zero by varying the habitat-specific beta values (Fig. 2, Equation 6 in Supplementary Material). This exercise was conducted without constraints regarding the relationships between the different beta values. The resilience/sensitivity estimation of a specific habitat (Fig. 2) thus usefully emerged as a result of the calibration exercise. Running the DIVA_WCM with the optimized beta values (Equation 6, Supplementary Material) against the six calibration studies produced a RMD value of 0.000227 with a mean difference of 0.00002% (loss per 5 years), indicating a close fit of model values with reported loss rates.

Fig. 4 shows the DIVA_WCM model outputs against the SLAMM and WARMER calibration studies. Interestingly, the WARMER model, which is not a derivative of SLAMM but a numerical saltmarsh model that includes biophysical feedbacks, performed in a very similar manner to the SLAMM models when it came to comparisons with the DIVA_WCM model. Outliers relate to a small number of particular DIVA segment comparisons across two SLAMM studies (Craft et al., 2009; Geselbracht et al., 2011). It is clear that these examples of poor model fit are not related to vegetated wetland habitats but rather to problems with estimating changes in 'unvegetated low' habitat (i.e. mudflat/sandflat). This raises the need for an improvement in model formulation regarding the mechanisms in place when vegetated wetlands are drowning. Not considering the site exposure to wave activity may partly explain the poor model representation of the 'unvegetated low' at these sites. While this comparison illustrates the difficulty of model calibration, these results are calibrated to these more detailed simulations, improving on the earlier methods of Hoozemans et al. (1983), Nicholls et al. (1999) and McFadden et al. (2007). Further efforts at improved model calibration should receive high priority in future research efforts.

Figure 4 near here

2.7. Model validation

In order to undertake independent validation at a scale appropriate to the DIVA scale of analysis, model outputs of the calibrated DIVA_WCM were compared with two broad-scale coastal wetland vulnerability studies, one concerned with the modelled vulnerability of Indo-Pacific mangrove forests to sea-level rise and one a qualitative assessment of wetland stability along the US mid-Atlantic coast.

Lovelock et al. (2015) developed a model (hereafter referred to as the 'Lovelock model') to predict the time to submergence of mangrove ecosystems subject to accelerated sea level rise based on the concept of the loss of 'elevation capital', the potential of a mangrove ecosystem to remain within a suitable inundation regime (between Highest Astronomical Tide (HAT) and Mean Sea Level (MSL)). The key controlling parameters are the rate of sea level rise, the tidal range and suspended sediment supply. Sites with a tidal range of 10 m need to lose 5m of elevation capital to bring them to the critical survival threshold of MSL whereas sites with a tidal range of 1 m only have to lose 0.5 m of elevation to bring them to this threshold. Thus the Lovelock model predicts that sites with low tidal range are significantly more vulnerable to loss than those experiencing a high tidal range. Loss of elevation capital can be offset by elevation gains from vertical accretion as sea level rises. Thus mangrove forest sites with high sediment supply are less vulnerable to conversion to open water than sites with low sediment supply. Total suspended matter in coastal waters was acquired from remotely sensed imagery and converted to elevation gain through established relationships between sea-level rise, suspended sediment concentrations and measured changes in surface elevation from SET sites. The Lovelock model excludes consideration of an accommodation space term but it does identify the importance of the relations between rates of sea level rise, tidal range and sediment supply in determining mangrove forest vulnerability to sea-level rise in a similar manner to the DIVA_WCM. The difference in model structure makes Lovelock et al. (2015) an appropriate validation case for the DIVA_WCM. The two models cannot be compared directly because i) the Lovelock model provides a binary survival or loss indicator whereas the DIVA_WCM estimates percentage loss of mangrove forest over time; and ii) the Lovelock outputs are reported on a 4 km resolution grid defined by the remotely sensed TSM data whereas the DIVA_WCM results are mapped onto the variable length DIVA coastal segments. However, a qualitative assessment is possible, for comparable sea level rise scenarios to 2100 (Fig. 5). The areas of mangrove submergence predicted by the Lovelock model (Fig. 5b) map well onto the areas of highest coastal wetland loss predicted by the DIVA_WCM (Fig. 5a). Apart from Australia and Brunei, of the top ten areas of expected mangrove loss identified by the DIVA_WCM in the region shown in Figure 5, eight areas are also highlighted by the Lovelock model: Cambodia (55% coastal wetland loss at country level by 2100 in the DIVA_WCM); Philippines (50%); Sri Lanka (48%); Thailand (46%); Indonesia (40%); Federated States of Micronesia (40%); Papua New Guinea (39%); and Solomon Islands (39%).

Figure 5 near here

A qualitative assessment of wetland stability on the eastern seaboard of the USA was performed on behalf of the US Environmental Protection Agency (EPA) (Reed et al., 2008). As with the first validation exercise, a direct comparison between the EPA assessment and the DIVA_WCM output is not possible. This is partly because the DIVA_WCM segments along the eastern seaboard do not allow the level of disaggregation seen in the EPA assessment and partly because Reed et al. (2008) rely on a more qualitative, expert judgement approach. Nevertheless, validation at the level of aggregation associated with the DIVA_WCM model was possible. Reed et al. (2008) assume a current rate of sea-level rise of 3 mm a^{-1} and provide estimates for future wetland development for three linear SLR scenarios: a continuation of the current rate of sea-level rise; the current rate plus 2 mm a^{-1} (i.e. 5 mm a^{-1}); and the current rate plus 7 mm a^{-1} (i.e. 10 mm a^{-1}) (Fig. 6a). The calibrated DIVA_WCM was run for each of these three scenarios for each DIVA_WCM segment that falls within this study area; it assumed that no dikes are present, since the primary driver analysed by Reed et al. (2008) was wetland drowning due to insufficient vertical wetland growth. Percentage wetland losses as predicted by the DIVA_WCM, and mapped into groups suggested by the Reed et al. (2008) categories, are shown in Fig. 6b-6d for each of the three sea-level rise scenarios. The categorical comparison shows that the DIVA_WCM reproduces the general patterns of increasing wetland vulnerability with increasing rates of SLR. While Reed et al. (2008) conclude that most parts along the US mid-Atlantic marshes are unlikely to be converted to open water under current rates of SLR, modelled loss rates with DIVA_WCM for the linear 3 mm a^{-1} SLR are <50% in most coastal segments of the study area. Following Reed et al. (2008), with 5 and 10 mm a^{-1} SLR rates wetlands are expected to survive to a marginal extent only or completely disappear respectively. Equivalent conclusions can be drawn from the model validation runs, indicating wetland loss rates between 50 and 75% and >90%, respectively.

While the general trend of modelled wetland loss rates compares well with the EPA assessment, the spatial patterns in the area, as suggested by Reed et al. (2008), are poorly represented in the model results. The most important reason for this is the relatively large length of coastal segments in estuarine environments, smoothing estuarine gradient and neglecting local variations in tidal range and sediment supply. This in turn highlights the spatial scale at which the

DIVA_WCM results have to be interpreted and the conclusions that can be drawn from them. The model is suitable for identifying hotspot regions (~200 km coastline length) of coastal wetland loss but is not applicable for sub-regional (< 100 km) scale analysis.

Figure 6 near here

3. Results

The DIVA database indicates a mapped total global coastal wetland stock (in 2011) of 756 x10^3 km^2. This figure compares to the 302 x10^3 km^2 reported by Hoozemans et al. (1993), for data collected in the 1980s. Absolute and relative rates of global wetland loss between 1995 and 2100 are shown in Figure 6 for the high, medium and low scenarios of global sea-level rise and the three dike scenarios, as outlined earlier (sections 2.1, 2.2.2. respectively). These combinations give wetland loss by 2100 in the range from 281 to 592 x10^3 km^2, or between 37 and 78 % of the total stock of global coastal wetlands (Table 3). Total wetland loss from 1995 (mean sea level during 1985-2005 baseline period) to 2100 strongly varies with sea-level rise, with wetland losses being 27 - 31% lower for the lowest SLR scenario in comparison to the highest SLR scenario, independent of the dike scenario (‘no dikes’, ‘widespread dikes’, ‘maximum dikes’) applied (Fig. 7, Table 3).

Figure 7 near here

Table 3 near here

In order to obtain a better understanding of which of the applied forcing factors are primarily responsible for these wetland losses, we report the results of a sensitivity analysis for the weights of the different forcing factors (see Supplementary Material Equation 4).

3.1. Global coastal wetland loss rates by weighting of environmental forcing factors under high sea-level rise

Under the high sea-level rise scenario of 110 cm by 2100 (95% quantile, RCP8.5; Table 1) and with no dike building, the DIVA_WCM model predicts a loss of between 392 and 578 x10^3 km^2 of coastal wetlands worldwide by 2100 (Fig. 8a), or 52 - 76% of the total global stock, depending upon the comparative weighting of the three environmental forcing factors (Table 4). The loss of total global stock is 11 – 18% by the 2020s, 27 - 43% by the 2050s and 42 - 65% by the 2080s (Fig. 8a).

Figure 8 near here

A sensitivity analysis shows that, in the absence of dikes, the variation in loss rate is strongly controlled by the influence of the accommodation space term. Where accommodation space has a relatively high weighting (and wetlands can migrate inland over low coastal slopes), loss rates are at the lower bound (Fig. 8a, Table 4(a)); where the influence of accommodation space is neglected by the model, all combinatorial weightings of sea-level rise and sediment supply give rise to high rates of total wetland loss by 2100 (Table 4(b)).

Table 4 near here

The importance of accommodation space points to the critical importance of dike construction under the high sea-level rise scenario. Under the most extreme scenario of dike building tested, 'maximum dikes', the DIVA_WCM is largely insensitive to any of the model parameters (Fig. 8b, Table 5), as the benefit of accommodation space is lost (cf. Table 4(a)). Global wetland loss rates are very high, at 574 – 619 x10^3 km^2 of the total stock of 760 x10^3 km^2 (Fig. 8b).

Table 5 near here

3.2. Global coastal wetland loss rates by weighting of environmental forcing factors under low sea-level rise

Wetland loss rates are significantly less (Table 3) under the low sea-level rise scenario (5% quantile, RCP2.6, Table 1) and there is less acceleration in the wetland loss rate towards 2100 (Fig. 7). With no dike building, the DIVA_WCM model predicts a loss of between 222 – 356 x10^3 km^2 of coastal wetlands worldwide by 2100, or 29 – 47% of the total global stock, depending upon the comparative weighting of the three environmental forcing factors (Fig. 8c). The accommodation space term remains an important discriminator within this range but the overall range in loss rate is a third less than under the high sea level scenario (Fig. 8c, Table 6(a)). When the accommodation space term is removed, it is clear that the main control on wetland loss is the sea-level rise / tidal range term, *rslr_d*, (Table 6(b)) with lower loss rates where this term is high. Under the highest level of dike construction ('maximum dikes'), the envelope of loss rates narrows and rises but not greatly, to between 312 – 418 x10^3 km^2 of coastal wetlands worldwide by 2100, or 41 – 55% of the total global stock (Fig. 8d). Similar to the results when accommodation space is neglected, the loss rates are controlled by the slr / tidal weight, with lower loss rates when the slr / tidal weight is high (Table 7).

Table 6 near here

Table 7 near here

3.3. Global patterns in predicted wetland loss rates

As well as the global estimates of wetland loss, the results can be disaggregated down to individual segment level where wetlands have been recorded. It is thus possible to view both the global pattern of potential absolute wetland loss (Fig. 9a) and relative wetland loss (Fig. 9b). These plots assume 'widespread dikes' and the medium sea-level rise scenario (median, RCP4.5; Table 1). In these contexts, the wetlands that appear most at risk are those characterised by micro-tidal settings. Regional hotspots include the Mediterranean Sea, the Caribbean Sea and the Baltic Sea.

Figure 9a near here

Figure 9b near here

4. Discussion

These results show that coastal wetlands are sensitive to sea level rise and, based on credible scenarios for the 21st century, there is a potential for considerable wetland loss at the global scale. This will be exacerbated by coastal squeeze caused by the construction, and upgrading, of dikes which, whilst providing flood defence to coastal populations and infrastructure, prevent the onshore and upslope migration of wetlands. This model-based conclusion is consistent with other assessments in the scientific literature (e.g. Nicholls et al., 2007; Wong et al., 2014). It is also consistent with earlier global assessments. While considering a smaller global wetland stock, Hoozemans et al. (1993) concluded that a 1 m sea-level rise might cause coastal wetland loss of 154 – 180 x10^3 km^2, or 51 – 60% of total global stock, depending upon assumptions about development and dike construction. For a similar sea-level rise scenario, Nicholls et al. (1999) estimated wetland losses of up to 46% of global coverage. The losses associated with a 38 cm rise in sea level by the 2080s were estimated at 0 – 2% by the 2020s, 2 – 11% by the 2050s and 6 – 22% by the 2080s. In this analysis, evaluating the contribution of lateral accommodation space and sediment supply controls as well as sea-level rise, the most comparable sea-level rise scenario, the 5% quantile of RCP2.6 (29 cm by 2100), gives loss rates of 10-11% by the 2020s, 23-28% by the 2050s and 32-40% by the 2080s. However, under the 95% quantile of the RCP8.5 sea-level rise scenario (110 cm by 2100), the wetland loss rates rise to 14-15% in 2020s, 33-40% in the 2050s and 53-66% in the 2080s. Hence, in its current form the DIVA_WCM model shows higher sensitivity to sea-level rise than these earlier analyses, and losses two or more times higher than these earlier estimates appear possible.

