Environmental Challenges 9 (2022) 100593

Contents lists available at ScienceDirect

Environmental Challenges

journal homepage: www.elsevier.com/locate/envc

Revised global estimates of resilience to sea level rise for tidal marshes

Xiaoguang Ouyang[a,b,c,*], Rod M. Connolly[d], Shing Yip Lee[c,*]

[a] Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou), Guangzhou, 511458, China
[b] Guangdong Provincial Key Laboratory of Water Quality Improvement and Ecological Restoration for Watersheds, School of Ecology, Environment and Resources, Guangdong University of Technology, Guangzhou, 510006, China
[c] Simon F.S. Li Marine Science Laboratory, School of Life Sciences, The Chinese University of Hong Kong, Shatin, Hong Kong Special Administrative Region, China
[d] Coastal and Marine Research Centre, Australian Rivers Institute, School of Environment and Science, Griffith University, Gold Coast, Queensland, Australia

ARTICLE INFO

Keywords:
Sea level rise
Nature-based human adaptation
Human disturbance
Sediment accretion
Surface elevation change
Tidal marshes

ABSTRACT

Earth system models are widely used to estimate future changes in wetland extent but do not incorporate surface elevation change (SEC) into predicting wetland's real responses to sea level rise (SLR). A machine learning model (MLM) was used to investigate the impact of multiple drivers on SEC and sediment accretion rate (SAR) in tidal marshes, and an earth system model (i.e. integrated climate and wetland migration model) was developed to predict the response of tidal marshes to SLR. The earth system model incorporates factors influencing SEC found by the MLM. Firstly, global data on SAR and SEC for tidal marshes was synthesised and the MLM was used to examine the drivers for SEC and SAR, including tidal range and frequencies, sediment loadings, precipitation, elevation, latitude, sea ice and/or relative SLR (RSLR). Human disturbance resulted in less sediment accretion and existing conservation activities were inefficient in promoting sediment accretion. Secondly, an integrated climate and wetland migration model was developed to assess the resilience of global tidal marshes responding to future SLR in Matlab by incorporating SEC, RSLR, climatic zones, tidal inundation, elevation and latitude into the model. The model was implemented under representative concentration pathways (RCPs) 2.6, 4.5 and 8.5, as well as nature-based human adaptation scenarios. Under the RCPs and nature-based human adaptation scenarios, tidal marshes will gain 53%-58% of the current global area by 2100 if sufficient sediment loadings and accommodation space allow landward migration. If current accommodation space is maintained, net global areal losses of 23%-30% are possible. Hotspots of future marsh loss are largely in North America, Australia and China. Projections for most SLR scenarios see marsh area peaking in the mid rather than late 21st century. Ecogeomorphic feedbacks affect rates of sediment accumulation but cannot be incorporated into the earth system model. The importance of nature-based adaptation was highlighted in enhancing the resilience of tidal marshes to future SLR.

1. Introduction

Tidal marshes now face an even more perilous future because of sea level rise (SLR). Loss of tidal marshes to SLR is partly mitigated by vertical sediment accretion, resulting from the balance of below-ground root production and decomposition (Ouyang et al., 2017), and sediment input from marine (Chmura and Hung, 2004) and/or riverine sources (Craft, 2007). Sediment accretion may alleviate the impact of SLR on tidal marshes when surface elevation increases at or exceeds the rate of local relative SLR (RSLR) (Anisfeld et al., 2016). SLR creates accommodation space which allows tidal marshes to migrate landward (Schuerch et al., 2018). Conversely, tidal marshes could be submerged (Andersen et al., 2011) and drowned, compromising C sequestration and other services (Ouyang and Lee, 2014). Potentially, massive losses of tidal marshes are possible.

The best-known existing model of global wetland responses to SLR is by Schuerch et al. (2018) while other models on wetland responses to SLR are local or regional such as Reed et al. (2020). Schuerch et al. (2018) predicted the responses of coastal wetlands to SLR considering accommodation space created by SLR and nature-based human adaptation scenarios. Nature-based human adaptation scenarios define different human population density thresholds. High populations in urban areas can create more accommodation space whereas low populations in nearly uninhabited land can create less accommodation space. Törnqvist et al. (2019) point out that the model of Schuerch et al. (2018) misuses suspended sediment concentration as a parameter for sediment supply (surplus or deficit). The model violates the accommodation /sediment supply (A/S) theory, i.e. coastal wetlands migrate landward only where there is sufficient sediment supply to fill the accommodation space created by SLR. Schuerch et al. (2018) uses wetland adaptation scores to represent the adaptability of coastal wetlands to SLR through vertical sediment accretion. This is problematic as the score relies on suspended sediment concentrations as a proxy for sediment supply (Törnqvist et al., 2019). By contrast, in situ measure-

* Corresponding authors.
E-mail address: x.ouyang@gmlab.ac.cn (X. Ouyang).

https://doi.org/10.1016/j.envc.2022.100593
Received 22 March 2022; Received in revised form 29 July 2022; Accepted 30 July 2022

Table 1
A comparison of studies evaluating the response of coastal wetlands to sea level rise.

Meta-analysis				
Land building via vertical sediment accretion	**Lateral landward migration via accommodation space**	**Controls on sediment accretion/surface elevation change**	**Geographic regions**	**References**
Using **real data** on surface elevation change to assess the response of mangroves to sea level rise	**Not considered**	**Assessed** the impact of controls such as climatic, geomorphic, geographic factors on mangrove sediment accretion/surface elevation change	Indo-Pacific	Lovelock et al. (2015)
Comparing **real data** on sediment accretion and relative sea level rise to show marsh submerging or aggrading without considering shallow or deep subsidence	Not considered but **stated the limitation**	**Not considered**	Global	Kirwan et al. (2016)
Approximate land building using a wetland adaptation score that relies on suspended sediment concentration to describe sediment supply, which is conflated with the former	**Assessed** accommodation space available for wetland landward migration	**Not considered**	Global	Schuerch et al. (2018)
Reviews				
Contributions		**Geographic regions**		**References**
Described historical sea level fluctuations in the region, sediment supply to maintain marsh elevation change, and controls on accommodation space for marsh migration		Atlantic and southern North Sea coasts of Europe		Allen (2000)
Stated whether wetlands continue to survive sea level rise depends largely on how human impacts interact with rapid sea level rise, and socio-economic factors that influence transgression into adjacent uplands		NA		Kirwan and Megonigal (2013)

ments of surface elevation change (SEC) describe the real vertical movement under current conditions and SEC in the future can be projected by establishing the relationship between SEC and SLR (Lovelock et al., 2015).

Further, recent evaluations of the vulnerability of coastal wetlands to SLR are mainly derived from SEC and short-term sediment accretion rate (SAR) (Lovelock et al., 2015; Kirwan et al., 2016) or calibrate their results using short-term SAR (Schuerch et al., 2018), but lack long-term rates estimated by methods such as radiometric geochronology (Parkinson et al., 2017). The short-term records are very unlikely to incorporate the cumulative effects of subsurface processes (Parkinson et al., 2017), e.g. root growth and compaction (Allen, 2000; Rybczyk and Cahoon, 2002), which also strongly influence sediment accretion (Kolker et al., 2009). Table 1 compared studies on the response of coastal wetlands to SLR.

There are feedbacks and interactions amongst plant growth, geomorphology and hydrodynamics that allow tidal marshes to resist submergence due to SLR (Gedan et al., 2011; Kirwan and Megonigal, 2013; Marani et al., 2006). Tidal marsh sediments also show different deposition patterns dependant on morphodynamics, which shape tidal marshes through combined ecogeomorphology and hydrodynamics (Friedrichs and Perry, 2001). In addition to sediment accretion, tidal marsh SEC depends on erosion and subsurface processes, including compaction, shrink-swell, subsidence, decomposition and tectonic adjustments (Cahoon et al., 2011; Rogers et al., 2006). Sediment accretion and surface elevation in tidal marshes are regulated by biotic and abiotic factors (including climatic, geographic, tidal, and local factors such as supply of suspended sediment). Rain and storm events may not only increase sediment availability but also erode marsh edges and surfaces (Orson et al., 1998; Nyman et al., 1993). Tidal marsh productivity, changing with latitudes, contributes to sediment accretion either through autochthonous organic matter input or slowing erosion rates (Kirwan et al., 2009; Gedan et al., 2011). Inundation is predicted to result in >40% loss of tidal marshes in Louisiana, USA (Reed et al., 2020). Sea ice influences tidal inundation and thus SAR in high-latitudes (Ward et al., 2014). Sediment accretion may also vary over different time scales (Breithaupt et al., 2018). While these factors likely drive the change in sediment accretion and/or surface elevation change, their relative influences on the global pattern of tidal marsh sediment accretion is poorly known. An understanding of this pattern can substantially improve projections of tidal marsh response to SLR in future earth system models.

This study aims to synthesise the global data to (1) properly assess the important relationship between sediment accretion/elevation change and their potential drivers, and (2) estimate the response of tidal marshes to future SLR. It is hypothesized that the area of tidal marshes increases with accommodation space created by future SLR surpassing elevation deficit (i.e. the difference between tidal inundation and SEC). For aim 1, data on both short- and long-term global tidal marsh SAR and SEC (Fig. 1a) were reviewed and the first systematic test of the quantitative influence of potential drivers on global tidal marsh SAR and SEC was provided using a machine learning model. Our results demonstrate that both sediment supply (Törnqvist et al., 2019) and landward migration contributing to elevation capital (Schuerch et al., 2018, 2019) are important. This study discusses and provides mechanistic explanations on the drivers of SEC and SAR but the illustration on the mechanisms is not our focus as they were discussed in many other studies (e.g. Cahoon et al., 2021; Lee et al., 2014; Friess and Mckee, 2021). Based on the results of aim 1, our study predicts the resilience of tidal marshes to future SLR by establishing an earth system model (i.e. integrated climate and wetland migration model) incorporating the effects of vertical sediment accretion described by SEC and lateral landward migration. Particularly, the earth system model (aim 2) incorporates variables of the BRT model (aim 1), including SEC, RLSR, climatic zones (as a proxy for precipitation), tidal inundation, elevation and latitude. In comparison with studies in Table 1, this study is novel because it estimates the response of tidal marshes to SLR by considering both elevation change and available accommodation space due to SLR under future scenarios of climate change.

