Tidal marsh resilience to sea level rise controlled by vertical accretion and landward migration under nature-based human adaptation scenarios

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Competing Interests

No competing interests need to be declared in relation to the work described.

Author Contributions

X.O. and S.Y.L designed the study with R.M.C contributing ideas to the study. X.O. collected, analysed the data and conducted mathematical modelling. Manuscript writing was led by X.O. with contributions from S.Y.L. and R.M.C.

Abstract: Tidal marshes are not only lost to human disturbance but also face the threat of sea level rise (SLR). However, current earth system models used to estimate future changes in wetland extent omit wetland's real responses to SLR without field observations. We synthesised global data on sediment accretion rate (SAR) and surface elevation change (SEC) for tidal marshes and developed a mathematical model to assess their resilience to future SLR. Sediment loadings and precipitation largely explain the variance of marsh SAR and SEC. Human disturbance resulted in less sediment accretion and existing conservation activities were inefficient in promoting sediment accretion. Under the representative concentration pathways and nature-based human adaptation scenarios, tidal marshes will gain up to 63% of the current area by 2100 if sufficient sediment loadings and accommodation space allow landward migration. If current accommodation space maintains, net areal losses of > 30% are possible and 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. This implicates that tidal marshes may contribute to achieve a climate neutral world by 2050. We highlight the importance of nature-based adaptation in enhancing the resilience of tidal marshes to future SLR.

Key Words: Sea level rise; Nature-based human adaptation; Human disturbance; Climate neutral; Sediment accretion; Surface elevation change

1 Introduction

Tidal marshes are widely distributed 'blue carbon' ecosystems, providing substantial ecosystem services (e.g. coastal protection, water purification and nursery ground for fisheries) (Barbier 2012) valued at US$194,000 ha^{-1} yr^{-1} (Costanza et al., 2014). Nonetheless, the area of marshes has been declining globally due to direct adverse anthropogenic impacts (Craft et al., 2008; Doody 2004; Gedan et al., 2009; Koch et al., 2009) and wind-wave erosion of marsh edges (Leonardi et al., 2018; Marani et al., 2011), the effect of which on marsh loss has not been accounted for. Tidal marshes now also 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).

Further, there are feedbacks and interactions among 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 dependent on morphodynamics, which shape tidal marshes through combined ecogeomorphology and hydrodynamics (Friedrichs and Perry, 2001). In addition to sediment accretion, tidal marsh surface elevation change 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 may alleviate the impact of SLR on tidal marshes when surface elevation increases at or exceeds the rate of local relative SLR (Aniesfeld et al., 2016). 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, in line with that described for mangroves across the Indo-Pacific region, i.e. more than half the mangrove forests have already lost elevation relative to sea level (Lovelock et al., 2015).

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). 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.