However, this sensitivity may be reduced in future iterations if appropriate feedbacks from changing plant physiology and tidal hydrodynamics can be included in the model structure. Thus, for example, increased atmospheric CO_2 and warmer temperatures, allied to mid-range rates of sea level rise, may lead to increases in the rates of plant productivity and wetland accretion (Langley et al., 2009; Cherry et al., 2009; Kirwan and Gutenspergen, 2012; Kirwan and Mudd, 2012), These dynamics might be further reinforced by increased sediment supply to wetland surfaces with greater tidal energetics under higher sea levels, albeit with limits to ‘ecogeomorphic’ adaptability at higher rates of sea level rise (Kirwan et al., 2010).

These rates also need to be seen in the context of wetland losses resulting from anthropogenic impacts. Thus, for example, Dodd and Ong (2008) have estimated that the coastal populations of nation states with mangroves will rise by 50%, from 1.8 billion to 2.7 billion, in the period between 2000 and 2025. Human pressures on mangroves include direct conversion to urban use for industry, port development, and housing; conversion for aquaculture and agriculture; timber extraction; and modification of hydrology and pollution, particularly oil pollution, nutrients associated with agricultural intensification, and heavy metals contamination. These pressures will be imposed upon mangrove systems (plus other wetlands) already suffering significant long-term declines in extent (Spencer and Möller, 2013). Whilst the exact figure for loss may be debateable, the general sentiment of Nicholls et al.’s (1999, S82) statement that ‘when combined with the direct loss scenarios due to direct human destruction, in the worst case 36 % to 70 % of the world’s wetlands (up to 210,000 km^2) could be lost by the 2080s’ surely remains true (and with the total global wetland area reported here the 70% would equate to 529 x10^3 km^2).

This paper emphasises the importance of lateral accommodation space in mitigating high rates of wetland loss under high rates of sea-level rise. Such a finding gives support to those management strategies that aim to create or re-create space into which coastal wetlands can retreat landwards under sea level forcing (e.g. UK: Rupp, 2010; Dawson et al., 2011; Canada: Djeza et al., 2011; Australia: Abel et al., 2011). However, it is also clear that in many localities such set-back is not possible, either because of existing human occupation and development (e.g. McLeod et al., 2011) or because natural topographic settings are often not conducive to such migration. Thus, for example, the rapid onshore steepening of coastal profiles inland from wetland fringes along most of the Californian coast severely limits migration sites along this coast (Committee on Sea Level Rise in California, Oregon and Washington, 2012).

The broad-scale nature of the model presents a major challenge to model calibration and validation and this in turn depends on the development of more systematic national to regional scale assessments of wetland behaviour. A key model output has been the derivation of a series of habitat-specific wetland response curves describing the transition between different wetland types. Based on recently published estimates for habitat-specific regional wetland change, the calibration of these curves provides an important focus for the linking of regional scale assessments to global scale wetland modelling. Similarly, such regional scale assessments, either empirical or modelled, are necessary for model validation and, within this study, have been shown to give important information on the temporal and spatial accuracy of the DIVA_WCM. An appropriate choice of calibration and validation data smooths over the fine scale variability in wetland response to environmental forcing which characterises the vegetation 'mosaic' of many wetlands and of which there are many studies. Model validation should be taken over long timescales so as not to give undue weight to the impacts of individual high-magnitude events or even long-term cycles in tidal flooding regimes. However, this remains a considerable challenge because of the lack of suitable large-scale data that explicitly address this question in a truly quantitative manner. Progress in better understanding wetland response to sea-level rise requires continued improvement of the underlying datasets, and studies across scales from local to global, with bridging regional assessments as utilised in this study.

5. Conclusions

The DIVA_WCM has been developed to better identify the vulnerability of coastal wetlands at the macro-scale, over a timescale of up to 100 years and at global, continental and national scales spatial scales. The utility of the model is therefore directed towards decision-makers and analysts interpreting and evaluating wetland vulnerability to climate change on these scales. It gives a new and important perspective on coastal wetland behaviour at a spatial scale where existing models are limited and data is surprisingly poor. Here we focus on the global results as a diagnostic output.

The modelling approach described in this paper, which considers three environmental factors, suggests that the potential rates of global coastal wetland loss over the coming decades to 2100 are substantial. Countering these potential losses will require both climate mitigation (a global response) to minimise sea-level rise, and promotion of accommodation space and sediment supply (a regional response) to promote wetland survival. Collectively, these measures could greatly reduce losses if applied at a sufficient scale but some net loss appears inevitable given current trends and lock-in to some sea-level rise. Given the now clear ecosystem service value of coastal wetlands, and the magnitude of these long-term predicted losses, wetland management should become an environmental policy priority, even in areas where the existing threat from sea-level rise appears currently minimal. Results from DIVA_WCM suggest that developing a greater understanding of the specific geomorphic natural slope settings which result in greatest levels of forcing on wetland loss would be useful in developing coastal wetland protection policy.

Further development of the model is now needed to better assess the role of ecogeomorphic feedbacks to see if the incorporation of these terms fundamentally affects model outcomes (e.g. Kirwan et al., 2010; Shile et al., 2014). In addition, independent validation of the results predicted by the DIVA_WCM, particularly across different geographical regions and timeframes, remains an important but difficult task. It is hoped that this broad-scale modelling of coastal wetlands will stimulate both the quantity and approach of field measurements, such that the data required to validate this type of model become more widely available. Changes to coastal wetlands need to be evaluated at multiple scales, including the macro-scale considered here.

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Fig. 1. Model structure in the revised DIVA_WCM wetland loss and transition algorithm.

Fig. 2. Proportion of wetland loss versus wetland sensitivity as measured by the Ecological Sensitivity Score (ESS; see text for definition). Values of beta: Unvegetated sediments (Sabka and Mudflat/Sandflat) (0.093); Freshwater Marsh (0.188); Saltmarsh (0.137); and Coastal Forest and Mangrove Forest (0.074).

Fig. 3. Model of wetland loss and transition between wetland types and open water for low to moderate environmental forcing (Vulnerability Score < 4). For high environmental forcing (Vulnerability Score >= 4) all wetland areas are lost to open water.

Fig. 4. DIVA_WCM model outputs vs. wetland loss rates derived from the one WARMER and five SLAMM studies. In (a) all available data points are displayed (CSLID = DIVA segment number). In (b) only the central data points are shown. The blue line denotes the 1:1 line (perfect fit). Negative wetland losses (wetland gains), reported by the SLAMM studies were put to zero for all wetland types, where no gain is possible (all habitat types except unvegetated low).

Fig.5. Coastal wetland loss in the Indo-Pacific region. A: Predicted relative coastal wetland loss by DIVA segment. DIVA_WCM simulation with medium sea-level rise scenario (RCP4.5 median, 50 cm by year 2100) and SSP2 scenario with 'widespread dikes'; B: Predicted loss of mangrove habitat under an RCP6 sea level rise scenario of 0.48 m by year 2100, as modelled by Lovelock et al. (2015).

Green indicates mangrove extent in 2011 (after Giri et al., (2011)) and red identifies areas of predicted mangrove habitat loss to sea level rise.

Fig. 6. Comparison of the qualitative assessment by Reed et al. (2008) (a) with the outputs of the calibrated DIVA WCM for constant sea-level rise of 3 (b), 5 (c), and 10 (d) mm a^{-1}. (a): Reed et al. (2008) assumes a current SLR rate of sea-level rise of 3 mm a^{-1}. Future scenarios are a continuation of the current rate of sea-level rise; the current rate plus 2 mm a^{-1} (i.e. 5 mm a^{-1}); and the current rate plus 7 mm a^{-1}. Figures 6(b-d) can be compared to 6(a) as follows:

%Total Loss < 50%: Wetlands will not be converted to open water (“No”)
50%<%Total Loss < 75%: Wetlands will be marginal (“?”)
75%<%Total Loss < 90%: Wetland will be marginal or lost (“Yes?”)
%Total Loss > 90%: Wetlands will be converted to open water (“Yes”)

Fig. 7. Absolute and relative cumulative global coastal wetland loss from 1995 to 2100. Three scenarios describing the construction of sea dikes are considered: (i) ‘no dikes’; (ii) ‘widespread dikes’ built according to a ‘demand-for-safety function’, assuming an SSP2 scenario; (iii) ‘maximum dikes’. For each dike-scenario low (lower dashed), medium (full line) and high (upper dashed) sea-level rise scenarios are run: Low = RCP2.6 (5% quantile; 29 cm by 2100); medium = RCP4.5 (median; 50 cm); high = RCP8.5 (95% quantile; 110 cm).

Fig. 8. Absolute cumulative global wetland loss from 1995 to 2100 for different combinations of weights for the three environmental forcing factors (sea-level rise / tidal range (*rslr_tidal_score*); sediment supply (*sedsup*); accommodation space (*aspace*). See Tables 4 – 7 for more details. Dark line colours represent low weights for accommodation space, whereas bright colours indicate higher weights for accommodation space. Sensitivity runs were conducted assuming A) 'no dikes' and high sea level rise (HIG = 110 cm by year 2100); B: 'maximum dikes' and high sea level rise; C: 'no dikes' and low sea level rise (LOW = 29 cm by year 2100); and D: 'maximum dikes' and low sea level rise.

Fig. 9. Global wetland loss by DIVA segment between 1995 and 2100. A: absolute loss; B: relative loss. DIVA_WCM simulation with medium sea-level rise scenario (RCP4.5 median, 50 cm by year 2100) and SSP2 scenario with 'widespread dikes'.

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Table 1. Global mean sea-level rise in 2100 with respect to 1985-2005. Median values, with 5% and 95% quantiles in parentheses. After Hinkel et al. (2014). The DIVA_WCM uses low sea-level rise = RCP2.6 (5% quantile; 29 cm by 2100); medium sea-level rise = RCP4.5 (median; 50 cm); high sea-level rise = RCP8.5 (95% quantile; 110 cm).

Table 2. Location, habitat, sea-level rise scenario and model characteristics for the six calibration studies used to calibrate the behavioural curves used in the DIVA_WCM. Tidal range data: in reference or for USA sites from NOAA Tides and Currents (https://tidesandcurrents.noaa.gov/stations.html?type=Datums). Suspended sediment concentrations: (1) 2011 annual mean of MERIS geophysical product Total Suspended Matter (TSM) in 0.017 degree resolution, northern NSW, Australia (http://hermes.acri.fr/); (2) Howard and Frey (1985); (3) Heimann et al., (2011); (4) Buchanan and Morgan (2014); (5) You (2005).

Table 3. Absolute global wetland loss (x10^3 km^2) and relative loss of total global wetland stock (%) by 2100 under the diking and sea-level rise scenarios (see Table 1 and text for details on the scenarios employed).

Table 4. Percentage of total wetland area loss at 2100 under different weighting combinations of (a) three environmental forcing factors and (b) sea-level rise / tidal range and sediment supply only, given high sea-level rise scenario of 110 cm by 2100 (95% quantile, RCP8.5; Table 1) and ‘no dikes’. Shaded area = ‘standard’ DIVA_WCM output (see Equation 4, Supplementary Material for details).

Table 5. Percentage of total wetland area loss at 2100 under different weighting combinations of the three environmental forcing factors given high sea-level rise scenario of 110 cm by 2100 (95% quantile, RCP8.5; Table 1) and 'maximum dikes'. Shaded area = 'standard' DIVA_WCM output (see Equation 4, Supplementary Material for details).

Table 6. Percentage of total wetland area loss at 2100 under different weighting combinations of (a) three environmental forcing factors and (b) sea-level rise / tidal range and sediment supply only, given low sea-level rise scenario of 29 cm by 2100 (5% quantile, RCP2.6; Table 1) and 'no dikes'. Shaded area = 'standard' DIVA_WCM output (see Equation 4, Supplementary Material for details).

Table 7. Percentage of total wetland area loss at 2100 under different weighting combinations of the three environmental forcing factors given low sea-level rise scenario of 29 cm by 2100 (5% quantile, RCP2.6; Table 1) and 'maximum dikes'.

Supplementary Material

Background tables and equations used in the DIVA_WCM algorithm

1. Relative sea-level rise and tidal range forcing

We first compute rslr_tidal as:

rslr_d = rslr_annual^1.4 / htidal **Eq.1**

where rslr_annual is the annual rise in relative sea level in metres, htidal is the tidal range in metres derived from the LOICZ typology (Maxwell and Buddemeier, 2002) as shown in Table A1.

Tidal Range classes from LOICZ typology	Tidal Range (metres), LOICZ typology	htidal (Tidal forcing score within the DIVA Wetland Change Model)
<2	0-2.5	0.25
2	2.5-3.5	1.25
3	3.5-5.0	3
4	5.0-6.5	6
5	>6.5	9

Table A1 Derivation of tidal forcing scores (representing tidal range) based on the tidal range classes from the LOICZ typology.

Then we convert rsrl_d into an *rslr_tidal_score* between 1 and 5 based on the 95, 84, 50, 16 percentiles of all rslr_d values where wetlands are reported (assuming a current global SLR of 3 mm a^{-1}). Resulting class values are reported in the following table:

rslr_d	rslr_tidal_score
>=0.001121	5
>=0.000402	4
>=0.000178	3
>=0.000044	2
>0	1

Table A2: Assigning a forcing value to the impact of relative sea-level rise and tidal range on wetland vulnerability.

2. Lateral accommodation space

We initialize the forcing score for lateral accommodation space based on the coastal slope (degrees) using Table A3.

Average slope (slopecst, degrees)	**Forcing score for lateral accommodation space (aspace)**
>4.5	5
>1.5 < 4.5	4
> 0.5 < 1.5	3
> 0.25 < 0.5	2
<0.25	1

Table A3: Forcing score used to represent the impact of coastal slope on wetland vulnerability. slopecst is the average topographic slope (in degrees) along the segments.

aspace value is initialised using the average topographic slope, derived from the ETOPO2 (NGDC, 2001) dataset. This initialized *aspace* score is then updated based on the actual computed dike height within each time-step using Equation 2. DIVA_WCM builds sea dikes along the entire coastal segment given sea level and socio-economic forcing following the demand function of safety given in Hinkel et al. (2014).

if (sdikehght > htidal/2 and $aspace < 5$): $aspace = aspace + 0.25$ **Eq. 2**

Where htidal/2 is a critical value of sdikehght defining its functioning as barrier to landward movement of wetland and to flooding. This threshold value is based on expert judgement.