2. Methods

2.1. Literature review

References on SAR and SEC in tidal marshes were collected from http://www.sciencedirect.com/ and http://pcs.webofknowledge.com/. Our study collated 156 references containing 1229 independent measurements of SAR and 146 measurements of SEC (Fig. 1a). This database is much larger than the 179 measurements of SAR and SEC in Kirwan et al. (2016). SAR is the vertical dimension of sediment develop-

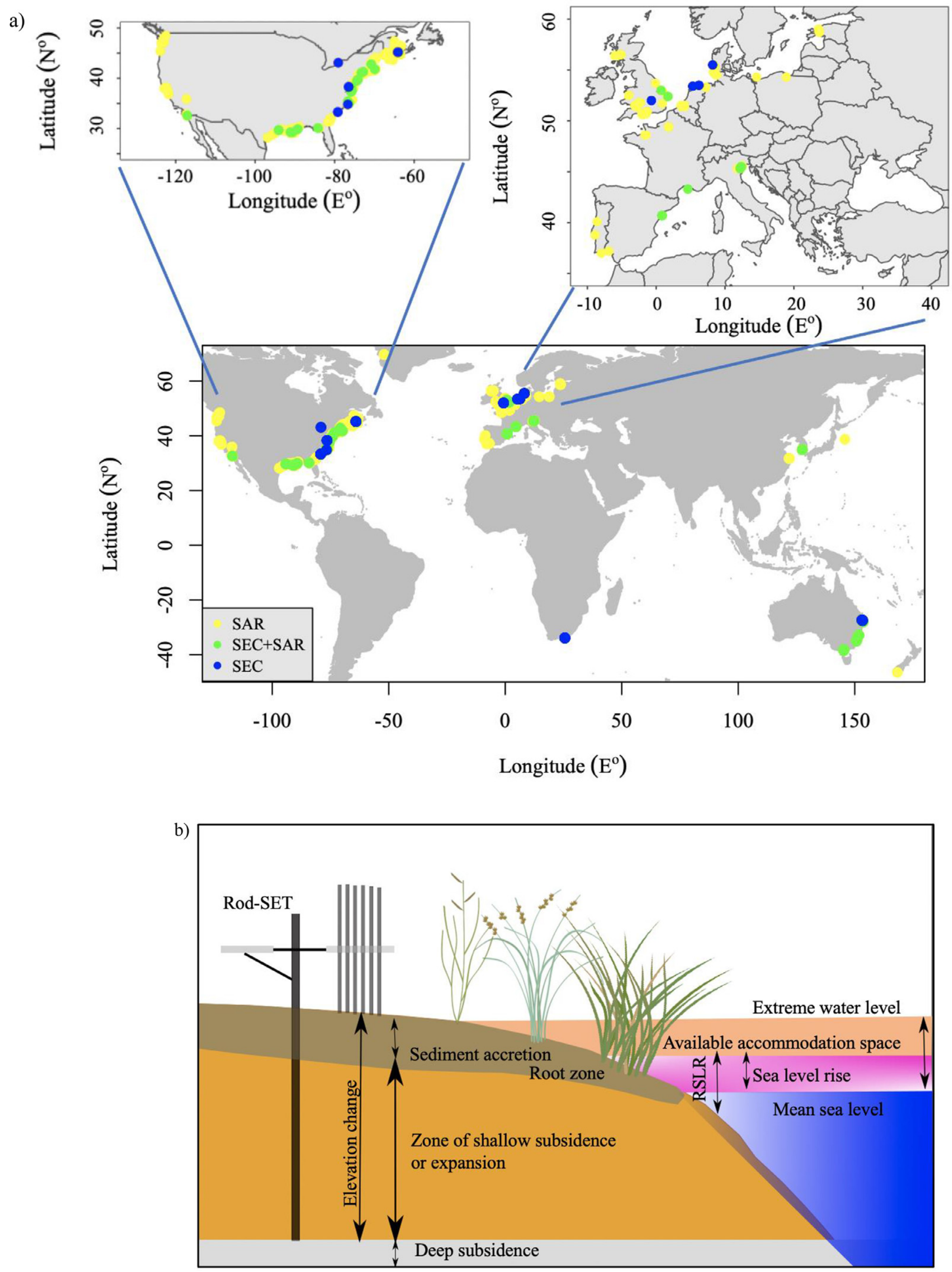


Fig. 1. Global distribution of study sites from the collated studies and a conceptual model showing marsh response to sea level rise. (a) sites of SAR and/or SEC; (b) tidal marshes responding to SLR via vertical sediment accretion and accommodation space available for lateral migration. The upper sub-panels in (a) show the sites in North America and Europe, respectively. SAR and SEC denote sediment accretion rate and surface elevation change, respectively. SET denotes surface elevation table. RSLR denotes relative sea level rise.

ment determined from short- and/or long-term markers, and integrates the sedimentological and biological processes contributing to organic and inorganic matter deposited on the sediment surface (Cahoon et al., 1995; Thom, 1992). SEC is the change in elevation relative to a subsurface datum, the depth of which is determined by the technique used (Thom, 1992). SAR results from sediment accretion from allochthonous and autochthonous sources, while SEC results from not only sediment accretion but also other processes (Fig. 1b) such as subsidence and autocompaction (Rogers et al., 2006). The data cover tidal marshes over a latitudinal range from 69.7°N to 46.5°S.

Besides SAR and SEC data, tidal range and tidal frequency at each sampling site were collected from data reported in relevant references. Where data are unavailable, tidal ranges were collected from the data at the nearest tidal stations, reported by National Oceanic and Atmospheric Administration, USA (http://tidesandcurrents.noaa.gov). Tidal frequencies were extracted from the map of world tidal patterns (Gabler et al., 2007), which are divided into diurnal, semi-diurnal and mixed tides. Tidal ranges were sorted into micro- (<2 m), meso- (2–4 m) and macro- (>4 m) tides. Marsh locations, geomorphology, sampling periods and methods were also extracted from the references. Marsh locations were reported as levee or back-marsh in our collected references. The former is close to the river/creek bank while the latter is located behind the former at a higher tidal elevation. Geomorphology was sorted into back-barrier, fluvial, transitional and bluff-toe marshes (Kelley et al., 1988). Species richness were categorised as 1 or >1, since some studies report the occurrence of mixed species and generally there are few studies at sites with three or more species. Plant types were divided into herb or herb + shrub, where herbaceous plants co-occur with shrubs. While SAR for shrubs were also reported, the number of studies is too few to allow a meaningful comparison, as are SEC data for all plant types. Fourteen methods were used to estimate SAR in our collated references, with time scales ranging from sub-decadal (e.g. several years), decadal, to millennial, mainly assessed by radiometric isotopic dating (e.g. ^{210}Pb, ^{137}Cs and ^{14}C) and marker horizons (Supplementary Material Fig. S1). SAR at millennial scales was estimated from ^{14}C. SEC was estimated by the surface elevation table method. For studies investigating the impact of human activities on SAR, data on SAR from locations subject to both human activities and undisturbed status in the same studies were collected. Human activities include two categories: (1) human disturbances, including canalling, damming, diking, impounding and open marsh water management, and (2) conservation activities, including rehabilitation and restoration.

2.2. Satellite data collection

Our study also collected data on precipitation, sea ice and total suspended matter, which are possible drivers of SAR and SEC. Monthly precipitation data were extracted from the gridded monthly total precipitation of Global Precipitation Climatology Centre, with a spatial resolution of 0.5 × 0.5° latitude by longitude and time periods between 1901 and 2013, and 2014 to date. Where data are unavailable, precipitation data were supplemented and extracted from the gridded monthly precipitation of British Atmospheric Data Centre. Sea ice data were extracted from the monthly gridded sea ice data set of the Met-Office Hadley Centre, with a spatial resolution of 1 × 1° latitude by longitude and time period between 1870 and 2017. The sea ice data are satellite microwave-based, compensating for the impact of surface melt effects on retrievals in the Arctic and for algorithm deficiencies in the Antarctic, and considering consistency with the historical *in situ* concentrations (Rayner et al., 2003). Level-3-processed suspended matter data binned monthly (available from http://hermes.acri.fr/) were used in our study. Suspended matter was extracted from the GlobColour primary data set of the European Space Agency's Envisat satellite (390 - 1040 nm), which is built using the Medium Resolution Imaging Spectrometer and provides total suspended matter of marine waters between 2002 and 2011 with a spatial resolution of four km. Data products were processed and validated as part of the European Space Agency's Data User Element GlobColour Global Ocean Colour for Carbon Cycle Research project (refer to http://www.globcolour.info/CDR_Docs/GlobCOLOUR_PUG.pdf for more information about data processing). Suspended matter in coastal waters is an indicator of river-runoff and resuspension as well as sediment loadings to coastal wetlands. This indicator is useful in both estuarine and reef lagoon waters (Blondeau-Patissier et al., 2014) and has been used as an estimate for mangrove SEC (Lovelock et al., 2015) and sediment availability for coastal wetlands (Schuerch et al., 2018). It is acknowledged that there is spatial variability in suspended sediment in an ecosystem (e.g. Chen et al., 2016; Coleman et al., 2020) which can account for uncertainties in our lateral analyses on the controls on SAR and SEC due to suspended matter.

2.3. Analysis of controls on SAR and SEC

Our study examined the relationship between SAR/SEC and influential factors, including latitude, precipitation, sea ice concentration, total suspended matter, elevation, tidal range, tidal frequencies and/or RSLR in a statistical model. RSLR was included in the statistical model for SEC but not for SAR because long-term records of RSLR are unavailable while many SAR measurements were long-term data (e.g. at the centennial scale). Large scale factors, e.g. tectonic rebound, may also affect SEC but these data are unavailable for our analysis. The categorical variables were number coded, with one level of each variable selected as the reference. The influences of other factors (e.g. species richness, plant type and location) on SAR and/or SEC were not included in the model due to limited available data, which would have substantially reduced the overall degrees of freedom if included. The model was started with multiple regression, but the hypothesis of normality was grossly violated and the residuals were highly heterogeneous. The relative influence of explanatory variables on SAR and SECs was analysed via a machine learning method, i.e. boosted regression tree (BRT) models. The models were established with a tree complexity of 5, learning rate of 0.005, back fraction of 0.5 and 10-fold cross-validation optimization. Gaussian distribution was set for SAR and SECs (Supplementary Material Fig. S2). Our study also examined the relationship between SEC and SAR using a linear regression.