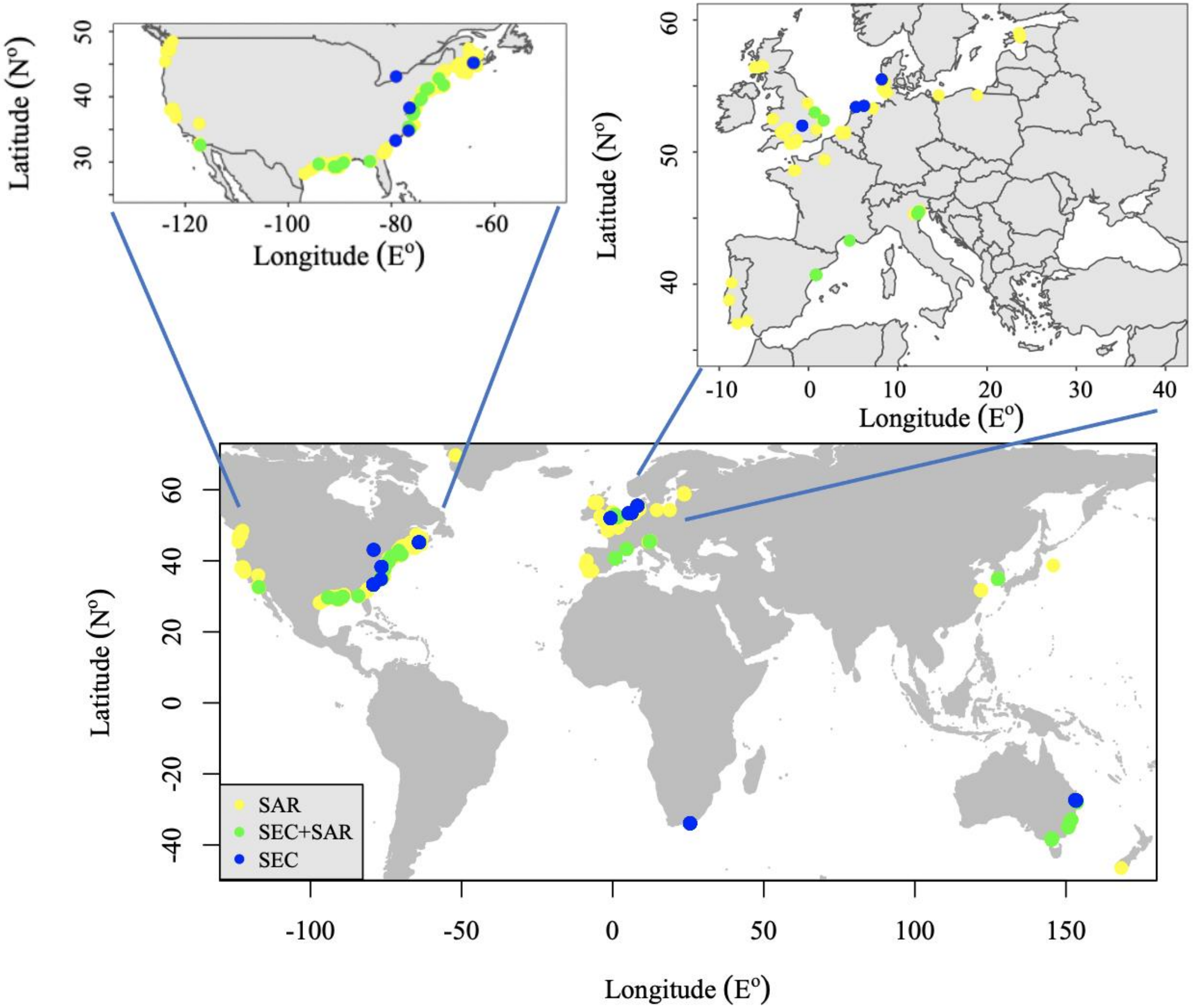
A recent study of the vulnerability of regional mangroves to SLR revealed the importance of time scales in evaluating coastal wetland vertical change in response to SLR (Breithaupt et al. 2018). The two distinct ecotypes of coastal wetlands, i.e. mangroves and tidal marshes, however, are different in nature, e.g. distribution (tropical and subtropical vs. global) and plant traits (mainly woody vs. shrubby/ herbaceous). 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). We aim to synthesise the global data to properly assess the important relationship between sediment accretion/ elevation change and their potential drivers (See Table 1 for comparison of studies on the response of coastal wetlands to SLR).