3. Sediment supply

External of DIVA we calculate a constant sediment supply factor *sedsup* based on a variety of biophysical coastal properties.

$$sedsup = (t * tw) + ((dis + d\_dis)/2) * fw) + (gl * glw) + (geo * gew) + (man * mw) + (his * hw)$$ **Eq. 3**

where:
t = Tectonic control parameter
tw = Tectonic control weighting
dis = Annual river discharge parameter
d_dis = Distance from point of discharge parameter
fw = Fluvial weighting
gl = Glacial limit parameter
glw = Glacial limit weighting
geo = Geomorphic setting parameter
gew = Geomorphic setting weighting
man = Management parameter (presence or absence of sea dikes)
mw = Management weighting
his = History of resource exploitation parameter
hw = History of resource exploitation weighting

In the DIVA database we have values of *sedsup* between 1.7 and 4.9.

Sediment Supply Factor	**Description**	**Key data reference/source**	**Category**	**Forcing Score**	**Weighting Factor**
Tectonic Context	Global tectonic setting	Inman and Nordstrom (1971)	Passive Margins	1	0.07
			Marginal Seas	3	
			Active Margins	5	
Fluvial Context	Annual river discharge	Ludwig and Probst (1998)	>500 F_{TSS} (10^{12} g/yr)	1	0.2
			100-500 F_{TSS} (10^{12} g/yr)	2	
			50-100 F_{TSS} (10^{12} g/yr)	3	
			5-10 F_{TSS} (10^{12} g/yr)	4	
			<5 F_{TSS} (10^{12} g/yr)	5	
	Distance to the point of fluvial discharge	Calculated by GIS	0-30km	1	
			30-70km	2	
			70-120km	3	
			120-180km	4	
			>180km	5	
Glacial Context	Location relevant to maximum extent of last glaciation	Williams et al. (1991)	100km-300km	1	0.1
			>300km	3	
			<100km	5	
Geomorphic Context	Coastal geomorphic setting	McGill (1958)	Sheltered coast (Inlet/delta/estuary)	1	0.03
			Open coast	5	
Management Context	Degree of coastal protection	DIVA adaptation algorithm or user inputs (Tol et al., 2005)	Sea dike absent ($\leq$ 0.5 m high)	1	0.3
			Sea dike present (> 0.5 m high)	5	
Historical Context	Timing of peak resource exploitation	Expert judgment	Classical	1	0.3
			Medieval	2	
			Colonial	3	
			20th Century	5	

Table A4 Factors influencing sediment supply and their incorporation into the DIVA_WCM via forcing scores and weighting factors.

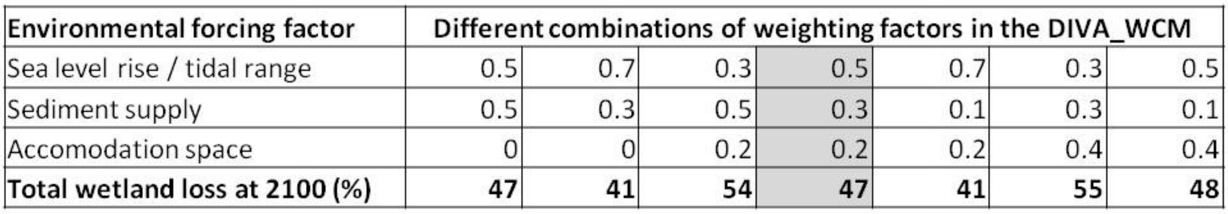
4. Coastal segment vulnerability score (csvs)

The above calculated three forcing scores are then combined into the coastal segment vulnerability score (csvs) following Equation (4)

$$\text{csvs} = \mathit{rslr\_tidal\_score} * 0.5 + \mathit{aspace} * 0.2 + \mathit{sedsup} * 0.3 \qquad \textbf{Eq. 4}$$

where *rslr_tidal score* is the relative sea-level rise and tidal range forcing (Equation 1), *aspace* the lateral accommodation space forcing score (Equation 2) and *sedsup* the sediment supply forcing score (Equation 3).

5. Ecological Sensitivity Score (ESS) by wetland type



Environmental forcing factor	Different combinations of weighting factors in the DIVA_WCM						
Sea level rise / tidal range	0.5	0.7	0.3	0.5	0.7	0.3	0.5
Sediment supply	0.5	0.3	0.5	0.3	0.1	0.3	0.1
Accomodation space	0	0	0.2	0.2	0.2	0.4	0.4
Total wetland loss at 2100 (%)	**47**	**41**	**54**	**47**	**41**	**55**	**48**

Finally, we compute the ecological sensitivity score (ess) by combining the csvs values of the current and last time step.

Eq. 5

where ESS_{type} is the ecological sensitivity score for the given wetland type, $csvs_{current}$ is the coastal segment vulnerability score and $csvs_{last}$ is the value of this variable calculated within the previous time step, $weight\_current_{type}$ is the lag weight associated to the current time step and $weight\_last_{type}$ is the lag weight associated to the csvs value from the previous time step. The weights used are given in Table 4.

Wetland Type (type)	**Previous 5 year lag weight ($weight\_last_{type}$)**	**Current 5 year lag weight ($weight\_current_{type}$)**	**Response time (yrs)**
Coastal forest	1	0	10
Freshwater marsh	0	1	<5
Saltmarsh	0	1	<5
Mangrove forest	1	0	10
Unvegetated wetland	0	1	<5
Mudflat and sand flat	0	1	<5

Table A5: Response to environmental change by wetland type as modelled by relative importance of previous and current ecological state. Response time = 5 / Current 5 year lag weight.

6. Wetland response (Annual wetland loss rate)

The ess values are then translated into relative 5-years wetland loss rates (RLR_5), which is the proportion of wetlands lost for a specific wetland type during a 5-year time step.

$$RLR_5 = 1- (\beta +1) * (1 - ESS_{type}/5) \wedge \beta + \beta * (1 - ESS_{type}/5) \wedge (\beta + 1) \qquad \textbf{Eq. 6}$$

Values of beta:

1. Unvegetated high and low: 0.093
2. Freshwater Marsh: 0.188
3. Saltmarsh: 0.137
4. Coastal Forest and Mangrove Forest: 0.074.

Supplementary material references

Inman, D.L., Nordstrom, C.E., 1971. On the tectonic and morphologic classification of coasts. Journal of Geology 79, 1-21.

Ludwig, W., Probst, J.L., 1998. River sediment discharge to the oceans: present-day controls and global budgets. American Journal of Science 298, 265-295.

Maxwell, B.A., Buddemeier, R.W., 2002. Coastal typology development with heterogeneous data sets. Regional Environmental Change 3, 77-87.

McGill, J.T., 1958. Map of coastal landforms of the world. Geographical Review 48, 402- 405.

NGDC (National Geophysical Data Centre), 2001. NGDC CD-ROM, ETOPO2 Global 2’ Elevations. Available at: http://www.ngdc.noaa.gov/mgg/fliers/01mgg04.html

Nicholls, R.J., Tol, R.S.J., 2006. Impacts and responses to sea-level rise: A global analysis of the SRES scenarios over the twenty-first century. Philosophical Transactions of the Royal Society of London 364A, 1073–1095.

Williams, M.A.J., Dunkerley, D.L., De Deckker, P., Kershaw, A.P., Stokes, T., 1991. Quaternary Environments. Edward Arnold, London.

Figure 1 bw

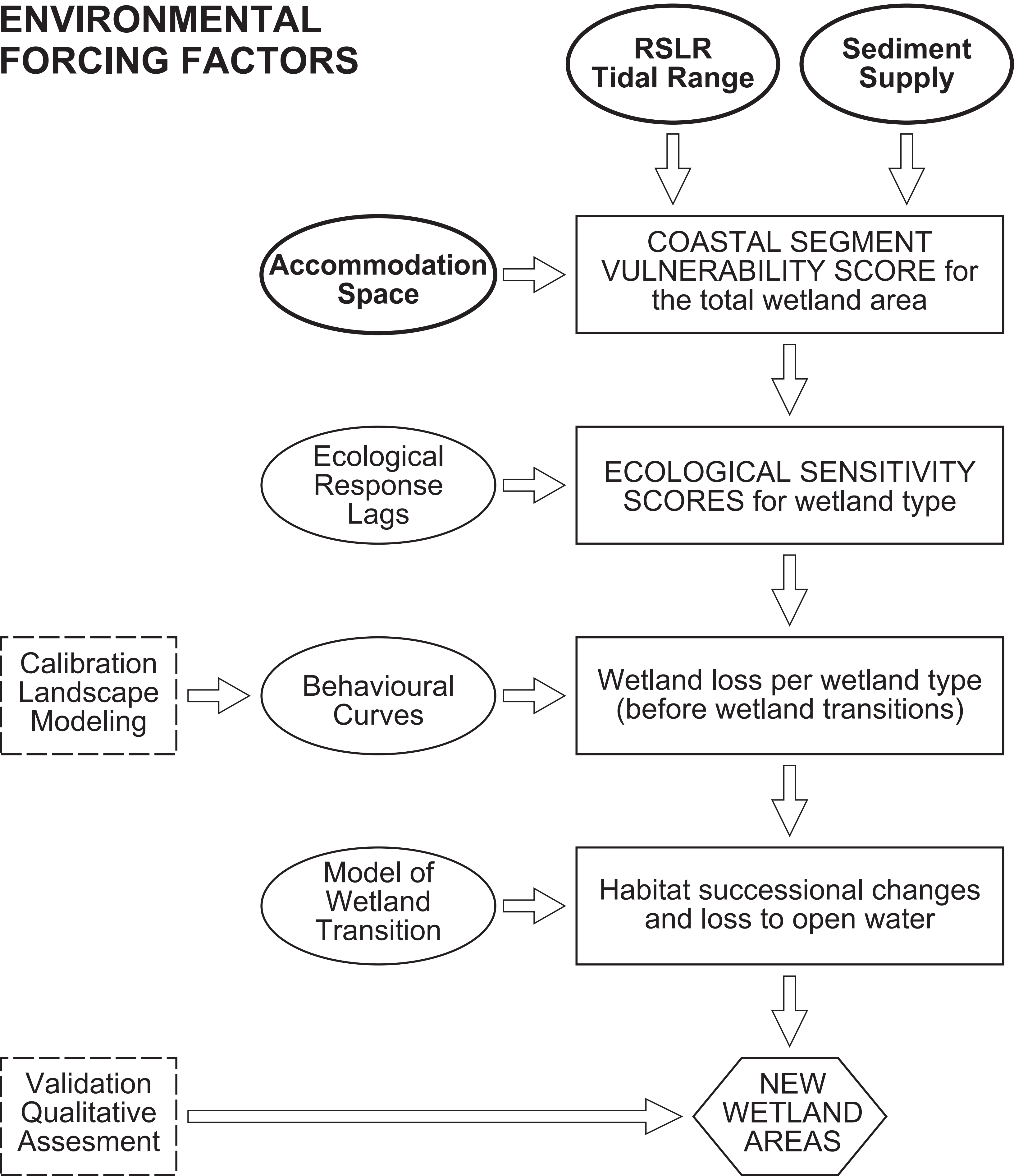

ENVIRONMENTAL FORCING FACTORS
RSLR Tidal Range
Sediment Supply
Accommodation Space
COASTAL SEGMENT VULNERABILITY SCORE for the total wetland area
Ecological Response Lags
ECOLOGICAL SENSITIVITY SCORES for wetland type
Calibration Landscape Modeling
Behavioural Curves
Wetland loss per wetland type (before wetland transitions)
Model of Wetland Transition
Habitat successional changes and loss to open water
Validation Qualitative Assesment
NEW WETLAND AREAS