In addition to the above analyses, our study examined the difference in SEC/SAR amongst categorical variables that were significant in the BRT models, and other factors using the Kruskal-Wallis rank sum test. Where significant differences were found, non-parametric Mann-Whitney U tests were used to identify significant differences amongst the groups. Paired t tests were used to compare the difference in SAR from the same sites at different time scales (i.e. sub-decadal, decadal, centennial and millennial), or from the same sites at short, mid- and long terms when the temporal span is different at the same time scales. These univariate analyses address how SAR/SEC are driven by the categorical variables that could not be addressed in the BRT models. To estimate the impact of future climate change on SEC, SEC was predicted considering precipitation change (±10 cm and ±20 cm) in the final BRT model. Different climatic zones were classified based on the difference in precipitation and temperature using the Köppen-Geiger climate classification. Climatic zones of SEC study sites were extracted from the world maps of the Köppen-Geiger climate classification (Rubel and Kottek, 2010). The variation of SEC within different climatic zones were examined (Fig. S3) and the 95% confidence interval was used as the thresholds of SEC in the earth system model in the lateral analysis.

2.4. Modelling the response of tidal marshes to SLR

Our study evaluated the response of tidal marshes to future SLR using an earth system model, which considers both the area gain and loss for tidal marshes (See the earth system modelling framework described in Fig. 2). Marsh area gains through the accommodation space available for marsh landward migration, while area losses occur due to inundation if marsh SEC cannot keep pace with RSLR, which is the resultant of SLR and other processes such as subsidence and tectonic activity. The earth system model incorporating SEC, RSLR, tidal inundation, elevation and latitude which affect the response of tidal marshes to SLR, indicated by the result of the BRT model.

In Fig. 2, main processes in light of the boxes and arrows in the modelling framework were clarified as below:

Accommodation space - (1) to (3): landward migration of tidal marshes is facilitated by the available accommodation space between mean sea level and mean high water spring. Marsh landward migration is likely obstructed by sea defences and other man-made infrastructures such as seawalls, aquaculture ponds and roads (Leonardi et al., 2018; Ma et al., 2014). Nonetheless, the global data on infrastructure inhibiting marsh landward migration is lacking. This study adopted the method of Schuerch et al. (2018) to approximate accommodation space via different population density thresholds, above which no accommodation space is considered available for tidal marshes to migrate landward. The population density thresholds include population density of 5, 20, 150 and 300 people km^{-2}, with lower and upper population boundaries corresponding to nearly uninhabited land (Mittermeier et al., 2003) and

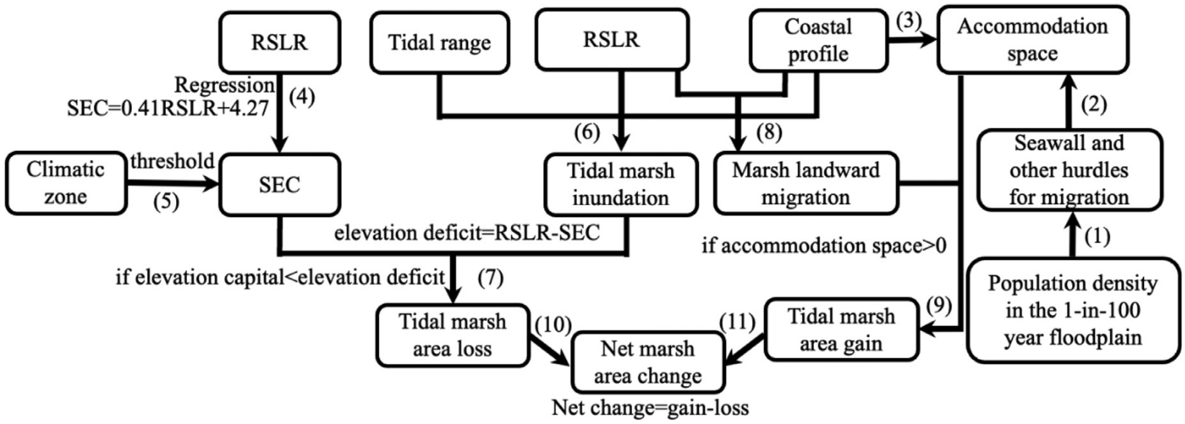


Fig. 2. A diagram describing the integrated climate and wetland migration modelling framework for simulating the response of tidal marshes to RSLR. RSLR denotes relative sea level rise. SEC denotes surface elevation change.

the European Commission's definition of urban areas (Dijkstra and Poelman, 2014), respectively. A 5-year-lag is assumed for wetland establishment when tidal marshes migrate landward, as evidenced by restoration practice (Wolters et al., 2008).

Tidal marsh loss - (4) to (7): with increasing sea levels, both the upper and lower boundaries of marsh migration shift, likely resulting in marsh drowning if marsh SEC cannot keep pace with RSLR. This study estimated global SEC in tidal marshes from RSLR (precision: 20 km) since our dataset cannot cover all the tidal marshes. Specifically, this study used the marsh SEC data collated from the references and associated RSLR data contemporaneous with SEC measurements obtain from NOAA (https://tidesandcurrents.noaa.gov/sltrends/sltrends.html). These data were used to establish the relationships between marsh SEC and RSLR.

$$\text{SEC} = 0.41\text{RSLR} + 4.27 \quad (1)$$

Future precipitation cannot be directly incorporated into the earth system model but SEC (95% confidence intervals) in different future climatic zones were used as the thresholds of future SEC estimated from RSLR. Climatic zones of tidal marshes in the future were extracted from the world maps of the Köppen-Geiger climate classification in 25-year-intervals from 2001 to 2025 to 2076–2100. The established relationships were used to estimate SEC of global tidal marshes under SLR scenarios, which was combined with RSLR and the coastal profile to determine marsh loss to inundation. Tidal marsh will be lost if the elevation capital is less than elevation deficit (i.e. the difference between RSLR and SEC) (Lovelock et al., 2015).

$$\text{Elevation deficit} = \text{RSLR} - \text{SEC} \quad (2)$$

Elevation capital was determined from the coastal profile. The SLR scenarios include the stringent mitigation scenario (RCP 2.6), intermediate scenarios (RCP 4.5), and the scenario with very high greenhouse gas emissions (RCP 8.5) (IPCC 2014). Coastal profiles were created by dividing the floodplain areas (Hinkel et al., 2014) per elevation increment (from <1.5 m to 16.5 m at eight intervals) by the length of the corresponding coastal segment to calculate the inundation lengths. Linear interpolation between the mean high-water spring and an elevation of 1.5 m (or higher) in the coastal profile was used to approximate high resolution light detection and range (LiDAR) derived elevations, with an error of less than 30 cm (Titus and Wang, 2008).

Net marsh areal change - (8) to (11): tidal marshes migrate landward with rising sea levels which create accommodation space in our model. This is a process that tidal marsh plants establish upland by raising the upper boundary (i.e. the mean high water spring) along the coastal profile. For tidal marsh area, the method of Schuerch et al. (2018) was used. Tidal marshes are considered to occur at elevations between mean sea level and mean high-water spring based on previous areal estimates on tidal marshes (Mcowen et al., 2017; Vafeidis et al., 2004). The upper and lower boundaries of tidal marshes will vary due to different vegetation species, tidal currents and waves in nature but this model used mean sea level as the lower and mean high water spring as the upper limits of tidal marsh boundaries. Tidal marsh areal gain was calculated as the converted upland to tidal marshes. The same assumption of Schuerch et al. (2018) was used to calculate the converted upland areas, i.e. the segment specific wetland/non-wetland proportion remains constant over time. Net marsh areal change is the difference between marsh area gain and loss.

$$\text{Net marsh areal change} = \text{tidal marsh area gain} - \text{tidal marsh area loss} \quad (3)$$

Statistical analyses were conducted using the R programming language (R Core Team, 2014). Precipitation, sea ice and total suspended matter data were extracted by the package 'ncdf4' (Pierce 2017). The packages 'dismo' (Hijmans et al., 2017) and 'gbm' (Greenwell et al., 2019) were used to undertake BRT. The R packages 'rgeos' (Bivand and Rundel, 2020) and others were used in the spatial analysis. The earth system modelling was performed in Matlab R2015b.

3. Results

3.1. Controls on tidal marsh SAR and SEC

Boosted regression tree (BRT) modelling was used to explore the relative influence of potential drivers on SAR and SEC (Supplementary Material Table S1). When excluding RSLR, the cross-validation procedure shows that the percentage of variance explained by the models are (mean, SE) 28.5% (3.3%) and 51.8% (12.1%) for SAR and SEC, respectively. When including RSLR for SEC, it shows that the percentage of variance explained by the model is 53.5% (9%) for SEC. The best-fit model shows that SAR is driven by suspended matter, precipitation, latitude, elevation, tidal range, tidal frequency and sea ice (Fig. 3a). The model suggests that suspended matter and precipitation are the dominant drivers and together account for 68.1% of the relative influences on SAR (Fig. S4). The best-fit model for SEC including RSLR shows that it is driven by RSLR, precipitation, suspended matter, latitude, elevation, tidal range and tidal frequency (Fig. 3b). RSLR, precipitation and suspended matter are the dominant drivers and account for 79.8% of the relative influences on SEC (Fig. S5).