We reviewed data on both short- and long-term global tidal marsh SAR and SEC (Fig. 1a), and provide the first systematic test of the quantitative influence of potential drivers on global tidal marsh SAR and SEC. We demonstrate that both sediment supply (Törnqvist et al., 2019) and landward migration contributing to elevation capital (Schuerch et al., 2018, 2019) are important, and predict the resilience of tidal marshes to future SLR by establishing an

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

Meta-analysis/Quantitative reviews				
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. [21]
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. [23]
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. [24]
Using **real data** on surface elevation change to **mode**l the response of tidal marshes to sea level rise	**Assessed** accommodation space available for tidal marsh landward migration under human adaptations	**Assessed** the impact of controls such as human disturbance, climatic, geomorphic, geographic factors on marsh sediment accretion/surface elevation change	Global	This study
Qualitative 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 [26]
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 [13]

a)



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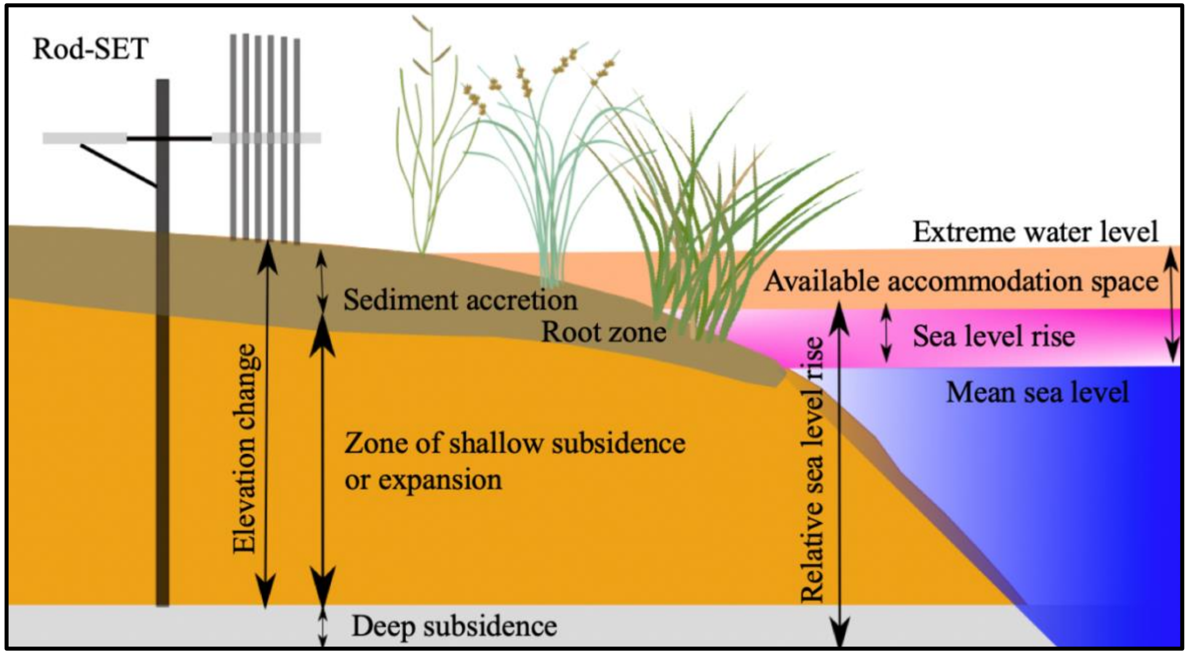

Fig. 1 Global distribution of study sites from the collated studies and a conceptual model showing marsh response to sea level rise. (a) sites of SAR and/or SEC; (b) tidal marshes responding to SLR via vertical sediment accretion and accommodation space available for lateral migration. The upper sub-panels 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.

integrated mathematical model incorporating the effects of vertical sediment accretion described by SEC and lateral landward migration.

2 Methods

2.1 Literature review

We collected references on SAR and SEC in tidal marshes from http://www.sciencedirect.com/ and http://pcs.webofknowledge.com/. We collated 156 references containing 1229 independent measurements of SAR and 146 measurements of SEC (Fig. 1a). SAR is the vertical dimension of sediment development determined from short- and/or long-term markers, and integrates the sedimentological and biologic 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.

2.2 Satellite data collection

We 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 degree 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 degree 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 - 1,040 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).