Figure 1 col

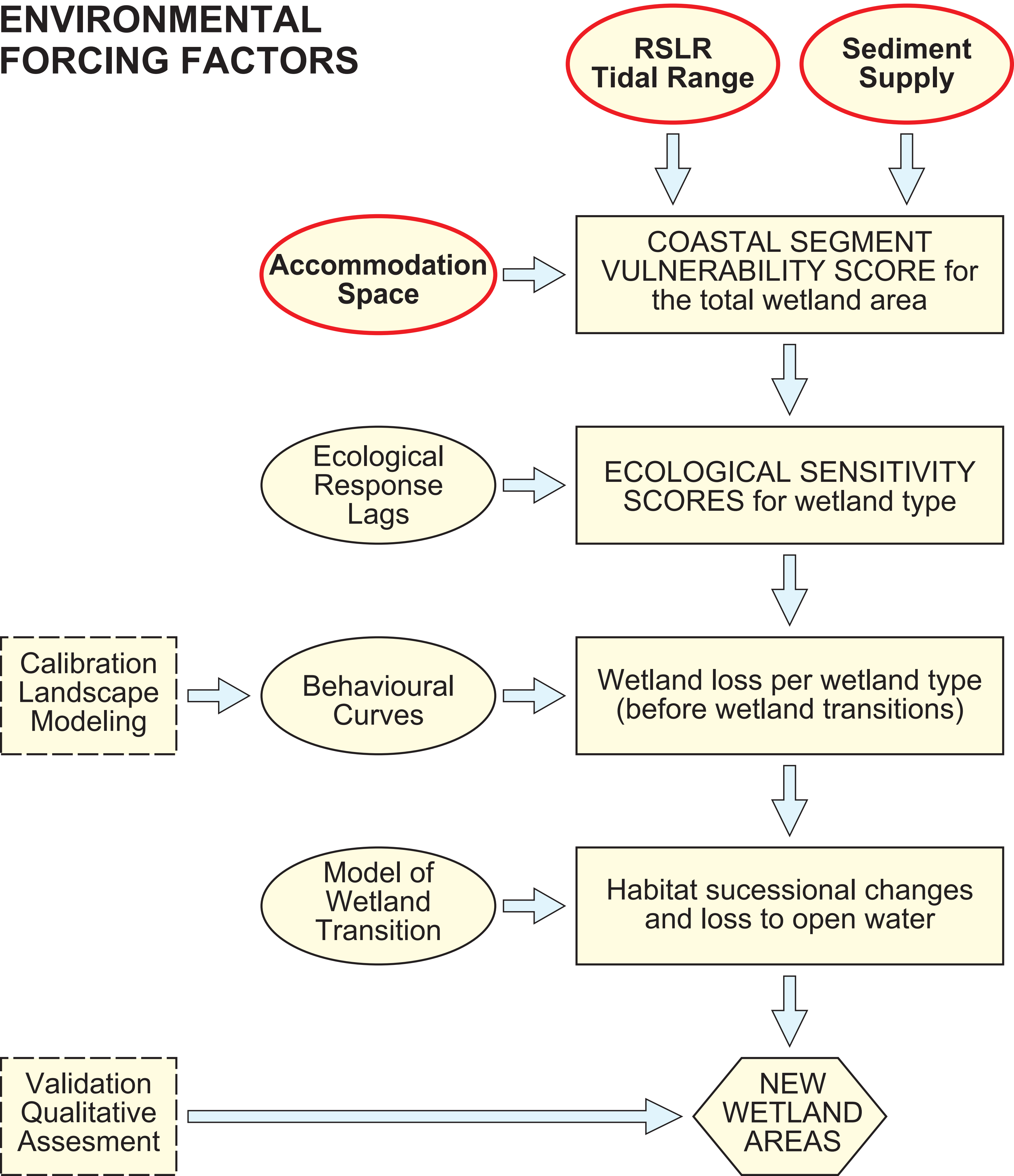

ENVIRONMENTAL FORCING FACTORS
RSLR Tidal Range
Sediment Supply
Accommodation Space
COASTAL SEGMENT VULNERABILITY SCORE for the total wetland area
Ecological Response Lags
ECOLOGICAL SENSITIVITY SCORES for wetland type
Calibration Landscape Modeling
Behavioural Curves
Wetland loss per wetland type (before wetland transitions)
Model of Wetland Transition
Habitat sucessional changes and loss to open water
Validation Qualitative Assesment
NEW WETLAND AREAS

Figure 2 bw

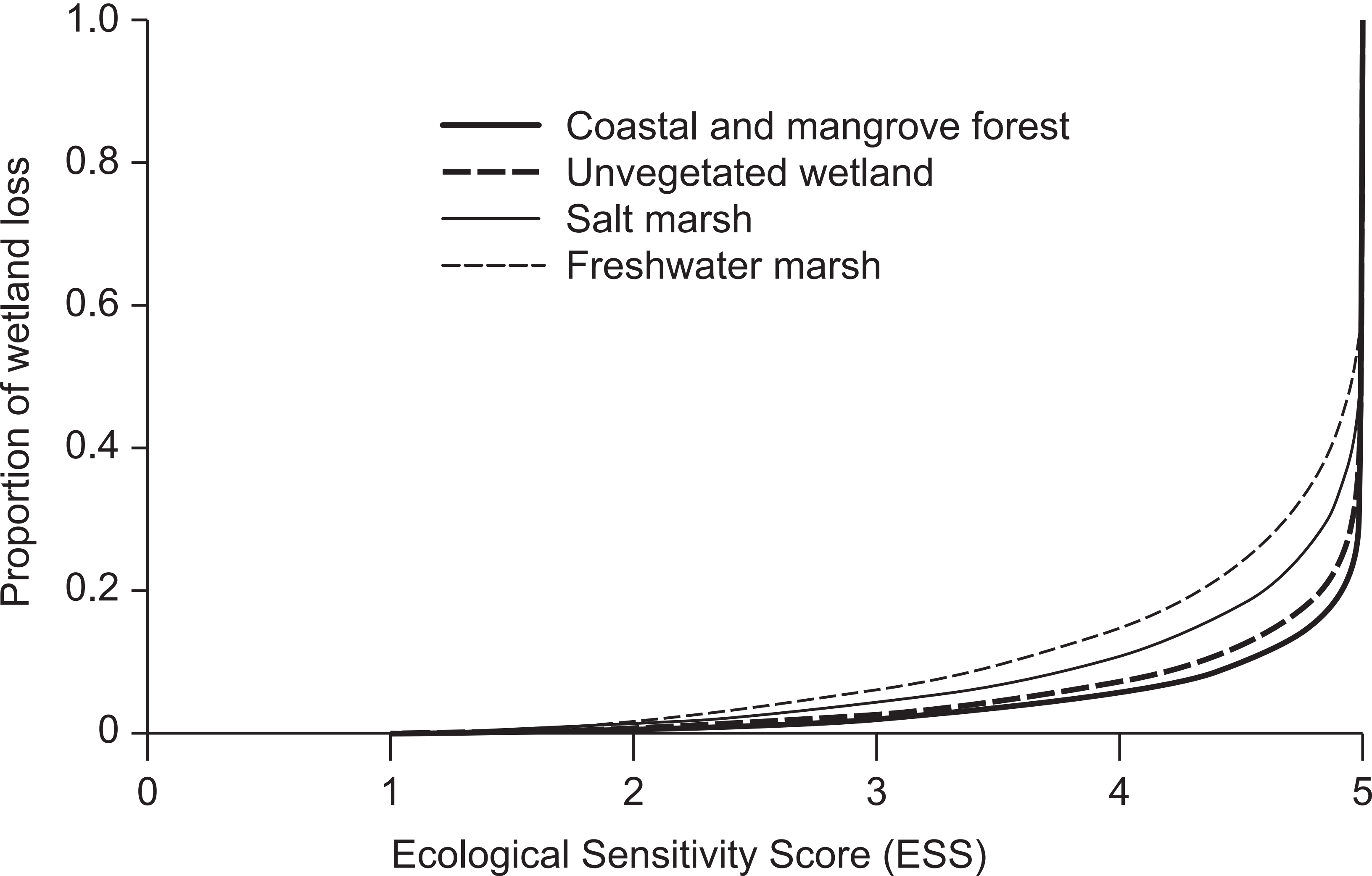

1.0
0.8
0.6
0.4
0.2
0
Proportion of wetland loss
0
1
2
3
4
5
Ecological Sensitivity Score (ESS)
Coastal and mangrove forest
Unvegetated wetland
Salt marsh
Freshwater marsh

Figure 2 col

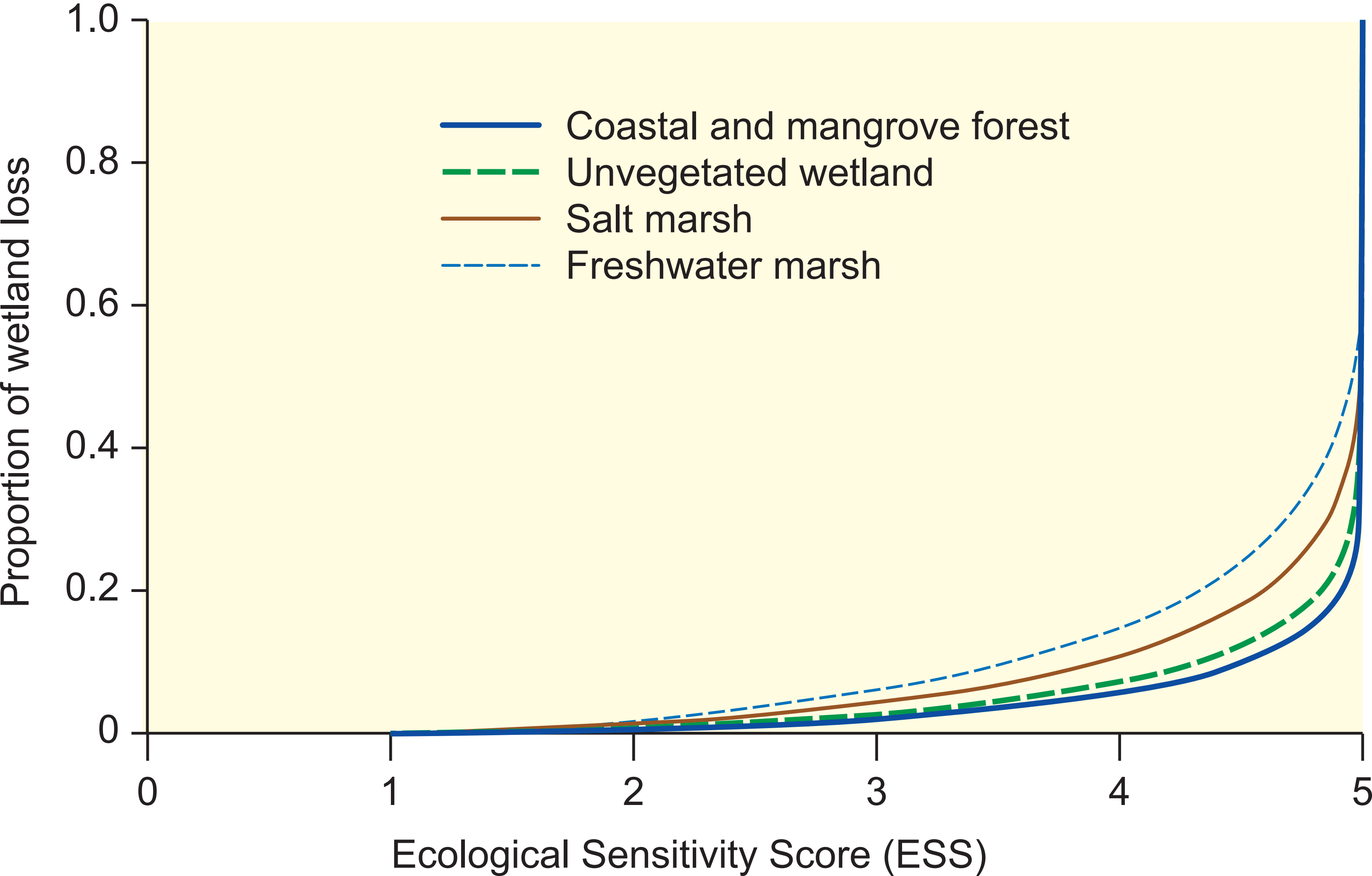

1.0
0.8
0.6
0.4
0.2
0
Proportion of wetland loss
Coastal and mangrove forest
Unvegetated wetland
Salt marsh
Freshwater marsh
0
1
2
3
4
5
Ecological Sensitivity Score (ESS)

Figure 3 bw

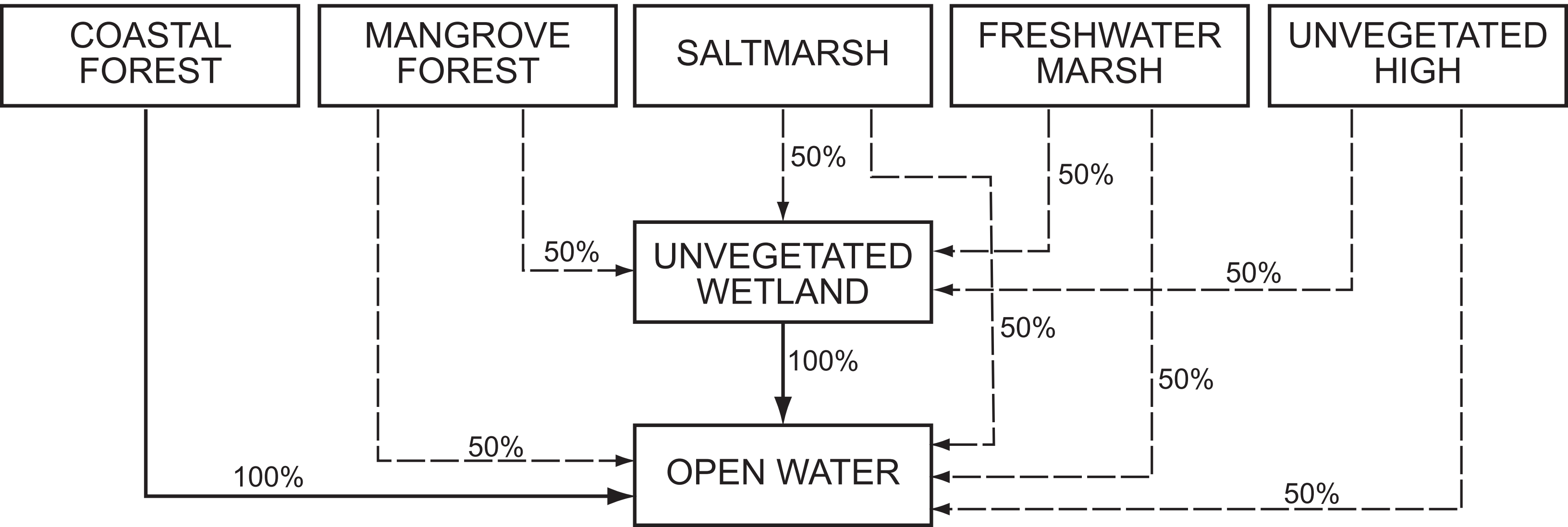
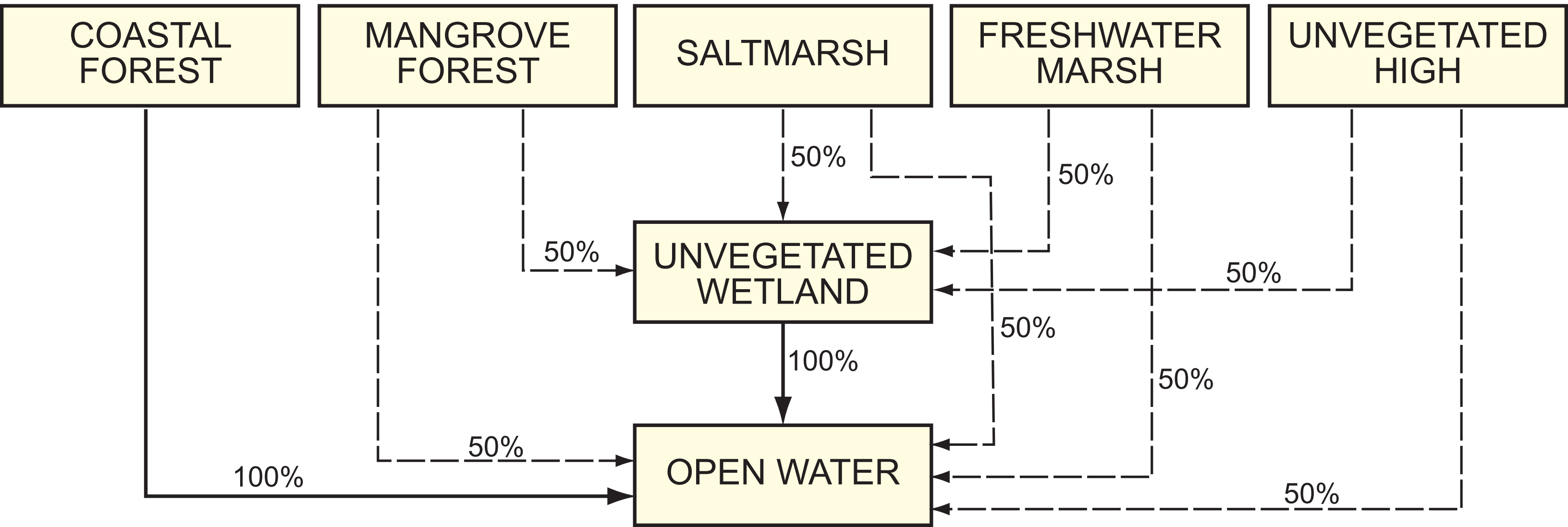