Further exploration shows that there is a strong positive relationship between SEC and SAR (Supplementary Material Fig. S6, $R^2 = 0.82$, $p << 0.001$, F test). Based on this relationship, surface elevation change in global saltmarshes was estimated (Fig. S7). The median values of surface elevation changes were used as the representative values of each latitudinal interval since both raw and transformed data did not meet

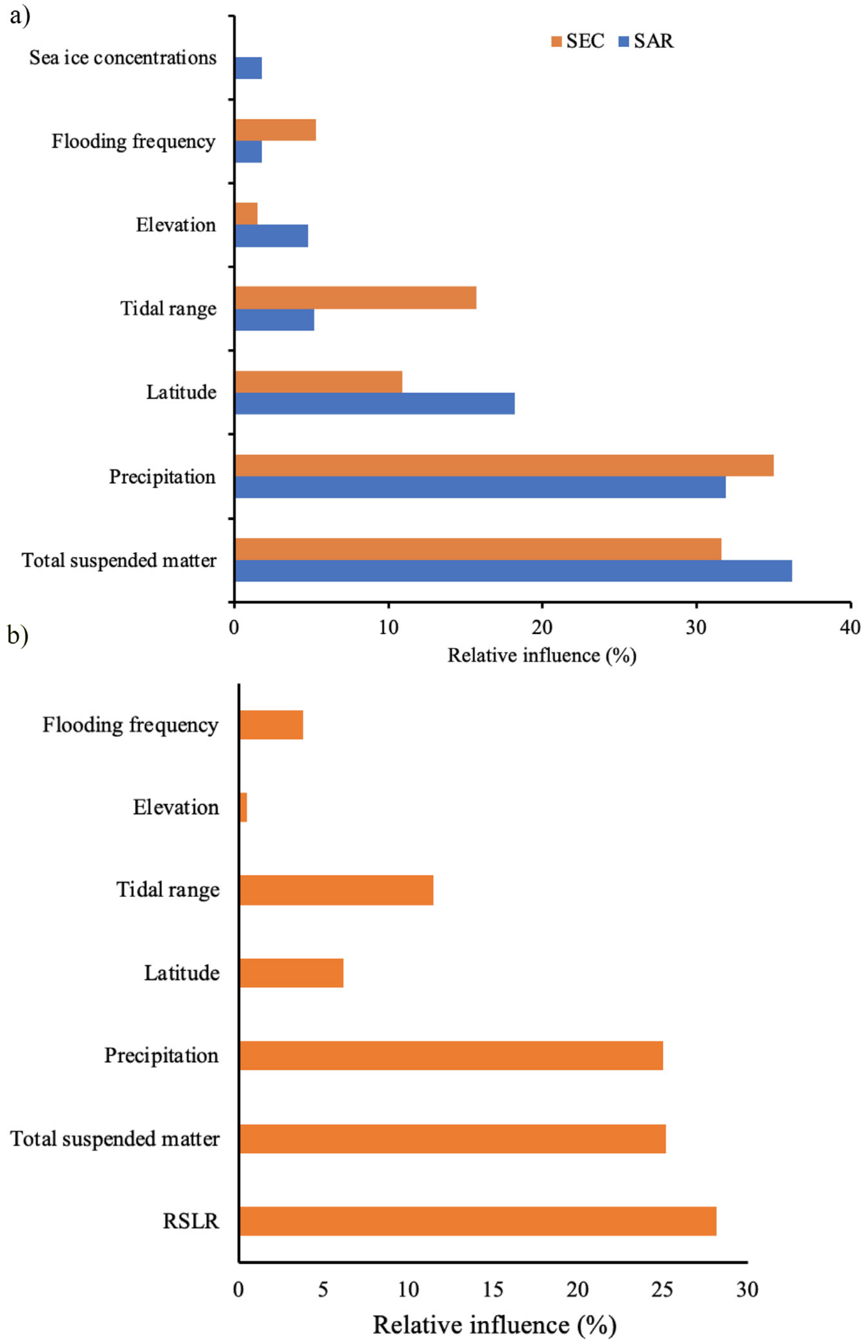


Fig. 3. Relative influences of the explanatory variables on saltmarsh sediment accretion rates and surface elevation change. (a) relative influences of the explanatory variables excluding RSLR for both SEC and SAR, (b) relative influences of the explanatory variables including RSLR for SEC. The blue and orange bars represent the relative influences on sediment accretion rates (SAR) and surface elevation change (SEC), respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the normal distribution assumption. Globally, the representative saltmarsh surface elevation changes are 5.9, 2.7, 2.3 and 2.2 mm yr^{-1} at the latitudinal ranges of <30°, 30–40°, 40–50° and >50°, respectively.

This study examined how SAR and SEC are driven by tidal frequencies and other potential drivers that were excluded in the above models owing to limited data but enough for univariate analyses. There are significant differences in both SAR and SEC amongst tidal marshes inundated at different frequencies (Fig. 4c and d), and amongst geomorphologic settings (Fig. 4a and b). In particular, SAR in tidal marshes flooded by diurnal cycles are significantly higher than those flooded by both semi-diurnal (Wilcoxon rank sum test, $W = 46{,}300$, $p << 0.001$) and mixed cycles ($W = 9372$, $p << 0.001$), while the latter two are not significantly different. However, SECs in tidal marshes flooded by mixed tides are significantly higher than those with semi-diurnal cycles ($W = 1235$, $p = 0.01$), but both show significant variances due to the limited data. SAR are significantly higher in fluvial and transitional than back-barrier marshes ($W = 32{,}904$, $p << 0.001$; $W = 16{,}924$, $p << 0.001$), while those of bluff-toe marshes are not different from all others. SECs are significantly higher in fluvial than back-barrier marshes ($W = 386$, $p = 0.012$), while that of transitional marshes are not different from other marsh types. SAR varies significantly with species richness ($W = 47{,}690$, $p << 0.001$, Fig. 4e) and plant types ($W = 20{,}133$, $p = 0.0028$, Supplementary Material Fig. S8a), while SECs do not vary significantly with species richness ($W = 778$, $p = 0.43$, Fig. 4f). The difference may lie in the limited observations on SEC, which show large variances. SAR at sites with two or more species (11.20 ± 1.52 mm yr^{-1}, mean ± SE) are

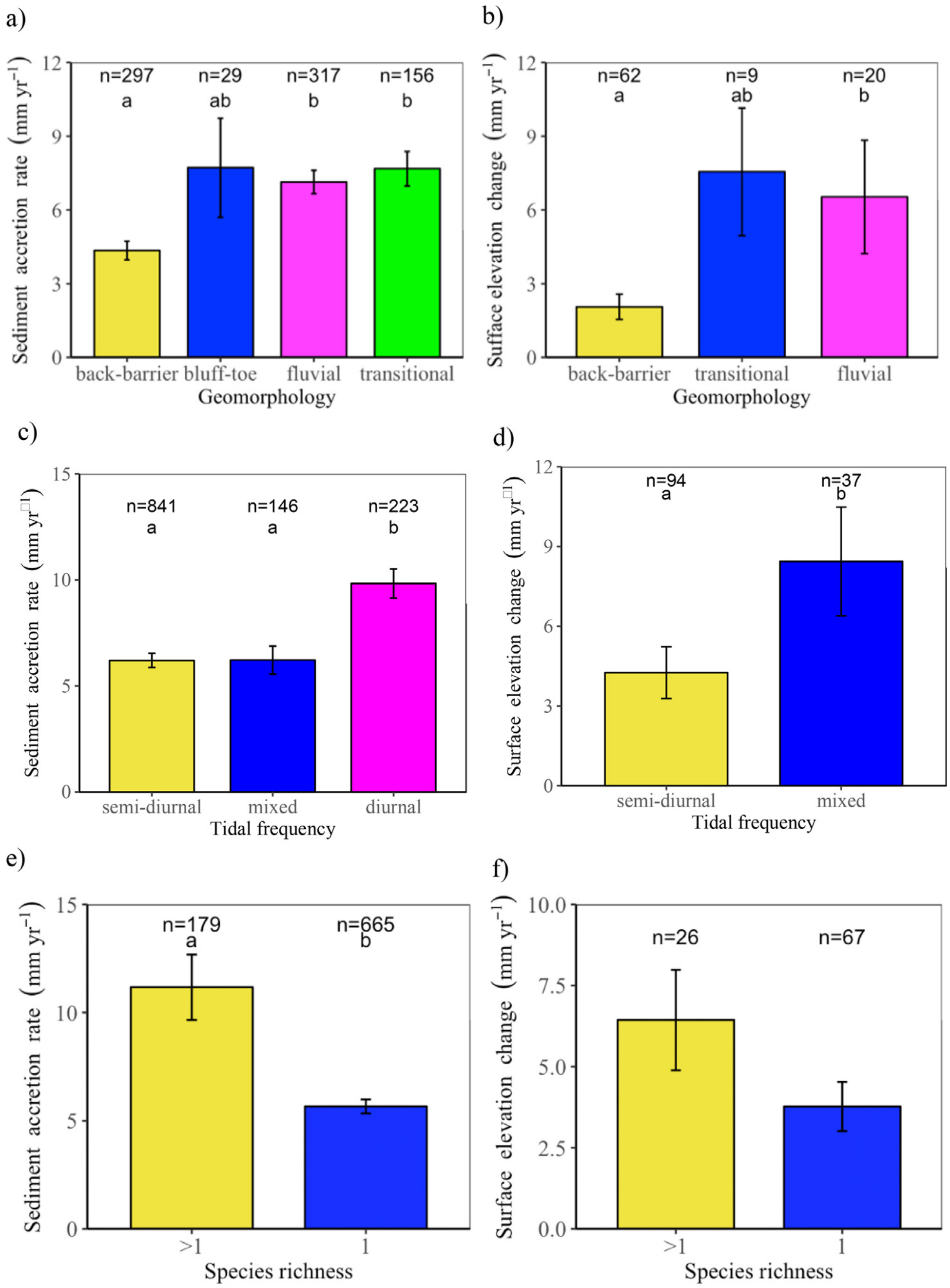


Fig. 4. Variation of sediment accretion rate and/or surface elevation change with natural and anthropogenic factors. (a) and (b), geomorphology; (c) and (d), tidal frequency; (e) and (f), species richness; (g) human activities. Human activities include human disturbance and conservation activities. OMWM denotes open marsh water management. Different sites in (g) are depicted by different colours. Significance values are given in the text. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

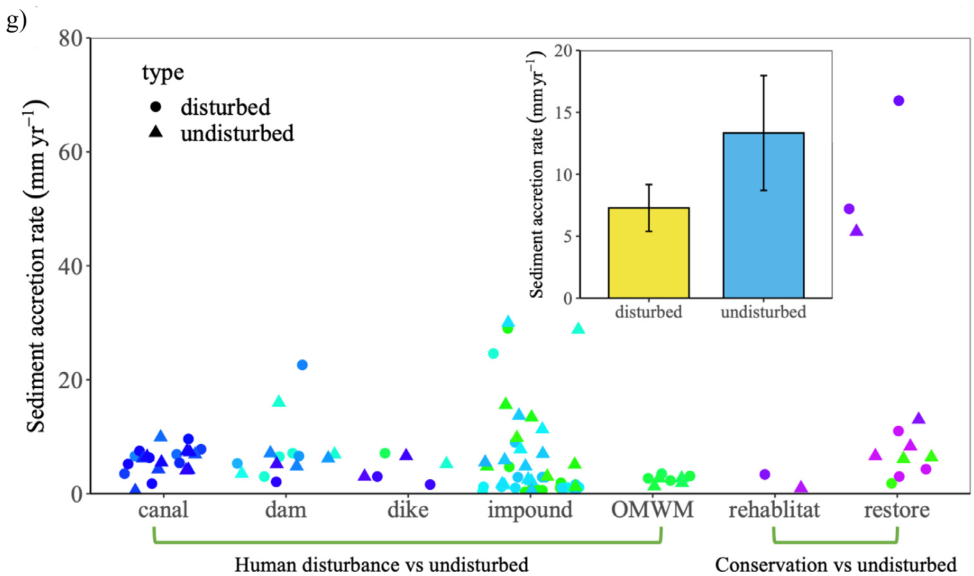
almost double those at monospecific sites (5.62 ± 0.32 mm yr^{-1}). In addition, there are significant differences in sediment accretion rates amongst locations ($W = 7179$, $p = 0.0004$, Supplementary Information Fig. S8b).