2.3 Analysis of controls on SAR and SEC

We examined the relationship between SAR/SEC and influential factors, including latitude, precipitation, sea ice concentration, total suspended matter, tidal range and tidal frequencies in a statistical model. The categorical variables are number coded, with one level of each variable selected as the reference. The influences of other factors (e.g. species richness, plant type, location, and elevation) 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. We started the model 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 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). We also examined the

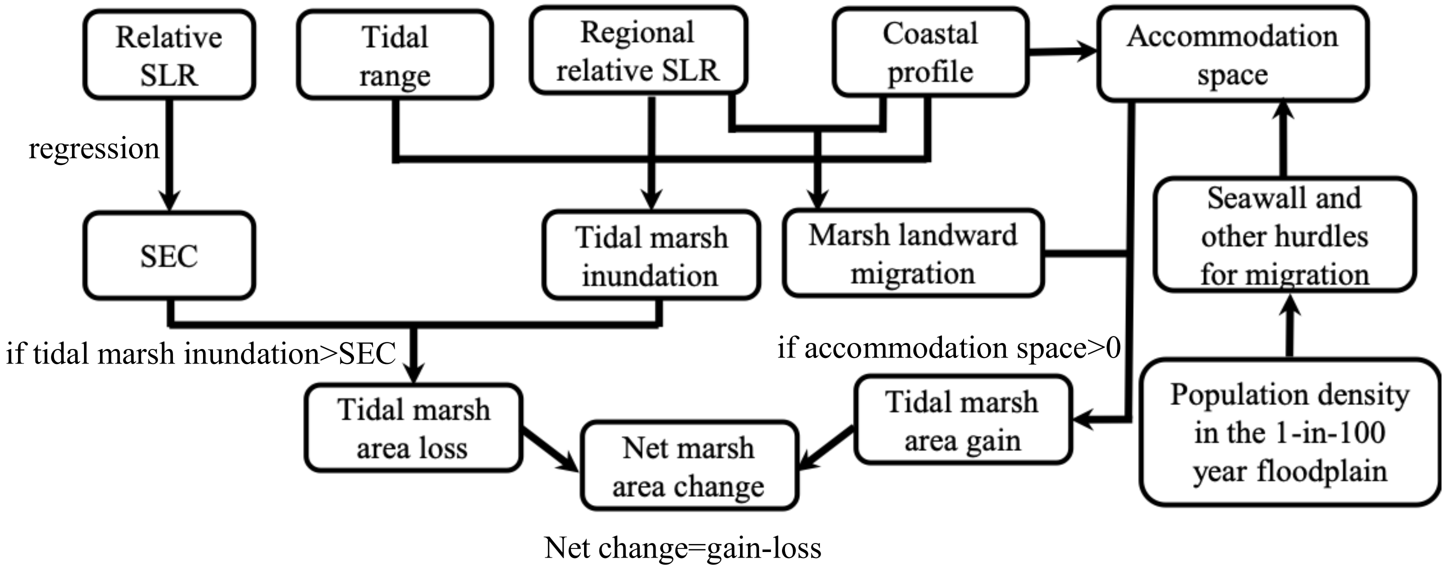

Fig. 2 A diagram describing the integrated mathematical modelling framework for simulating the response of tidal marshes to sea level rise. SLR denotes sea level rise. SEC denotes surface elevation change.

relationship between SEC and SAR, and the relationship between SEC/SAR and total suspended matter, using a linear regression.

In addition to the above analyses, we examined the difference in SEC/SAR among 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 among 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.

2.4 Modelling the response of tidal marshes to SLR

We evaluated the response of tidal marshes to future SLR using an integrated mathematic model, which considers both the area gain and loss for tidal marshes (See the mathematic 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.

Landward migration of tidal marshes is facilitated by the available accommodation space between mean seal 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. We 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 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).