COASTAL FOREST
MANGROVE FOREST
SALTMARSH
FRESHWATER MARSH
UNVEGETATED HIGH
UNVEGETATED WETLAND
OPEN WATER
100%
50%
50%
50%
50%
50%
50%
50%
100%
50%
50%
50%

Figure 3 col



COASTAL FOREST
MANGROVE FOREST
SALTMARSH
FRESHWATER MARSH
UNVEGETATED HIGH
50%
50%
50%
50%
UNVEGETATED WETLAND
50%
100%
50%
50%
100%
OPEN WATER
50%

Figure 4 bw

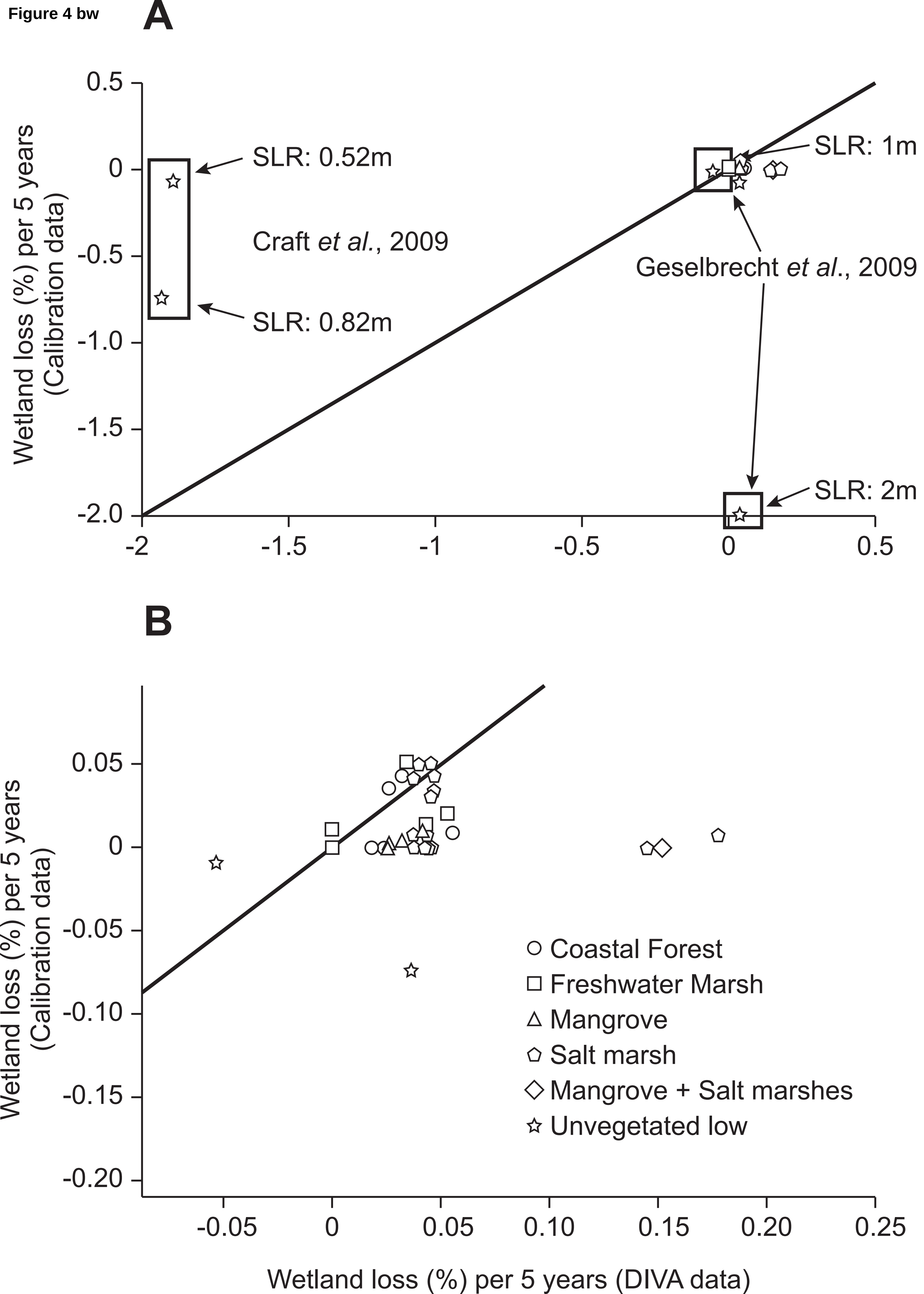

A
0.5
0
-0.5
-1.0
-1.5
-2.0
-2
-1.5
-1
-0.5
0
0.5
Wetland loss (%) per 5 years (Calibration data)
SLR: 0.52m
Craft *et al.*, 2009
SLR: 0.82m
SLR: 1m
Geselbrecht *et al.*, 2009
SLR: 2m
B
0.05
0
-0.05
-0.10
-0.15
-0.20
-0.05
0
0.05
0.10
0.15
0.20
0.25
Wetland loss (%) per 5 years (Calibration data)
Wetland loss (%) per 5 years (DIVA data)
○ Coastal Forest
□ Freshwater Marsh
△ Mangrove
⬠ Salt marsh
◇ Mangrove + Salt marshes
☆ Unvegetated low

Figure 4 col

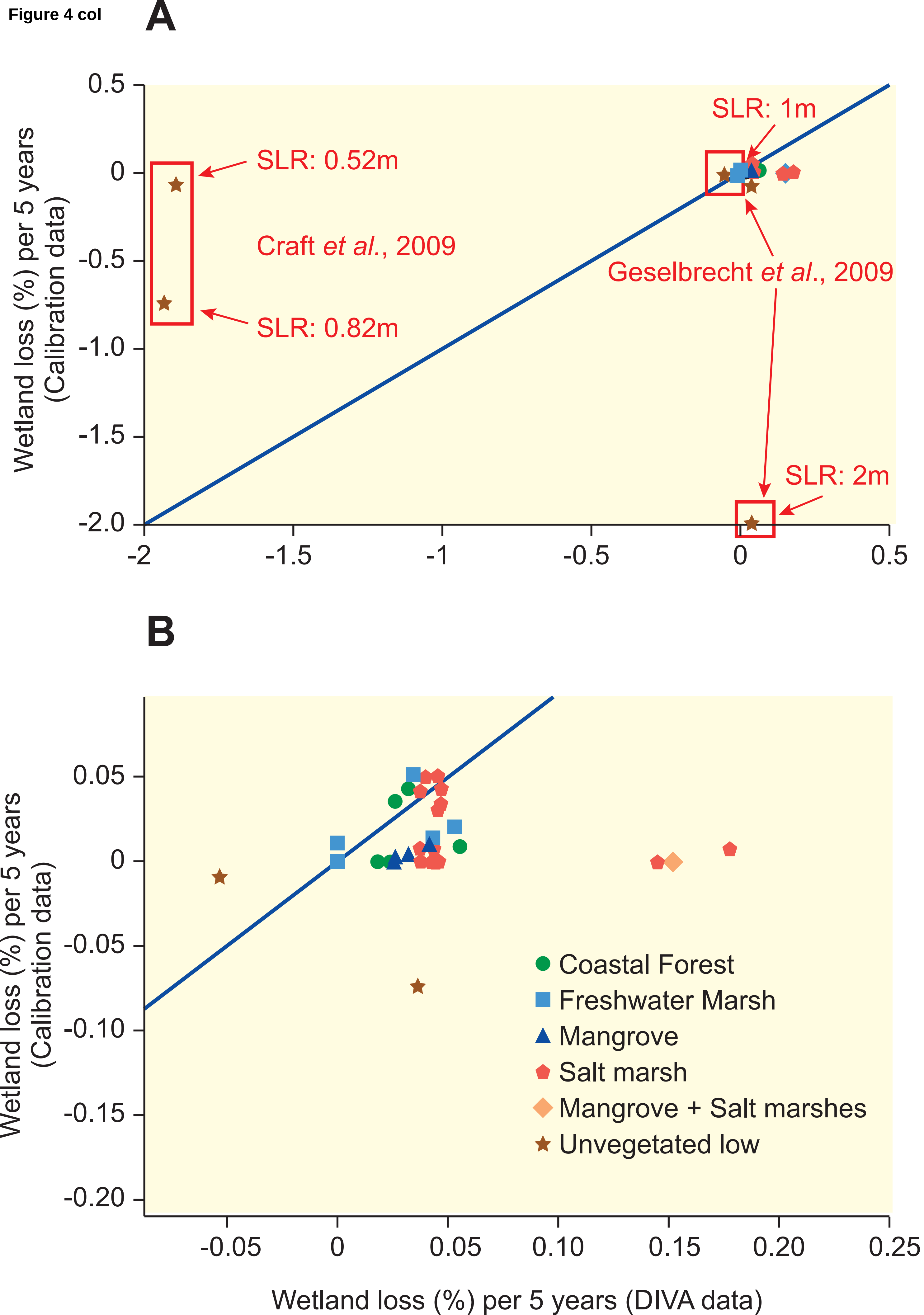

A
0.5
0
-0.5
-1.0
-1.5
-2.0
-2
-1.5
-1
-0.5
0
0.5
Wetland loss (%) per 5 years (Calibration data)
SLR: 0.52m
Craft *et al.*, 2009
SLR: 0.82m
SLR: 1m
Geselbrecht *et al.*, 2009
SLR: 2m
B
0.05
0
-0.05
-0.10
-0.15
-0.20
-0.05
0
0.05
0.10
0.15
0.20
0.25
Wetland loss (%) per 5 years (Calibration data)
Wetland loss (%) per 5 years (DIVA data)
● Coastal Forest
■ Freshwater Marsh
▲ Mangrove
⬟ Salt marsh
◆ Mangrove + Salt marshes
★ Unvegetated low