3.2. Temporal changes in SAR

Sediment accretion rates fluctuate over different time scales, ranging from sub-decadal to centennial scales. SAR at the decadal scale (2.4 ± 0.5 mm yr^{-1}) was significantly lower than that at the sub-decadal scale (2.9 ± 0.6 mm yr^{-1}) (Supplementary Material Fig. S9, Paired t-test, $t = 2.2$, $p = 0.033$, df = 36). For sediment accretion rates at the same temporal scale but different temporal span, differences between mid- and short centennial scales are significant (t=−4.2, $p = 0.002$, df = 9). This result further corroborates our conclusion that assessments of the vulnerability of coastal wetlands to sea level rise with only short-term sediment records are inappropriate.

3.3. The impact of human activities on SAR

The impact of different human activities on SAR was compared for sites where conservation and/or human disturbances are reported in conjunction with sediment accretion. SAR are significantly lower in human-disturbed than in undisturbed sites (Fig. 4 g, paired t-test, t=−2.02, $p = 0.048$, df = 50), while in-situ conservation (e.g. inclusion of tidal marshes in reserves) had no significant impact on SAR, probably because of the significance of ex-situ drivers, e.g. allochthonous sediment supply. amongst sites affected by human disturbances, impoundment is the most frequently reported activity. SAR at impounded sites are significantly lower than those of natural sites (Fig. 4 g, paired t-test, t=−2.1, $p = 0.047$, df = 23).



3.4. The resilience of tidal marshes to SLR

Based on SEC collected in our database, significant relationships exist between tidal marsh SEC and RSLR in the same measurement period ($R^2 = 0.53$, $p < 0.01$, F test) (Supplementary Material Table S2). This relationship is significant to estimating global SEC since SEC cannot be collected from all the tidal marshes while global RSLR data are available at relatively high precisions. The relationship was incorporated into the modelling framework (Fig. 2) to simulate the response of tidal marshes to SLR. This study estimated global tidal marsh areal change by 2100 at decadal intervals under the representative concentration pathways (RCPs) of global SLR (RCP2.6: 29 cm, RCP4.5: 50 cm and RCP8.5: 110 cm) and thresholds of population density (5, 20, 150 and 300 people km^{-2}, Fig. 5). The thresholds of population density correspond to the lower and upper boundaries of three human adaptation scenarios: (1) a high level of nature-based adaptation with population density thresholds of 150–300 people km^{-2} in the 1-in-100-year coastal floodplain; (2) a moderate level of nature-based adaptation with population density thresholds of 20–150 people km^{-2}; and (3) a business-as-usual scenario with population density thresholds of 5–20 people km^{-2}. Nature-based adaptation at high levels corresponds to urban areas where more accommodation space can be created while that at low levels corresponds to nearly uninhabited land, where solutions are less necessary to create accommodation space. Human adaptation scenarios 1 to 3 correspond to a decrease in additional accommodation space created by human beings through nature-based adaptation solutions. Globally, under human adaptation scenario 1, tidal marsh areal change fluctuates between −6.2% and −4.4% for RCP2.6, and between 53.1% and 57.5% for RCP8.5. Under scenario 2, tidal marsh areal change fluctuates between −22.9% and −6.2% for RCP2.6, and between 32.5% and 53.1% for RCP8.5. Scenario 3 would see tidal marsh areal change fluctuate between −29.5% and −22.9% for RCP2.6, and between 10.0% and 32.5% for RCP8.5.

This study evaluated the resilience of tidal marshes to SLR by estimating spatially-explicit tidal marsh area changes by 2100 under different RCP scenarios (Fig. 6). At the lower boundary of the business-as-usual scenario (5 people km^{-2}), this study estimated the hotspots of tidal marsh loss (i.e. countries with areal loss > 100 km^2) would account for 66.6%, 67.3% and 67.8% of total areal marsh losses under RCP 2.6, RCP4.5 and RCP8.5, respectively. These hotspots of marsh loss mainly occur in USA, China, Australia and some European countries (including Romania, Italy and France) (Fig. 5).

4. Discussion

4.1. Relationships between sediment accretion/ elevation change and their drivers

The BRT model uses 1229 independent measurements of SAR and 146 measurements of SEC to estimate the multiple drivers of SAR and SEC. The database used in the model has eight folds more data than that (179 measurements) of Kirwan et al. (2016). Multiple factors influencing SAR and SEC including precipitation, sediment loadings, tidal range and frequencies, elevation, latitude and sea ice concentrations, while Kirwan et al. (2016) only examined the impact of elevation on SAR and SEC. This study has significantly advanced our knowledge on the drivers of SAR and SEC in tidal marshes.

Precipitation may regulate tidal marsh SAR and SEC through sediment loadings via marine or freshwater input. Sediment availability can increase during rainfall and storm events (French and Spencer, 1993; Orson et al., 1998). Tidal marsh SEC is the difference between sediment deposition rate and other processes driving elevation change (Allen, 1990; D'Alpaos et al., 2011). The influence of suspended sediments on SAR and SEC is corroborated by previous modelling studies. Mineral sediment deposition is related to marsh inundation height, which has a positive linear relationship with suspended sediment concentration (Temmerman et al., 2003). Suspended sediment concentrations also strongly influence the maximum SLR that marshes can survive (Kirwan et al., 2016). Precipitation may also have an impact on freshwater input, which carries allochthonous suspended sediments to tidal marshes (McKee et al., 2012). However, precipitation may not contribute significantly to sediments transported to tidal marshes without fluvial input. Our results show that fluvial tidal marshes ($n = 317$) account for the highest number of sampling sites in the collated references (Fig. 4a). This probably explains why precipitation is the dominant driver of SAR and SEC in our models.

Our results show that SAR predicts SEC ($R^2 = 0.98$), more closely than has been reported for mangroves (Lovelock et al., 2015), which is consistent with an earlier finding that showed the approximation of tidal marsh SAR to SEC concluded from a smaller database (Kirwan et al., 2016).

Tides bring allochthonous mineral sediments and contribute to tidal marsh sediment accretion, and help redistribute sediments within tidal marshes (Chmura et al., 2004). Larger tidal ranges correspond to stronger tidal flow and wider intertidal regions (Rogers et al., 2019),

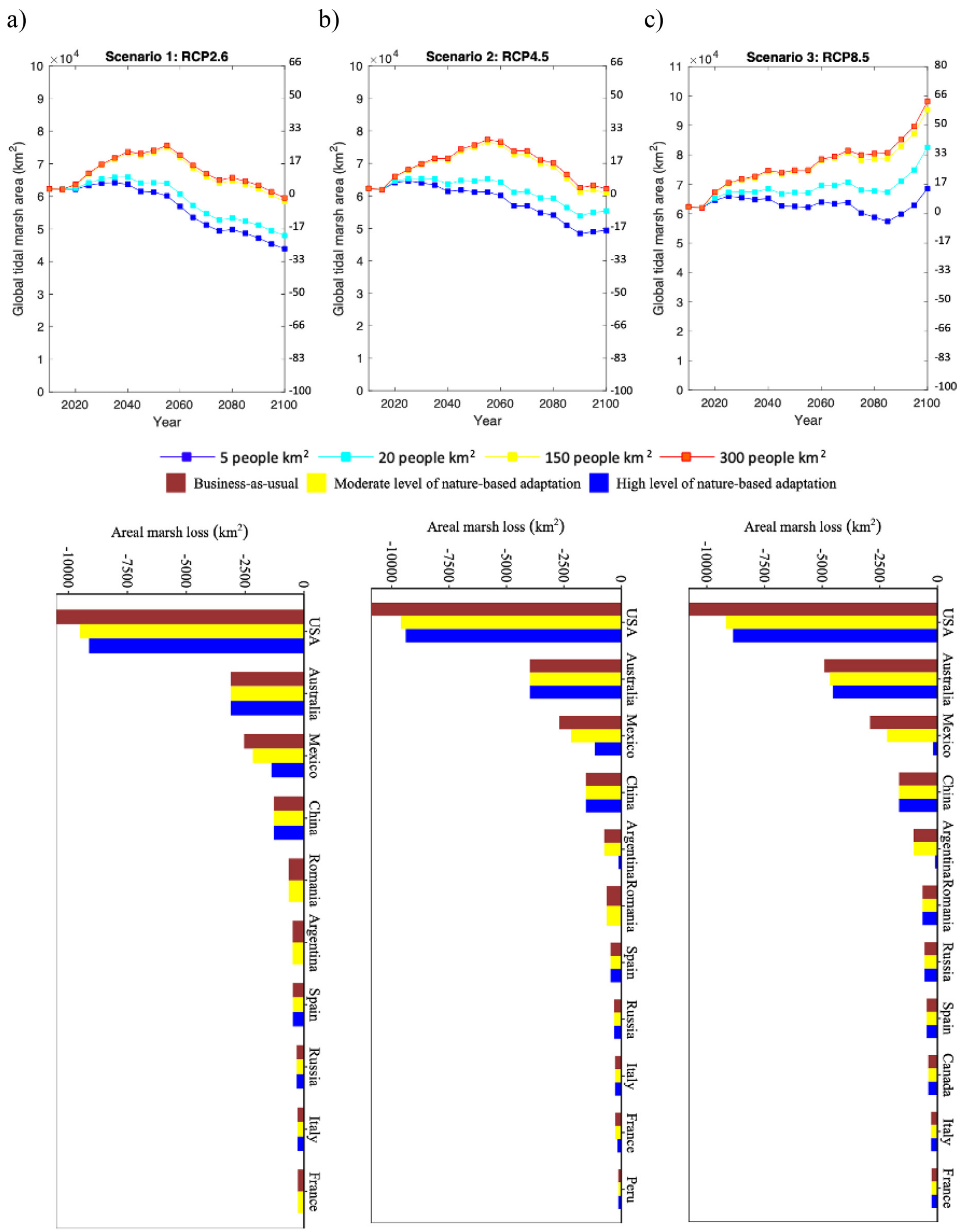


Fig. 5. Changes in global tidal marsh area under different scenarios of sea level rise and thresholds of coastal population density. The projections are made on three SLR scenarios: (a) RCP 2.6; (b) RCP4.5; and (c) RCP8.5. The lower panels indicate countries with hotspots of marsh areal loss (>100 km^2) under different adaptation and SLR scenarios by 2100. The upper panels indicate net wetland area change estimated under different IPCC SLR scenarios.

including the lower intertidal region where sediment accretion is most significant and noticeable, and hydroperiod is longer for sediment accumulation. Further, smaller tidal range means lower tidal energy, which limits inorganic sediment input from marine sources, whereas macrotides generate strong currents, which resuspend nearshore sediments and transport them onto tidal marsh surfaces (Hensel et al., 1999). Thus, macrotidal marshes (tidal range> 4 m) are more resilient to changes in the rate of relative SLR (RSLR) than microtidal marshes (tidal range< 2 m) [1]. In winter, the presence of sea ice affects tidal inundation and thus tidal marsh SAR in high-latitude regions (Ward et al., 2014).