With increasing sea levels, both the upper and lower boundaries of marsh migration shift, likely resulting in marsh inundation if marsh SEC cannot keep pace with RSLR. We estimated global SEC in tidal marshes from RSLR (precision: 20km) since our dataset cannot cover all the tidal marshes. Specifically, we used the marsh SEC data collated from the references and associated RSLR data under different SLR scenarios to establish the relationships between marsh SEC and RSLR for different scenarios. The established relationships were used to estimate SEC of global tidal marshes, which was combined with RSLR and the coastal profile to determine marsh loss to inundation. 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 area change is the difference between marsh area gain and loss.

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 integrated mathematical 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). The cross-validation procedure shows that the percentage of variance explained by the models are (mean, SE) 30.5% (2.7%) and 51.3% (14.1%) for SAR and SEC, respectively. The best-fit model shows that SAR is driven by suspended matter, precipitation, latitude, tidal range, tidal frequency and sea ice (Fig. 3). The model suggests that suspended matter and precipitation are the dominant drivers and together account for 71.6% of the relative influences on SAR. The best-fit model for SEC shows that it is driven by precipitation, suspended matter, latitude, tidal range and tidal frequency. Again, precipitation and suspended matter are the dominant drivers and account for 66.6% of the relative influences on SEC. Further exploration shows that there are significant relationships between both SAR/SEC and suspended matter (Supplementary Material Fig. S3a and b). There is a strong positive relationship between SEC and SAR (Supplementary Material Fig. S3c, R^2=0.82, p<<0.001, F test). Based on this relationship, we estimated surface elevation change in global saltmarshes (Fig. 4). 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 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.

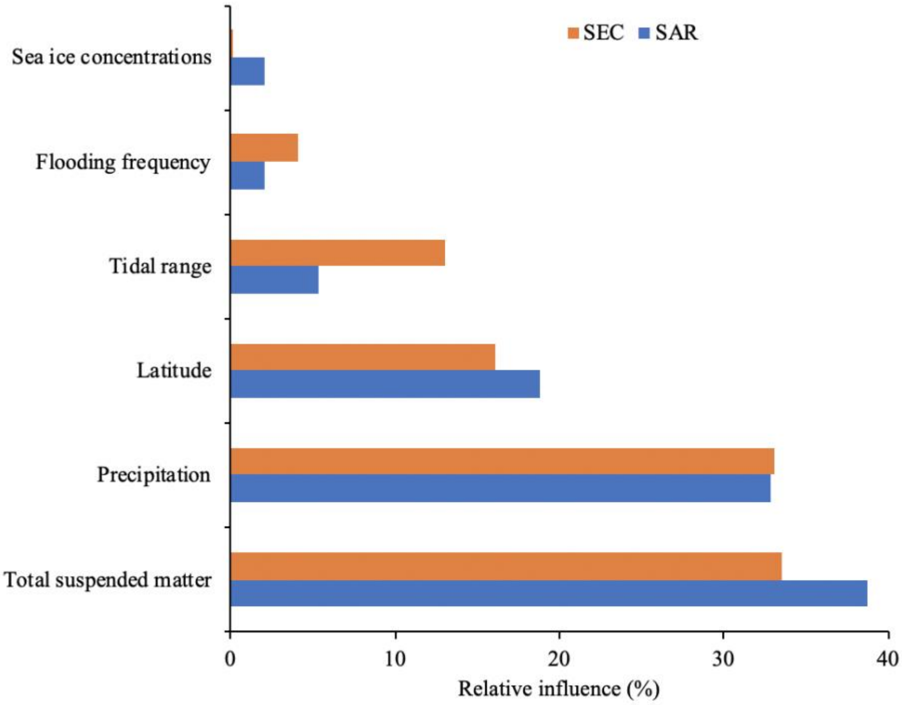

Fig. 3 Relative influences of the explanatory variables on saltmarsh sediment accretion rates and surface elevation change. The orange and blue bars represent the relative influences on sediment accretion rates (SAR) and surface elevation change (SEC), respectively.