Figure 5

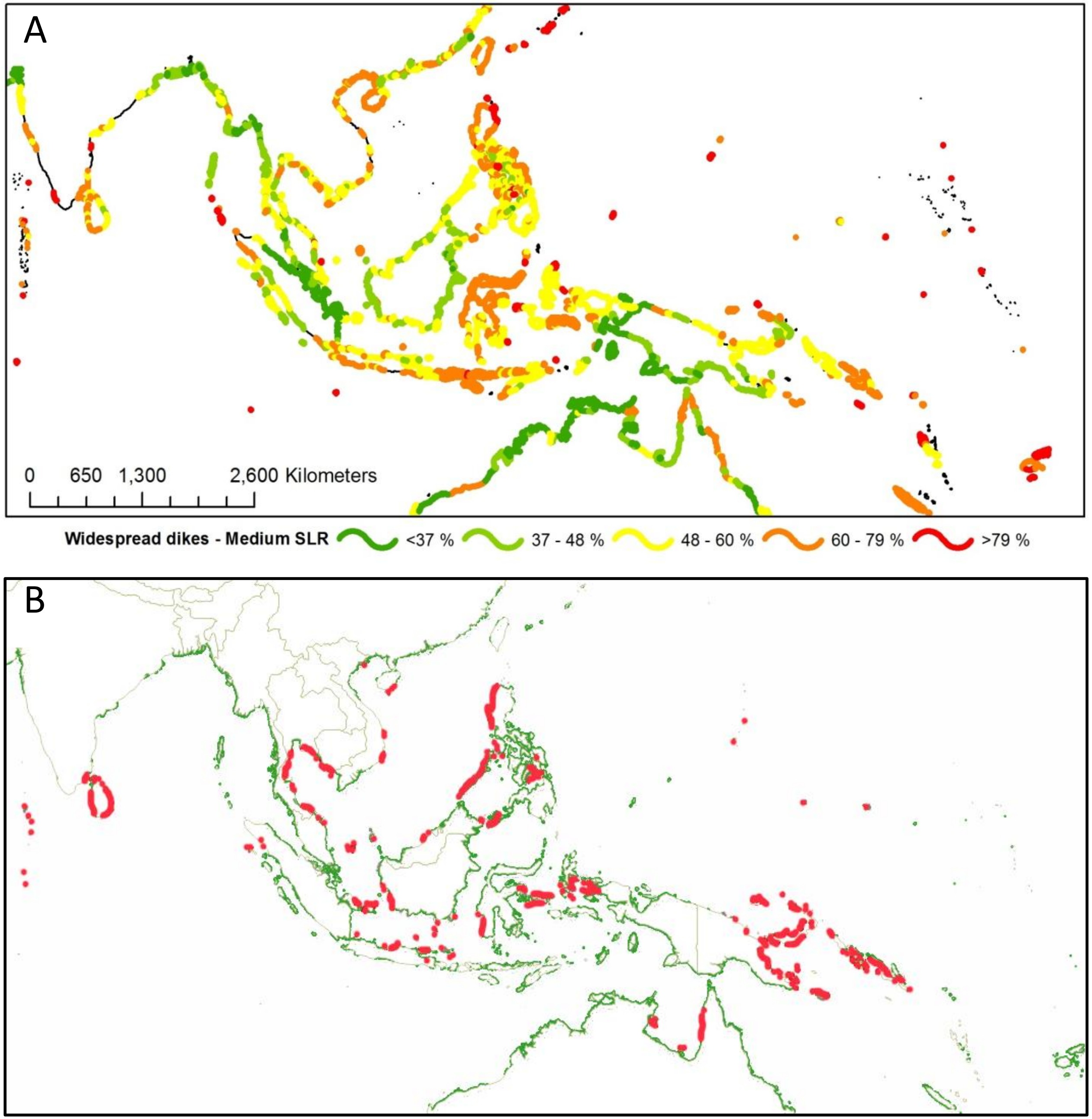
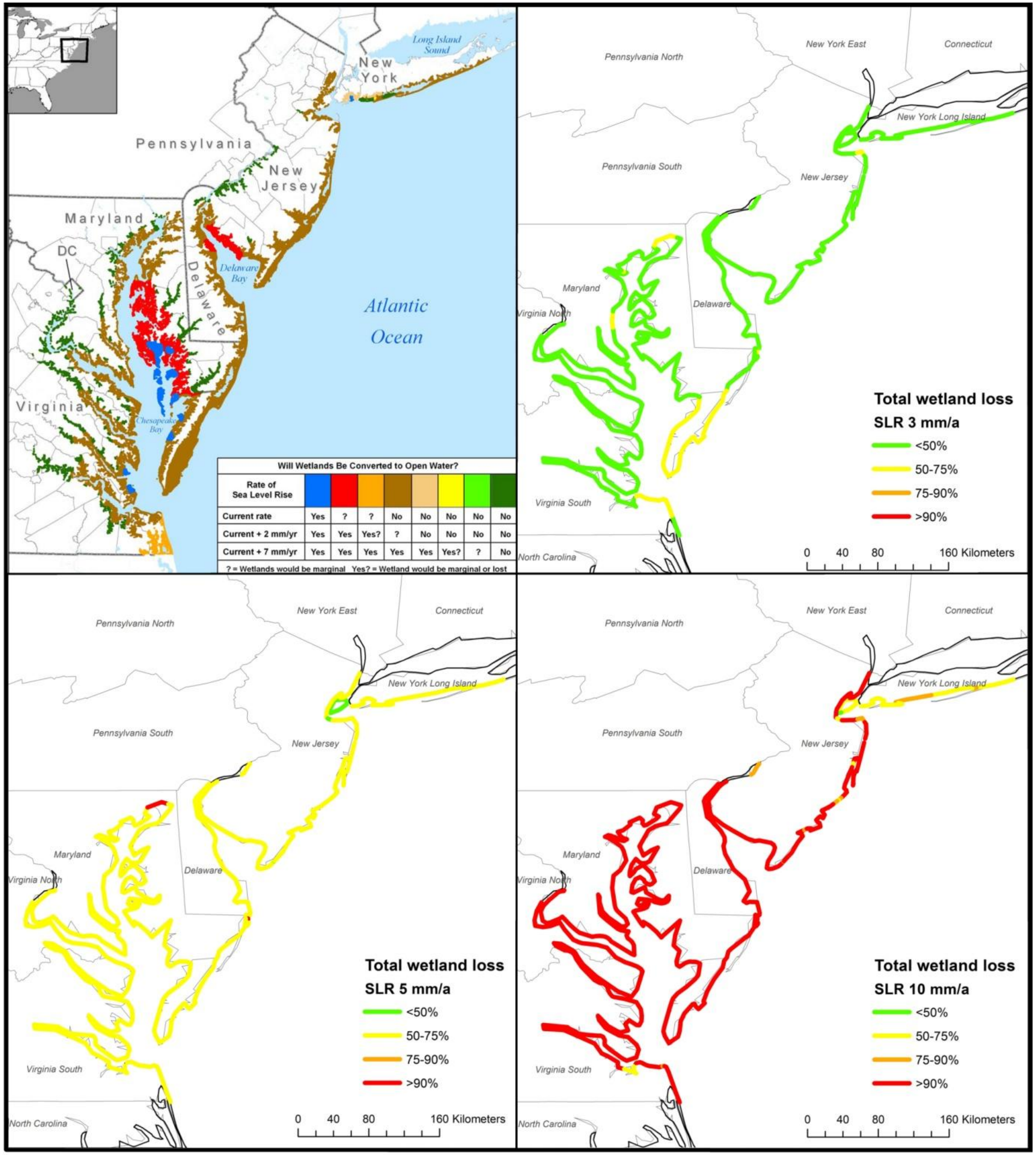

A
0 650 1,300 2,600 Kilometers
Widespread dikes - Medium SLR
<37 %
37 - 48 %
48 - 60 %
60 - 79 %
>79 %
B

Figure 6



Will Wetlands Be Converted to Open Water?

Rate of Sea Level Rise	🟦	🟥	🟧	🟫	🟫	🟨	🟩	🟩
Current rate	Yes	?	?	No	No	No	No	No
Current + 2 mm/yr	Yes	Yes	Yes?	?	No	No	No	No
Current + 7 mm/yr	Yes	Yes	Yes	Yes	Yes	Yes?	?	No

? = Wetlands would be marginal Yes? = Wetland would be marginal or lost

Figure 7 bw

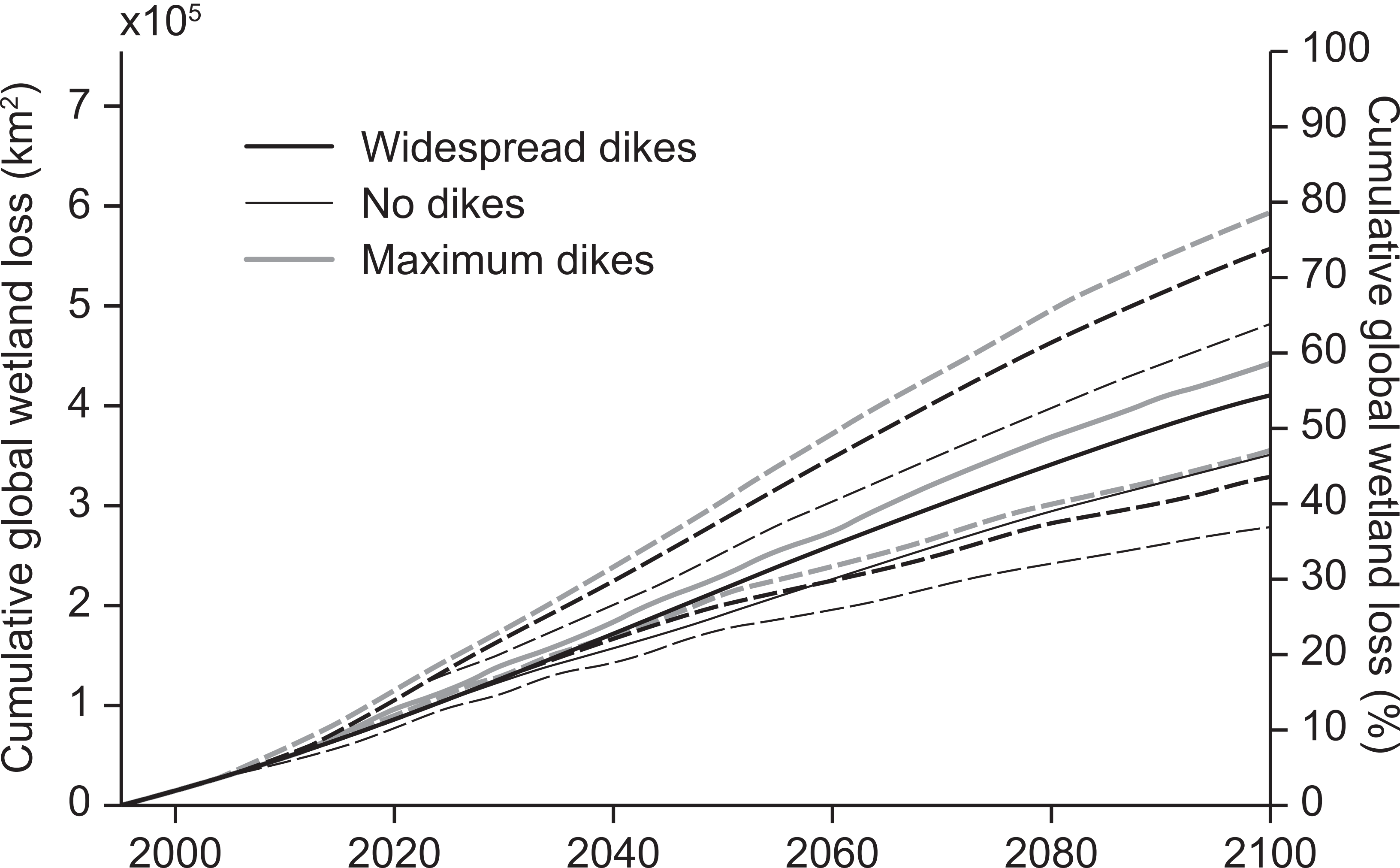

x10^5
Cumulative global wetland loss (km²)
Cumulative global wetland loss (%)
Widespread dikes
No dikes
Maximum dikes
0
1
2
3
4
5
6
7
0
10
20
30
40
50
60
70
80
90
100
2000
2020
2040
2060
2080
2100

Figure 7 col

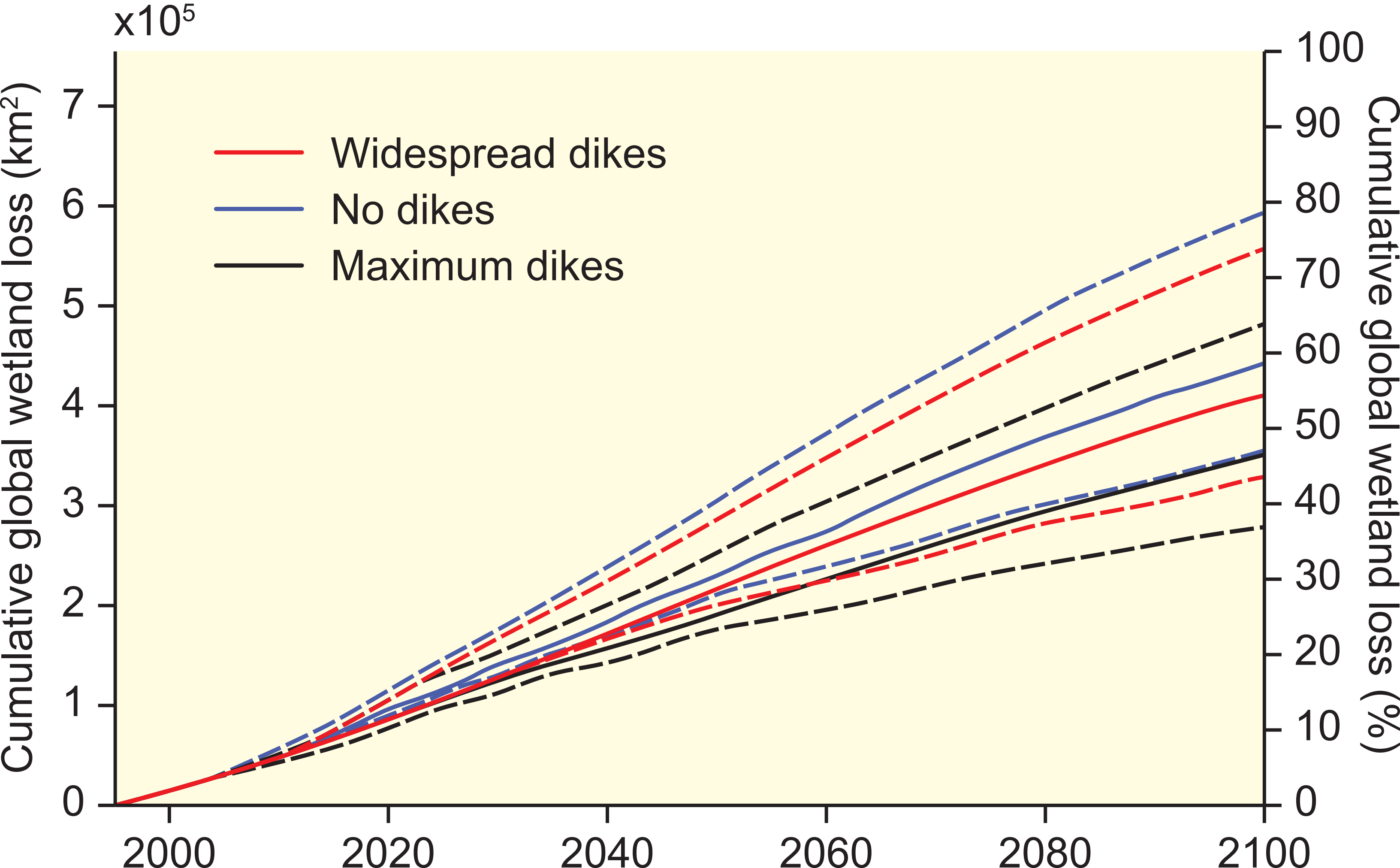

x10^5
Cumulative global wetland loss (km^2)
0
1
2
3
4
5
6
7
Cumulative global wetland loss (%)
0
10
20
30
40
50
60
70
80
90
100
2000
2020
2040
2060
2080
2100
Widespread dikes
No dikes
Maximum dikes