Autochthonous marsh production contributes to sediment accretion, and changes with latitude (Kirwan et al., 2009). Both tidal marsh plant

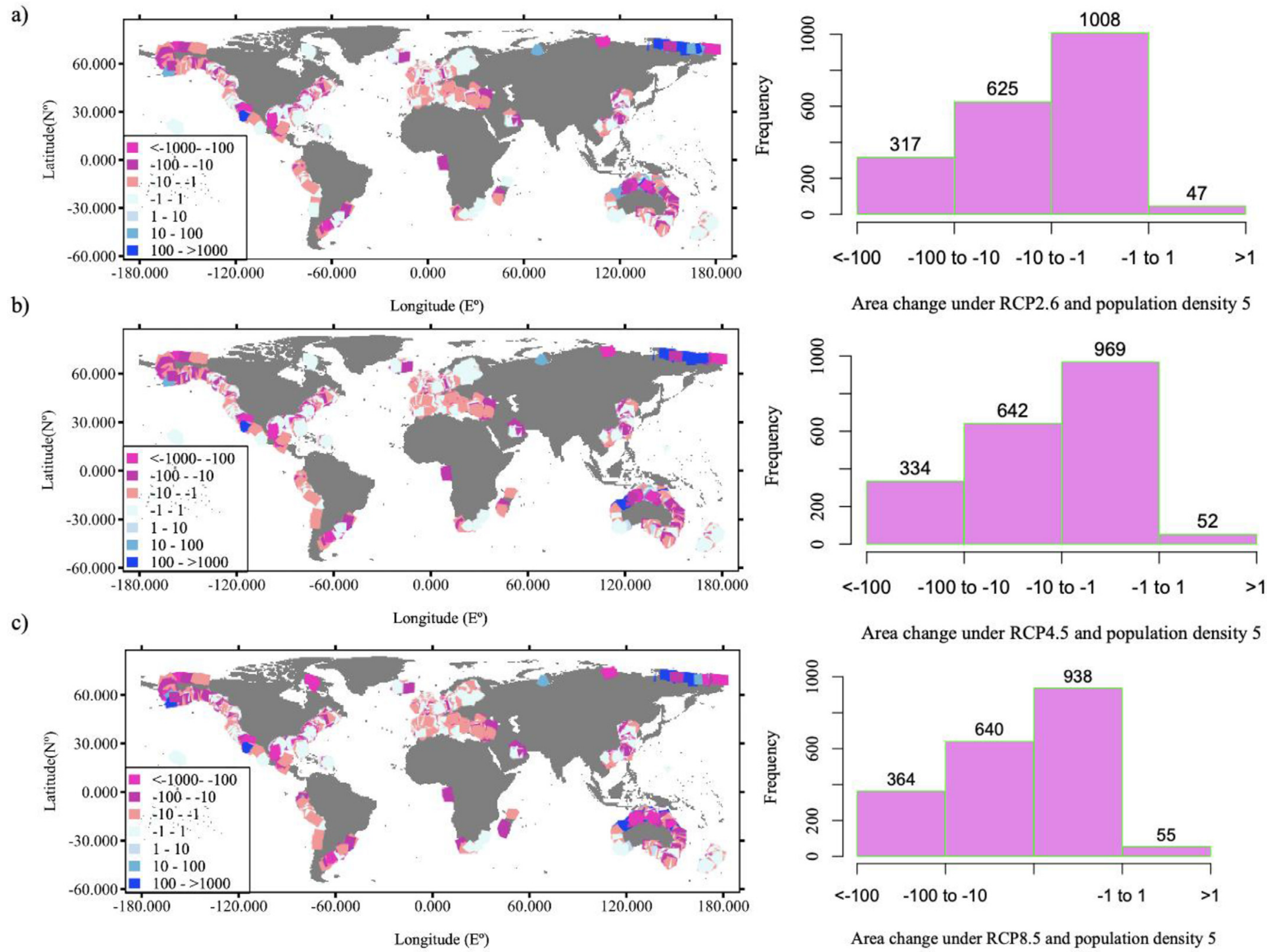


Fig. 6. Frequency of absolute changes in tidal marsh area by 2100 under different scenarios of sea level rise and coastal population density of 5 people km^{-2}. Net wetland area change is estimated under different IPCC SLR scenarios of (a) RCP 2.6; (b) RCP 4.5; and (c) RCP 8.5.

shoots and roots add organic matter to the sediment surface and promote mineral sediment deposition, with roots also slowing erosion rates (Gedan et al., 2011). Highly productive marshes will approach a new equilibrium state responding to a step change in the RSLR faster than less productive marshes (D'Alpaos et al., 2011). Therefore, latitude may have an indirect impact on SAR and SEC due to the latitudinal influence on marsh productivity. A similar outcome may exist also via the tidal subsidy effect (Odum, 1980).

Tidal flooding, geomorphology and plant traits may determine tidal marsh SAR and SEC via indirect avenues, including erosion, sediment and organic/mineral matter sources. High hydrodynamic energy from waves or currents during frequent flooding can result in tidal marsh erosion, which causes loss of tidal marsh surfaces (Bouma et al., 2005). Tidal marsh geomorphology may affect the dominant sources of sediment input, i.e. riverine or marine input (Macreadie et al., 2017). Our results show that SAR at sites with two or more species was significantly higher than that at monospecific sites. Marsh plant above-ground growth can enhance the strength of the feedback between tidal inundation and mineral sedimentation (Kirwan et al., 2013), while below-ground components contribute mainly to organic matter accretion. Various plant types with different morphology and complexity may enhance the retention of sediments. We put forward the hypothesis that SAR increases with species richness of tidal marshes, which can be further tested in controlled filed experiments in the future. However, while plant traits may determine the input of organic or mineral material to sediments in tidal marshes, they cannot simply account for other subsurface processes, e.g. subsidence. Shrubs were reported to effectively trap sand while herbaceous plants are efficient in trapping finer particles (Corenblit et al., 2009), accounting for the higher SAR with shrub occurrence. The distance to creek banks may influence inputs of sediments from the water column in riverine marshes (Craft et al., 1993).

Anthropogenic disturbance compromises tidal marsh SAR because the contribution of resuspended sediments to tidal marsh accretion can be greatly attenuated by dredged canals, spoil banks and impoundments (Boumans and Day, 1994; Reed et al., 2006). Our study found that SAR at impounded sites was lower than natural sites since these sites have similar precipitation but sediments are more available in natural sites than those in impounded sites. Some human activities (e.g. disturbance) have negative effects on SAR whereas others (e.g. restoration) do not.

4.2. Responses of tidal marshes to future SLR

The earth system model developed in this study incorporates influential factors on SEC found by the BRT model and improves the prediction on the response of tidal marshes to future SLR. RSLR, precipitation, tidal inundation, elevation and latitude are driving factors of SEC in the BRT model. The factors were incorporated in the earth system model directly or indirectly (e,g, the use of climatic zones as a proxy for precipitation).

A better understanding on these factors is important as they reflect the changes in SEC with influences at the local (e.g. elevation) and global (e.g. climatic zones) scales, and thus can improve the prediction of the earth system model by considering small-to-large scale changes. Our results forecast that the areal extents of tidal marshes fluctuate between −29.5% and −4.4% in the lowest SLR scenario but all increase (10.0% to 57.5%) in the highest SLR scenario under different human adaptation scenarios. The areal increase is attributed to the elevation capital that allows tidal marshes to migrate landward and survive through the long-term conversion of terrestrial vegetation (Schuerch et al., 2019), and sediment surplus favouring vertical accretion partly explained by the A/S model (Törnqvist et al., 2019). Inland migration of tidal marshes is driven by the conversion of terrestrial vegetation to tidal marshes. This is a process that occurs within a few years (Craft et al., 2002) and is mainly controlled by hydrological factors (Schuerch et al., 2019). In contrast, the decrease in marsh area extent in the lowest SLR scenario is mainly driven by increasing sediment deficiency, which weakens the capacity of tidal marshes to keep pace with SLR. For example, the future loss of tidal marshes in the Mississippi Delta was shown in our results which is consistent with the local analysis in the area considering the tipping points (Törnqvist et al., 2020).

The trend of tidal marsh areal changes is generally in line with the previous projection (Schuerch et al., 2018) but occurrence of the areal peak is different. The areal peak occurs around the mid-21st century under RCP 2.6 and RCP 4.5 and late-21st century under RCP8.5 in our projections, compared to occurrences in the late-21st century under all SLR scenarios in the previous projection. Tidal marshes are less resilient to future SLR in this study than the estimate of Schuerch et al., 2018 due to the less increase (up to 58%) in areal extent compared to the lateral (up to 60%). Tidal marshes are highly efficient in sequestering CO_2 from the atmosphere and accumulate carbon in sediments for millennium (Ouyang et al. 2014). Tidal marshes, as a component of blue carbon, has been suggested for carbon abatement in Australia (Kelleway et al., 2020). Our projections of their areal peak around the mid-21st century are consistent with the target of a climate neutral world by 2050 as enshrined in the Paris Agreement. Since their sediment carbon accumulation rates are around 50× those of terrestrial ecosystems (Ouyang et al. 2014), future areal increase in tidal marshes will contribute to the climate neutral target. Our study may facilitate future estimates on the contribution of tidal marshes to the target.

A previous assessment of countries with coastlines most vulnerable to SLR identified very different areas of vulnerability to our modelled hotspots of marsh loss (Nicholls and Cazenave, 2010). This highlights the impact of our findings - tidal marshes in countries experiencing the most serious SLR will not necessarily be submerged if sufficient accommodation space allows lateral migration. In contrast, at the upper boundary of the high level of nature-based adaptation scenario (300 people km^{-2}), the proportion of hotspots of tidal marsh loss is 3.1–5.5% lower than the lower boundary of the low level of nature-based adaptation scenario (5 people km^{-2}), accounting for 64.0–65.3% of total marsh areal losses under different SLR scenarios (Supplementary Material Fig. S10). This finding highlights the ineffectiveness of nature-based adaptation for shrinking hotspots of tidal marsh loss.

4.3. Limitations and uncertainties

Our method cannot precisely account for ecogeomorphic feedbacks which are the interaction between plant growth, geomorphology and hydrodynamics. Ecogeomorphic feedbacks tend to increase rates of sediment accumulation when marshes become more flooded (Kirwan et al., 2016) under future SLR scenarios. However, it is difficult to estimate the extent of SAR increase due to ecogeomorphic feedbacks in the future, in particular vegetation type changes at local scales (Reed et al., 2020). Moreover, geomorphologic systems often react with relatively long time lags, with the response interval depending partly on the magnitude, frequency and duration of energy factors (Wright and Thom, 1977). Allen (1990) demonstrated a clear lag between SAR and RSLR for immature marshes. The lag was analysed through a numerical model (Kirwan and Murray, 2008), and an analytical model which captures the role of governing factors such as suspended sediment concentrations and plant productivity. This study used a 5-year lag, which may not be enough to account for feedbacks at the local scale, adding uncertainty to our analysis of tidal marsh resilience to future SLR. Additionally, the resolution of the satellite data in our models may have limited the precision of the estimate on suspended matter, precipitation and sea ice. Other uncertainties may result from future precipitation changes. SEC decreases with increased precipitation from −20 cm to +70 cm but increases with increased precipitation again after a threshold of precipitation change of around +80 cm (Table S3). Decrease in precipitation may hinder sediment erosion and thus gives rise to SEC, while moderate increase in precipitation facilitates sediment erosion (Tolhurst et al., 2008) and thus reduce SEC. However, strong rainfalls may increase sediment availability (Orson et al., 1998) which more than counteracts sediment erosion, and enhance SEC. This change cannot be incorporated into the earth system model since future precipitation changes vary amongst different climatic zones under various IPCC scenarios (IPCC 2014). However, our earth system model provides new insights on assessing the resilience of tidal marshes to SLR with real elevation change data by incorporating both vertical sediment accretion and lateral landward migration.

5. Conclusions

This study provides the first quantitative analysis to examine the relative influence of drivers on SAR and SEC in tidal marshes using a machine learning method (i.e. BRT modelling) based on data collected from 156 references and satellite data on precipitation, suspended matter and sea ice. The best-fit model shows that suspended matter and precipitation are the major drivers and together explain 68.1% of the relative influence on SAR. RSLR, suspended matter and precipitation are the major drivers and together explain 79.8% of the relative influence on SEC. Minor drivers of the variation in SAR and SEC include latitude, elevation, sea ice, tidal range and frequency.

This study assessed the resilience of tidal marshes to SLR by incorporating the effects of vertical sediment accretion described by SEC and lateral landward migration using an earth system model under different SLR and human adaptation scenarios. The results show that tidal marsh area changes within the range from −29.5% to −4.4% under RCP 2.6 but increases within the range from 10.0% to 57.5% under RCP 8.5 at the end of this century. The areal peak appears around the mid-21st century under RCP 2.6 and RCP 4.5 and late-21st century under RCP 8.5 in our analysis. This can be used to estimate the ecosystem services provided by tidal marshes (e.g. carbon sequestration and accumulation) in the future. Eqs. 1–(3)

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Funding sources

This study was supported by Key Special Project for Introduced Talents Team of Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou) (GML2019ZD0403), Guangdong Provincial Key Laboratory Project (2019B121203011), a Postdoctoral Fellowship at The Chinese University of Hong Kong, and The Global Wetlands Project.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.envc.2022.100593.

References

Allen, J., 1990. Constraints on measurement of sea-level movements from salt-marsh accretion rates. J. Geol. Soc. London 147, 5–7.

Allen, J., 2000. Morphodynamics of Holocene salt marshes: a review sketch from the Atlantic and Southern North Sea coasts of Europe. Quat. Sci. Rev. 19, 1155–1231.

Andersen, T., Svinth, S., Pejrup, M., 2011. Temporal variation of accumulation rates on a natural salt marsh in the 20th century—The impact of sea level rise and increased inundation frequency. Mar. Geol. 279, 178–187.

Anisfeld, S.C., Hill, T.D., Cahoon, D.R., 2016. Elevation dynamics in a restored versus a submerging salt marsh in Long Island Sound. Estuar. Coast. Shelf. Sci. 170, 145–154.

Bivand, R., Rundel, C., 2020. rgeos: interface to Geometry Engine - Open Source ('GEOS'). R Package Version 0.5-3.

Blondeau-Patissier, D., Schroeder, T., Brando, V., Maier, S., Dekker, A., Phinn, S., 2014. ESA-MERIS 10-year mission reveals contrasting phytoplankton bloom dynamics in two tropical regions of Northern Australia. Remote Sens. (Basel) 6, 2963–2988.

Bouma, T., Vries, M.D., Low, E., Kusters, L., Herman, P., Tanczos, I., Temmerman, S., Hesselink, A., Meire, P., Van Regenmortel, S., 2005. Flow hydrodynamics on a mudflat and in salt marsh vegetation: identifying general relationships for habitat characterisations. Hydrobiologia 540, 259–274.

Boumans, R.M., Day, J.W., 1994. Effects of two Louisiana marsh management plans on water and materials flux and short-term sedimentation. Wetlands 14, 247–261.

Breithaupt, J.L., Smoak, J.M., Byrne, R.H., Waters, M.N., Moyer, R.P., Sanders, C.J., 2018. Avoiding timescale bias in assessments of coastal wetland vertical change. Limnol. Oceanogr. 63, 477–495.

Cahoon, D.R., Reed, D.J., Day, J.W., 1995. Estimating shallow subsidence in microtidal salt marshes of the southeastern United States: kaye and Barghoorn revisited. Mar. Geol. 128, 1–9.

Cahoon, D.R., Perez, B.C., Segura, B.D., Lynch, J.C., 2011. Elevation trends and shrink–swell response of wetland soils to flooding and drying. Estuar. Coast. Shelf. Sci. 91, 463–474.

Cahoon, D.R., McKee, K.L., Morris, J.T., 2021. How plants influence resilience of salt marsh and mangrove wetlands to sea-level rise. Estuar. Coasts 44 (4), 883–898.

Chen, S., Torres, R., Goñi, M.A., 2016. The role of salt marsh structure in the distribution of surface sedimentary organic matter. Estuar. Coasts 39 (1), 108–122.

Chmura, G.L., Hung, G.A., 2004. Controls on salt marsh accretion: a test in salt marshes of Eastern Canada. Estuaries 27, 70–81.

Coleman, D.J., Ganju, N.K., Kirwan, M.L., 2020. Sediment delivery to a tidal marsh platform is minimized by source decoupling and flux convergence. J. Geophys. Res. 125 (8) p.e2020JF005558.

Corenblit, D., Steiger, J., Gurnell, A.M., Tabacchi, E., Roques, L., 2009. Control of sediment dynamics by vegetation as a key function driving biogeomorphic succession within fluvial corridors. Earth Surf. Process. Landforms 34, 1790–1810.

Craft, C., Seneca, E.D., Broome, S.W., 1993. Vertical accretion in microtidal regularly and irregularly flooded estuarine marshes. Estuar. Coast. Shelf. Sci. 37, 371–386.

Craft, C., Broome, S., Campbell, C., 2002. Fifteen years of vegetation and soil development after Brackish-Water Marsh Creation. Restor. Ecol. 10, 248–258.

Craft, C., 2007. Freshwater input structures soil properties, vertical accretion, and nutrient accumulation of Georgia and US tidal marshes. Limnol. Oceanogr. 52, 1220–1230.

D'Alpaos, A., Mudd, S.M., Carniello, L., 2011. Dynamic response of marshes to perturbations in suspended sediment concentrations and rates of relative sea level rise. J. Geophys. Res. 116 (F4).

Dijkstra, L., Poelman, H., 2014. A harmonised definition of cities and rural areas: the new degree of urbanisation. European Commission Working Paper WP.

French, J.R., Spencer, T., 1993. Dynamics of sedimentation in a tide-dominated backbarrier salt marsh, Norfolk, UK. Mar. Geol. 110, 315–331.

Friedrichs, C.T., Perry, J.E., 2001. Tidal salt marsh morphodynamics: a synthesis. J. Coast. Res. (Special issue 27) 7–37.

Friess, D.A., McKee, K.L., 2021. The history of surface-elevation paradigms in mangrove biogeomorphology. In: Dynamic Sedimentary Environments of Mangrove Coasts. Elsevier, pp. 179–198.

Gabler, R.E., Petersen, J.F., Trapasso, L.M., Sack, D., Sager, R.J., Wise, D.L., 2007. Essentials of Physical Geography, 8th Edition Thomson Higher Education, CA, USA.

Gedan, K.B., Kirwan, M.L., Wolanski, E., Barbier, E.B., Silliman, B.R., 2011. The present and future role of coastal wetland vegetation in protecting shorelines: answering recent challenges to the paradigm. Clim. Change 106, 7–29.

Greenwell, B., Boehmke, B., Cunningham, J., GBM, D., 2019. gbm: generalized Boosted Regression Models. R package version 2.1.5.

Hensel, P.E., Day Jr, J.W., Pont, D, 1999. Wetland vertical accretion and soil elevation change in the Rhone River delta, France: the importance of riverine flooding. J. Coast. Res. 15, 668–681.

Hijmans, R.J., Phillips, S., Leathwick, J., Elith, J, 2017. dismo: species Distribution Modeling. R package version 1.1-4.

Hinkel, J., Lincke, D., Vafeidis, A.T., Perrette, M., Nicholls, R.J., Tol, R.S., Marzeion, B., Fettweis, X., Ionescu, C., Levermann, A., 2014. Coastal flood damage and adaptation costs under 21st century sea-level rise. Proc. Nat. Acad. Sci. USA 111, 3292–3297.