Figure 8 bw

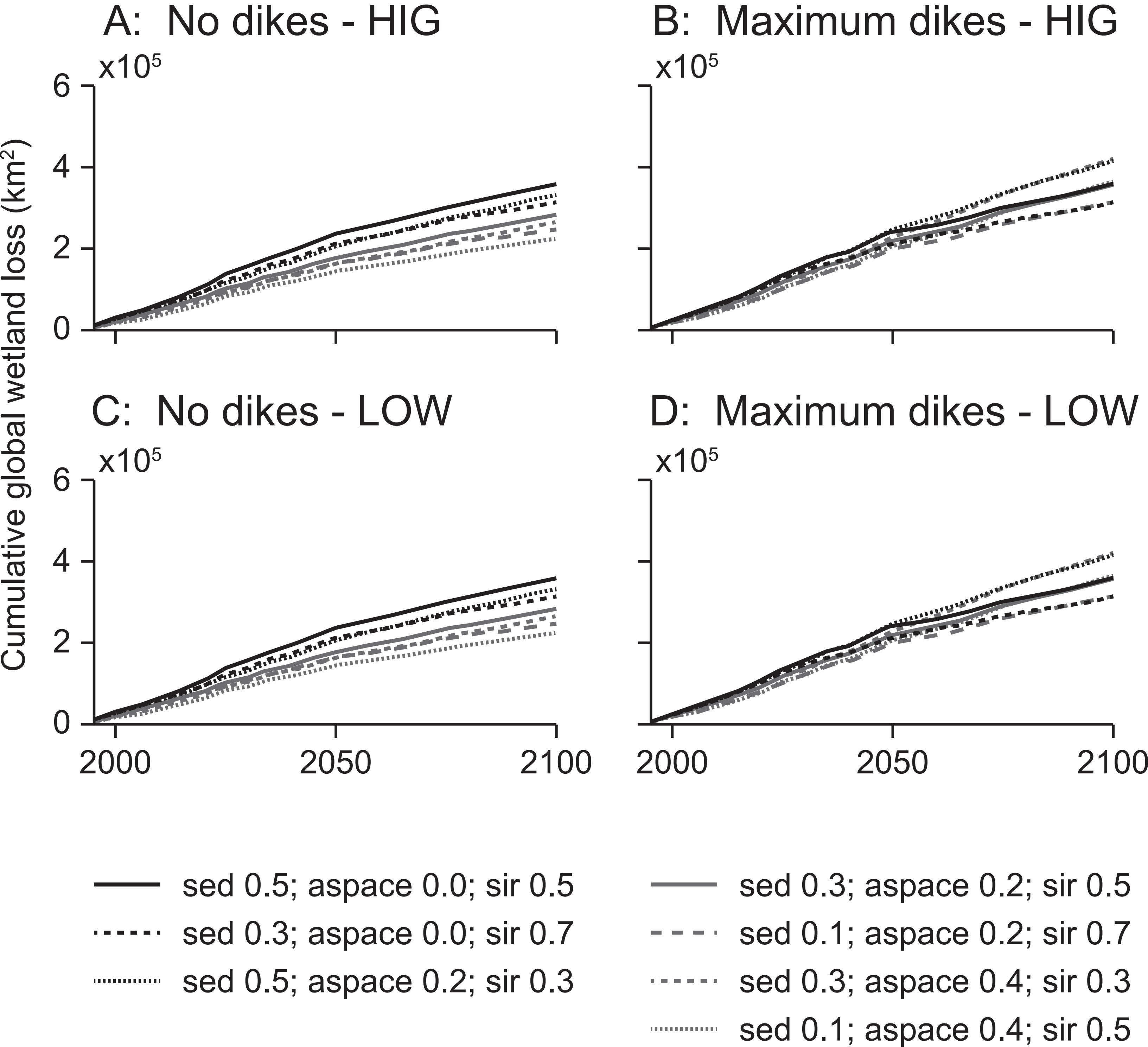

A: No dikes - HIG
B: Maximum dikes - HIG
C: No dikes - LOW
D: Maximum dikes - LOW
x10^5
Cumulative global wetland loss (km²)
6
4
2
0
2000
2050
2100
sed 0.5; aspace 0.0; sir 0.5
sed 0.3; aspace 0.0; sir 0.7
sed 0.5; aspace 0.2; sir 0.3
sed 0.3; aspace 0.2; sir 0.5
sed 0.1; aspace 0.2; sir 0.7
sed 0.3; aspace 0.4; sir 0.3
sed 0.1; aspace 0.4; sir 0.5

Figure 8 col

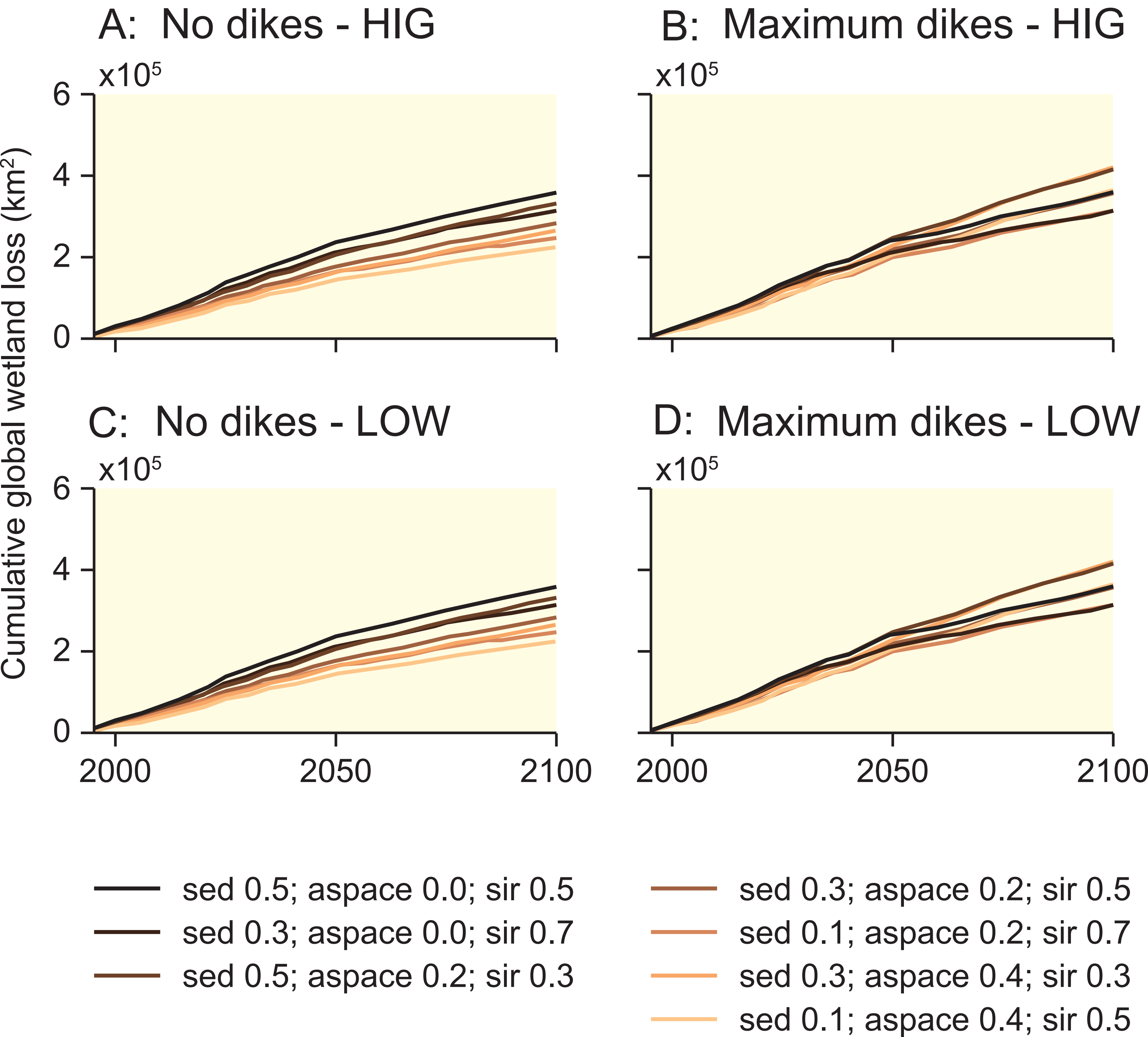

A: No dikes - HIG
B: Maximum dikes - HIG
C: No dikes - LOW
D: Maximum dikes - LOW
x10^5
Cumulative global wetland loss (km^2)
0
2
4
6
2000
2050
2100
sed 0.5; aspace 0.0; sir 0.5
sed 0.3; aspace 0.0; sir 0.7
sed 0.5; aspace 0.2; sir 0.3
sed 0.3; aspace 0.2; sir 0.5
sed 0.1; aspace 0.2; sir 0.7
sed 0.3; aspace 0.4; sir 0.3
sed 0.1; aspace 0.4; sir 0.5

Figure 9

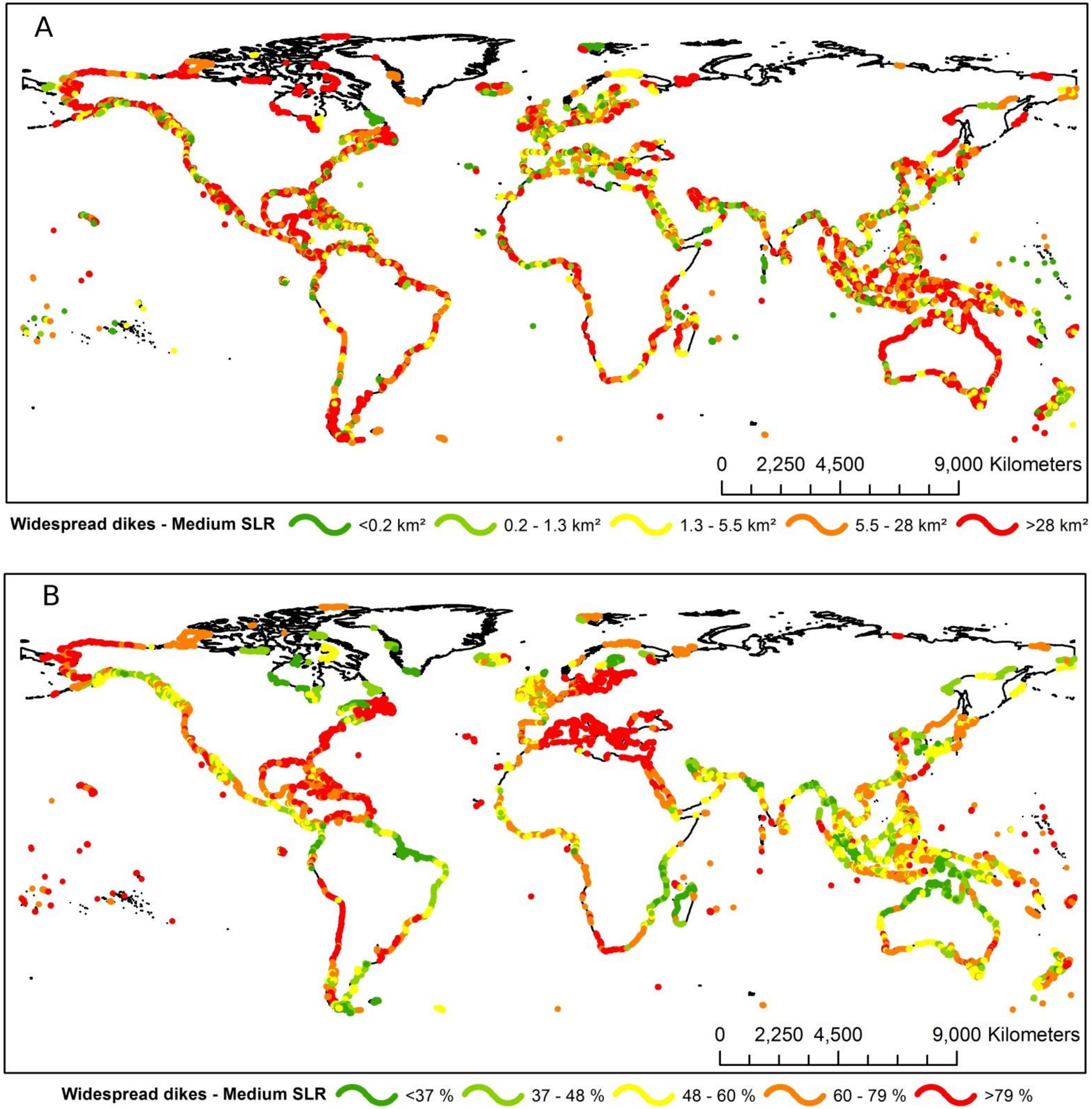

A
0
2,250
4,500
9,000 Kilometers
Widespread dikes - Medium SLR
<0.2 km²
0.2 - 1.3 km²
1.3 - 5.5 km²
5.5 - 28 km²
>28 km²
B
0
2,250
4,500
9,000 Kilometers
Widespread dikes - Medium SLR
<37 %
37 - 48 %
48 - 60 %
60 - 79 %
>79 %