Core Writing Team, 2014. In: Pachauri, R.K., Meyer, L.A. (Eds.), Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel On Climate Change. IPCC, Geneva, Switzerland, p. 151.

Kelleway, J.J., Serrano, O., Baldock, J.A., Burgess, R., Cannard, T., Lavery, P.S., Lovelock, C.E., Macreadie, P.I., Masqué, P., Newnham, M., Saintilan, N., 2020. A national approach to greenhouse gas abatement through blue carbon management. Glob. Environ. Chang. 63, 102083.

Kelley, J.T., Belknap, D.F., Jacobson Jr, G.L., Jacobson, H.A, 1988. The morphology and origin of salt marshes along the glaciated coastline of Maine, USA. J. Coast. Res. 4, 649–665.

Kirwan, M.L., Murray, A.B., 2008. Tidal marshes as disequilibrium landscapes? Lags between morphology and Holocene sea level change. Geophys. Res. Lett. 35, L24401.

Kirwan, M.L., Guntenspergen, G.R., Morris, J.T., 2009. Latitudinal trends in Spartina alterniflora productivity and the response of coastal marshes to global change. Glob. Chang. Biol. 15, 1982–1989.

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

Kirwan, M.L., Temmerman, S., Skeehan, E.E., Guntenspergen, G.R., Fagherazzi, S., 2016. Overestimation of marsh vulnerability to sea level rise. Nat. Clim. Chang. 6, 253–260.

Kolker, A.S., Goodbred, S.L., Hameed, S., Cochran, J.K., 2009. High-resolution records of the response of coastal wetland systems to long-term and short-term sea-level variability. Estuar. Coast. Shelf. Sci. 84, 493–508.

Lee, S.Y., Primavera, J.H., Dahdouh-Guebas, F., McKee, K., Bosire, J.O., Cannicci, S., Diele, K., et al., 2014. Ecological role and services of tropical mangrove ecosystems: a reassessment. Glob. Ecol. Biogeogr. 23 (7), 726–743.

Leonardi, N., Carnacina, I., Donatelli, C., Ganju, N.K., Plater, A.J., Schuerch, M., Temmerman, S., 2018. Dynamic interactions between coastal storms and salt marshes: a review. Geomorphology 301, 92–107.

Lovelock, C.E., Cahoon, D.R., Friess, D.A., Guntenspergen, G.R., Krauss, K.W., Reef, R., Rogers, K., Saunders, M.L., Sidik, F., Swales, A., 2015. The vulnerability of Indo-Pacific mangrove forests to sea-level rise. Nature 526, 559–563. doi:10.1038/nature15538.

Ma, Z., Melville, D.S., Liu, J., Chen, Y., Yang, H., Ren, W., Zhang, Z., Piersma, T., Li, B., 2014. Rethinking China's new great wall. Science 346, 912–914.

Macreadie PI, O.Q., Kelleway, J.J., Serrano, O., Carnell, P.E., Ewers Lewis, C.J., Atwood, T.B., Sanderman, J., Baldock, J., Connolly, R.M., Duarte, C.M., Lavery, P.S., Steven, A., Lovelock, C.E.., 2017. Carbon sequestration by Australian tidal marshes. Sci. Rep. 7, 44071.

Marani, M., Belluco, E., Ferrari, S., Silvestri, S., D'Alpaos, A., Lanzoni, S., Feola, A., Rinaldo, A., 2006. Analysis, synthesis and modelling of high-resolution observations of salt-marsh eco-geomorphological patterns in the Venice lagoon. Estuar. Coast. Shelf. Sci. 69, 414–426.

McKee, K., Rogers, K., Saintilan, N., 2012. Response of salt marsh and mangrove wetlands to changes in atmospheric CO_2, climate, and sea level. In: Global Change and the Function and Distribution of Wetlands. Springer, pp. 63–96.

Mcowen, C.J., Weatherdon, L.V., Van Bochove, J.-W., Sullivan, E., Blyth, S., Zockler, C., Stanwell-Smith, D., Kingston, N., Martin, C.S., Spalding, M., 2017. A global map of saltmarshes. Biodivers. Data J. (5) e11764. doi:10.3897/BDJ.5.e11764.

Mittermeier, R.A., Mittermeier, C.G., Brooks, T.M., Pilgrim, J.D., Konstant, W.R., da Fonseca, G.A., Kormos, C., 2003. Wilderness and biodiversity conservation. Proc. Nat. Acad. Sci. USA 100, 10309–10313.

Nicholls, R.J., Cazenave, A., 2010. A Sea-level rise and its impact on coastal zones. Science 328, 1517–1520.

Odum, E.P., 1980. The status of three ecosystem-level hypotheses regarding salt marsh estuaries: tidal subsidy, outwelling, and detritus-based food chains. In: Estuarine Perspectives. Elsevier, pp. 485–495.

Orson, R., Warren, R., Niering, W., 1998. Interpreting sea level rise and rates of vertical marsh accretion in a southern New England tidal salt marsh. Estuar. Coast. Shelf. Sci. 47, 419–429.

Ouyang, X., Lee, S.Y., 2014. Updated estimates of carbon accumulation rates in coastal marsh sediments. Biogeosciences 11, 5057–5071. doi:10.5194/bg-11-5057-2014.

Ouyang, X., Lee, S.Y., Connolly, R.M., 2017. The role of root decomposition in global mangrove and saltmarsh carbon budgets. Earth-Sci. Rev. 166, 53–63. doi:10.1016/j.compchemeng.2016.09.009.

Parkinson, R.W., Craft, C., DeLaune, R.D., Donoghue, J.F., Kearney, M., Meeder, J.F., Morris, J., Turner, R.E., 2017. Marsh vulnerability to sea-level rise. Nat. Clim. Chang. 7, 756.

Pierce, D., 2017. ncdf4: interface to Unidata netCDF (Version 4 or Earlier) Format Data Files. R package version 1.16.

R Core Team, 2014. A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Rayner, N., Parker, D.E., Horton, E., Folland, C., Alexander, L., Rowell, D., Kent, E., Kaplan, A., 2003. Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. J. Geophys. Res. 108 (D14), 4407. doi:10.1029/2002JD002670.

Reed, D.J., Peterson, M.S., Lezina, B.J., 2006. Reducing the effects of dredged material levees on coastal marsh function: sediment deposition and nekton utilization. Environ. Manage. 37, 671–685.

Reed, D., Wang, Y., Meselhe, E., White, E., 2020. Modeling wetland transitions and loss in coastal Louisiana under scenarios of future relative sea-level rise. Geomorphology 352, 106991.

Rogers, K., Wilton, K., Saintilan, N., 2006. Vegetation change and surface elevation dynamics in estuarine wetlands of southeast Australia. Estuar. Coast. Shelf. Sci. 66, 559–569.

Rogers, K., Kelleway, J., Saintilan, N., Megonigal, J., Adams, J., Holmquist, J., Lu, M., Schile-Beers, L., Zawadzki, A., Mazumder, D., Woodroffe, C., 2019. Wetland carbon storage controlled by millennial-scale variation in relative sea-level rise. Nature 567, 91–95. doi:10.1038/s41586-019-0951-7.

Rubel, F., Kottek, M., 2010. Observed and projected climate shifts 1901-2100 depicted by world maps of the Köppen-Geiger climate classification. Meteorol. Z. 19, 135–141.

Rybczyk, J.M., Cahoon, D.R., 2002. Estimating the potential for submergence for two wetlands in the Mississippi River Delta. Estuaries 25, 985–998.
Schuerch, M., Spencer, T., Temmerman, S., Kirwan, M.L., Wolff, C., Lincke, D., McOwen, C.J., Pickering, M.D., Reef, R., Vafeidis, A.T., 2018. Future response of global coastal wetlands to sea-level rise. Nature 561, 231–234.
Schuerch, M., Spencer, T., Temmerman, S., Kirwan, M.L., Wolff, C., Lincke, D., McOwen, C.J., Pickering, M.D., Reef, R., Vafeidis, A.T., Hinkel, J., Nicholls, R.J., B, S., 2019. Reply to “Global coastal wetland expansion under accelerated sea-level rise is unlikely. EarthArXiv doi:10.31223/osf.io/d2nhs.
Temmerman, S., Govers, G., Meire, P., Wartel, S., 2003. Modelling long-term tidal marsh growth under changing tidal conditions and suspended sediment concentrations, Scheldt estuary, Belgium. Mar. Geol. 193, 151–169.
Thom, R.M., 1992. Accretion rates of low intertidal salt marshes in the Pacific Northwest. Wetlands 12, 147–156.
Titus, J., Wang, J., 2008. Background Documents Supporting Climate Change Science Program Synthesis and Assessment Product 4.1 Coastal Elevations and Sensitivity to Sea-Level Rise. EPA 430R07004. United States Environmental Protection Agency, Washington, DC, p. 354.
Törnqvist, T., Cahoon, D., Day, J., Morris, J., 2019. Global coastal wetland expansion under accelerated sea-level rise is unlikely. EarthArXiv doi:10.31223/osf.io/d2nhs, July 16.
Törnqvist, T.E., Jankowski, K.L., Li, Y.X., González, J.L., 2020. Tipping points of Mississippi Delta marshes due to accelerated sea-level rise. Sci. Adv. 6 (21), eaaz5512.
Tolhurst, T.J., Watts, C.W., Vardy, S., Saunders, J.E., Consalvey, M.C., Paterson, D.M., 2008. The effects of simulated rain on the erosion threshold and biogeochemical properties of intertidal sediments. Cont. Shelf. Res. 28, 1217–1230.
Vafeidis, A.T., Nicholls, R.J., McFadden, L., Hinkel, J., Grasshoff, P.S., 2004. Developing a global database for coastal vulnerability analysis: design issues and challenges. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. 35, 801–805.
Ward, R.D., Teasdale, P.A., Burnside, N.G., Joyce, C.B., Sepp, K., 2014. Recent rates of sedimentation on irregularly flooded Boreal Baltic coastal wetlands: responses to recent changes in sea level. Geomorphology 217, 61–72.
Wolters, M., Garbutt, A., Bekker, R.M., Bakker, J.P., Carey, P.D., 2008. Restoration of salt-marsh vegetation in relation to site suitability, species pool and dispersal traits. J. Appl. Ecol. 45, 904–912.
Wright, L., Thom, B., 1977. Coastal depositional landforms: a morphodynamic approach. Prog. Phys. Geogr. 1, 412–459.