Table 1

Scenario	Model	Steric (cm)	Land-ice (cm)	Total (cm)	Acronym
RCP2.6	HadGEM2-ES	14	21 (16, 39)	35 (29,52)	LOW
RCP4.5	HadGEM2-ES	18	32 (23, 56)	50 (41,75)	MED
RCP8.5	HadGEM2-ES	29	44 (31, 81)	72 (60,110)	HIG

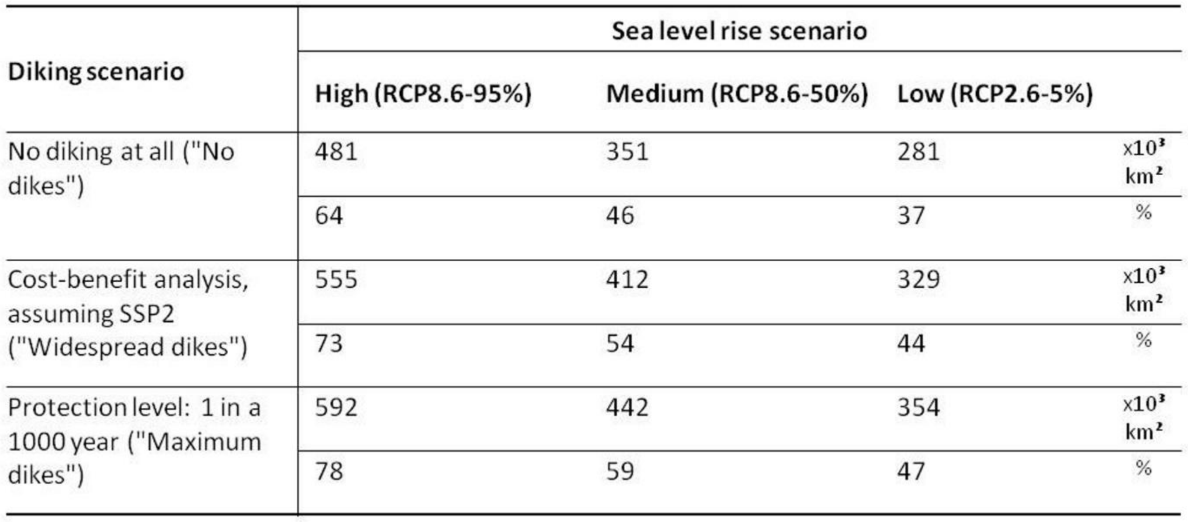
Table 1. Global mean sea-level rise in 2100 with respect to 1985-2005. Median values, with 5% and 95% quantiles in parentheses. After Hinkel et al. (2014). The DIVA_WCM uses low sea-level rise = RCP2.6 (5% quantile; 29 cm by 2100); medium sea-level rise = RCP4.5 (median; 50 cm); high sea-level rise = RCP8.5 (95% quantile; 110 cm).

Table 2

Study	Study area	Tidal range (m)	Suspended sediment concentration (mg/l)	Model	Wetland types	SLR scenarios
Akumu et al., 2011	NE New South Wales, Australia	1.20	153 (1)	SLAMM 6.0	coastalforest, freshwater, saltmarsh, mangrove, unvegetated low	SRES A1B, 2009-2100: 1m
Craft et al., 2009	Georgia coast, USA	2.20 - 3.40 (1)	230 (2)	SLAMM 5	coastalforest, freshwater, saltmarsh, unvegetated low	SRES A1B, 1999-2100: 0.52m, SRES A1B, 1999-2100: 0.82m
Geselbracht et al., 2011	Waccasassa Bay, USA	1.13	15 - 25	SLAMM 6.0.1	coastalforest, freshwater, saltmarsh, mangrove, unvegetated low	SRES A1B, 2004-2100: 0.64m, SRES A1B, 2004-2100: 1m, SRES A1B, 2004-2100: 2m
Glick et al., 2013	SE Louisiana, USA	0.28 - 0.60	289 (lower Mississippi River, post-1967); 334 (Atchafalaya River) (median, flow-weighted; (3))	SLAMM 6.0	coastalforest, freshwater, saltmarsh, unvegetated low	Linear, 2007-2100: 0.34m, SRES A1B, 2007-2100: 0.75m, SRES A1B, 2007-2100: 1.22m, SRES A1B, 2007: 1.9m
Takekawa et al., 2013	San Francisco Bay, USA	1.50 - 2.75	52 - 149 (4)	WARMER	saltmarsh	SRES A2, 2000-2100: 1.24m
Traill et al., 2011	SE Queensland, Australia	1.81	0 - 70 (150 during resuspension events) at 1.0m; 0 - 130 (625) at 0.2m (5)	SLAMM 5	coastalforest, freshwater, saltmarsh, mangrove	SRES A1FI, 2010-2100: 0.64m, SRES A1FI, 2010-2100: 1.8m

Table 2. Location, habitat, sea-level rise scenario and model characteristics for the six calibration studies used to calibrate the behavioural curves used in DIVA_WCM. Tidal range data: reference or for USA sites from NOAA Tides and Currents (https://tidesandcurrents.noaa.gov/stations.html?type=Datums). Suspended sediment concentrations: (1) 2011 annual mean of MERIS geophysical product Total Suspended Matter (TSM) in 0.017 degree resolution, northern NSW, Australia (http://hermes.acri.fr/); (2) Howard and Frey (1985); (3) Himann et al., (2011); (4) Buchanan and Morgan 92014); (5) You (2005).

Table 3



Diking scenario	Sea level rise scenario			
	High (RCP8.6-95%)	Medium (RCP8.6-50%)	Low (RCP2.6-5%)	
No diking at all ("No dikes")	481	351	281	x10^3 km^2
	64	46	37	%
Cost-benefit analysis, assuming SSP2 ("Widespread dikes")	555	412	329	x10^3 km^2
	73	54	44	%
Protection level: 1 in a 1000 year ("Maximum dikes")	592	442	354	x10^3 km^2
	78	59	47	%

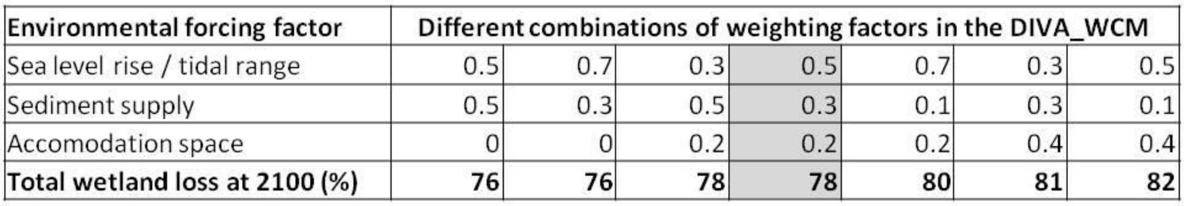
Table 3. Absolute global wetland loss (x10^3 km^2) and relative loss of total global wetland stock (%) by 2100 under the diking and sea-level rise scenarios (see Table 1 and text for details on the scenarios employed).

Table 4

Environmental forcing factor	Different combinations of weighting factors in the DIVA_WCM						
(a)							
Sea level rise / tidal range	0.5	0.7	0.3	0.5	0.7	0.3	0.5
Sediment supply	0.5	0.3	0.5	0.3	0.1	0.3	0.1
Accomodation space	0	0	0.2	0.2	0.2	0.4	0.4
Total wetland loss at 2100 (%)	**76**	**76**	**64**	**64**	**64**	**52**	**52**
(b)							
Sea level rise / tidal range	0.1	0.3	0.5	0.7	0.9		
Sediment supply	0.9	0.7	0.5	0.3	0.1		
Accomodation space	0	0	0	0	0		
Total wetland loss at 2100 (%)	**78**	**76**	**76**	**76**	**78**		

Table 4. Percentage of total wetland area loss at 2100 under different weighting combinations of (a) three environmental forcing factors and (b) sea-level rise / tidal range and sediment supply only, given high sea-level rise scenario of 110 cm by 2100 (95% quantile, RCP8.5; Table 1) and ‘no dikes’. Shaded area = ‘standard’ DIVA_WCM output (see Equation 4, Supplementary Material for details).

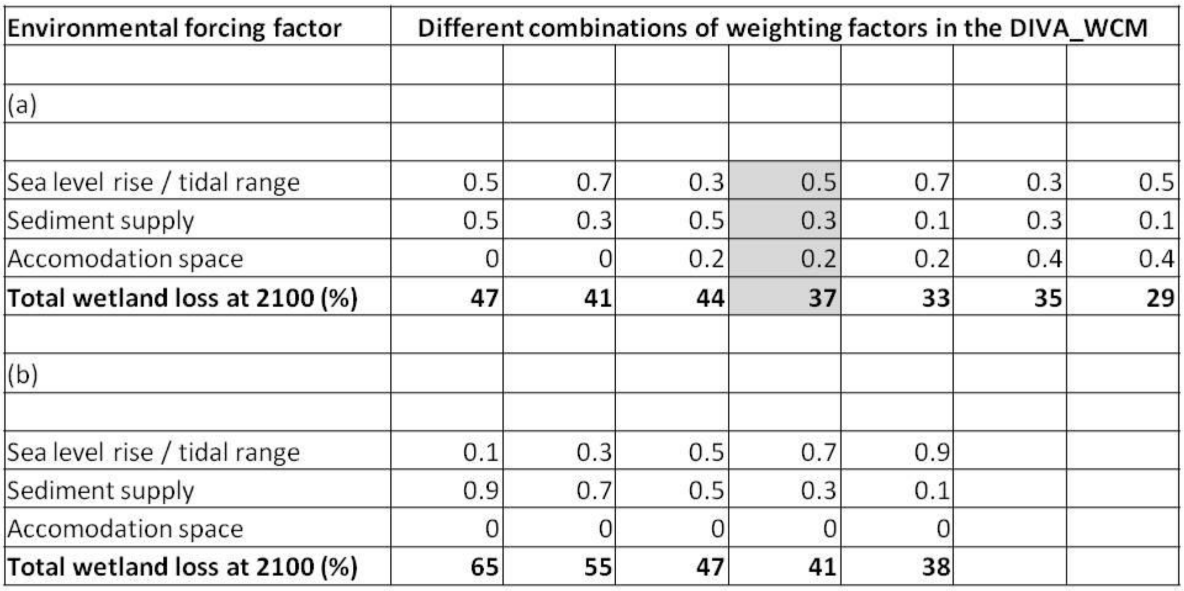
Table 5



Environmental forcing factor	Different combinations of weighting factors in the DIVA_WCM						
Sea level rise / tidal range	0.5	0.7	0.3	0.5	0.7	0.3	0.5
Sediment supply	0.5	0.3	0.5	0.3	0.1	0.3	0.1
Accomodation space	0	0	0.2	0.2	0.2	0.4	0.4
Total wetland loss at 2100 (%)	**76**	**76**	**78**	**78**	**80**	**81**	**82**

Table 5. Percentage of total wetland area loss at 2100 under different weighting combinations of the three environmental forcing factors given high sea-level rise scenario of 110 cm by 2100 (95% quantile, RCP8.5; Table 1) and ‘maximum dikes’. Shaded area = ‘standard’ DIVA_WCM output (see Equation 4, Supplementary Material for details).

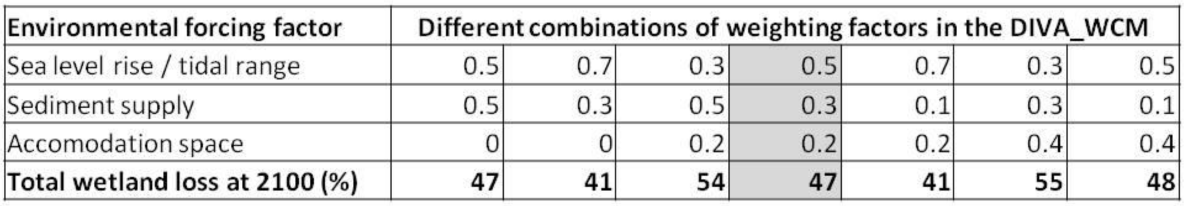
Table 6



Environmental forcing factor	Different combinations of weighting factors in the DIVA_WCM						
(a)							
Sea level rise / tidal range	0.5	0.7	0.3	0.5	0.7	0.3	0.5
Sediment supply	0.5	0.3	0.5	0.3	0.1	0.3	0.1
Accomodation space	0	0	0.2	0.2	0.2	0.4	0.4
Total wetland loss at 2100 (%)	**47**	**41**	**44**	**37**	**33**	**35**	**29**
(b)							
Sea level rise / tidal range	0.1	0.3	0.5	0.7	0.9		
Sediment supply	0.9	0.7	0.5	0.3	0.1		
Accomodation space	0	0	0	0	0		
Total wetland loss at 2100 (%)	**65**	**55**	**47**	**41**	**38**		

Table 6. Percentage of total wetland area loss at 2100 under different weighting combinations of (a) three environmental forcing factors and (b) sea-level rise / tidal range and sediment supply only, given low sea-level rise scenario of 29 cm by 2100 (5% quantile, RCP2.6; Table 1) and 'no dikes'. Shaded area = 'standard' DIVA_WCM output (see Equation 4, Supplementary Material for details).

Table 7



Environmental forcing factor	Different combinations of weighting factors in the DIVA_WCM						
Sea level rise / tidal range	0.5	0.7	0.3	0.5	0.7	0.3	0.5
Sediment supply	0.5	0.3	0.5	0.3	0.1	0.3	0.1
Accomodation space	0	0	0.2	0.2	0.2	0.4	0.4
Total wetland loss at 2100 (%)	**47**	**41**	**54**	**47**	**41**	**55**	**48**

Table 7. Percentage of total wetland area loss at 2100 under different weighting combinations of the three environmental forcing factors given low sea-level rise scenario of 29 cm by 2100 (5% quantile, RCP2.6; Table 1) and ‘maximum dikes’.

Supplementary Material for on-line publication only