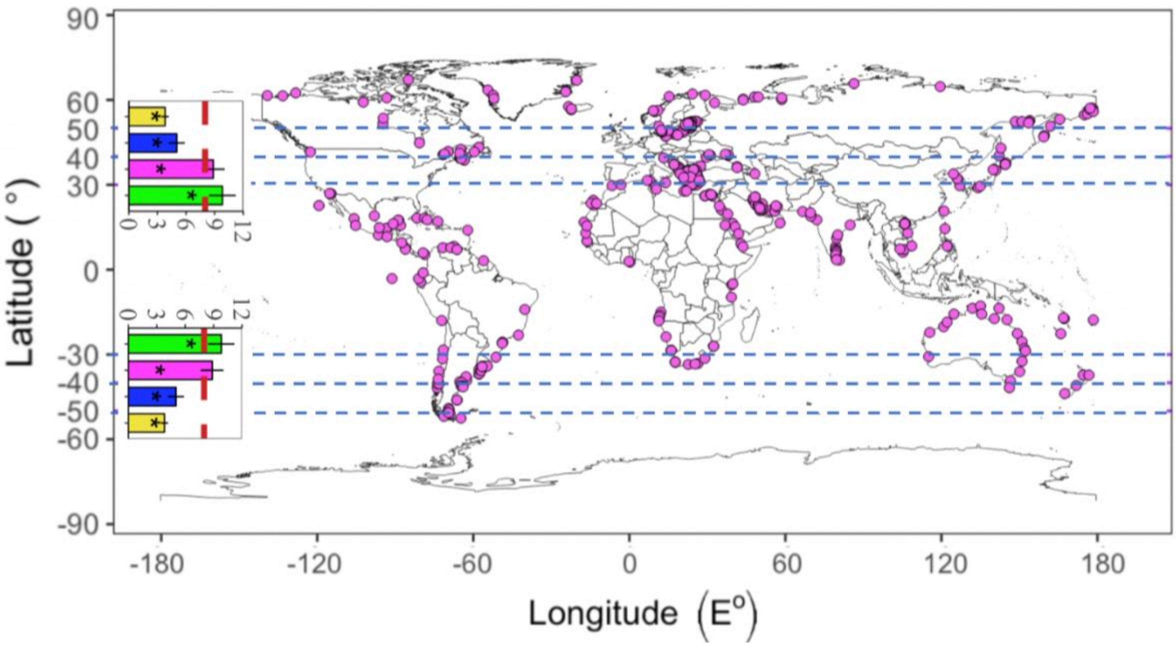

Fig. 4 Surface elevation change of global saltmarshes at latitudinal ranges. The background figure shows the global distribution of saltmarshes, depicted by pink dots. The error bar charts show the estimated SEC (mm yr^{-1}) based on observations of sediment accretion rates at latitudinal ranges <30°, 30-40°, 40-50° and >50° (n=198, 275, 451 and 283, respectively), as denoted by the blue dashed lines. The stars in each error bar denote the representative SEC at each latitudinal interval. The red dashed lines in the error bar charts are the lower limit of SLR for RCP 8.5 at medium confidence to 2100.

We 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 among tidal marshes inundated at different frequencies (Fig. 5c and d), and among geomorphologic settings (Fig. 5a 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=46300, $p<<0.001$) 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=32904, $p<<0.001$; W=16924, $p<<0.001$), 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 = 47690, $p<<0.001$, Fig. 5e) and plant types (W = 20133, p=0.0028, Supplementary Material Fig. S4a), while SECs do not vary significantly with species richness (W = 778, p=0.43, Fig. 5f). 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 almost double those at monospecific sites (5.62 ± 0.32 mm yr^{-1}). In addition, there are significant differences in sediment accretion rates among locations (W = 7179, p=0.0004, Supplementary Information Fig. S4b).

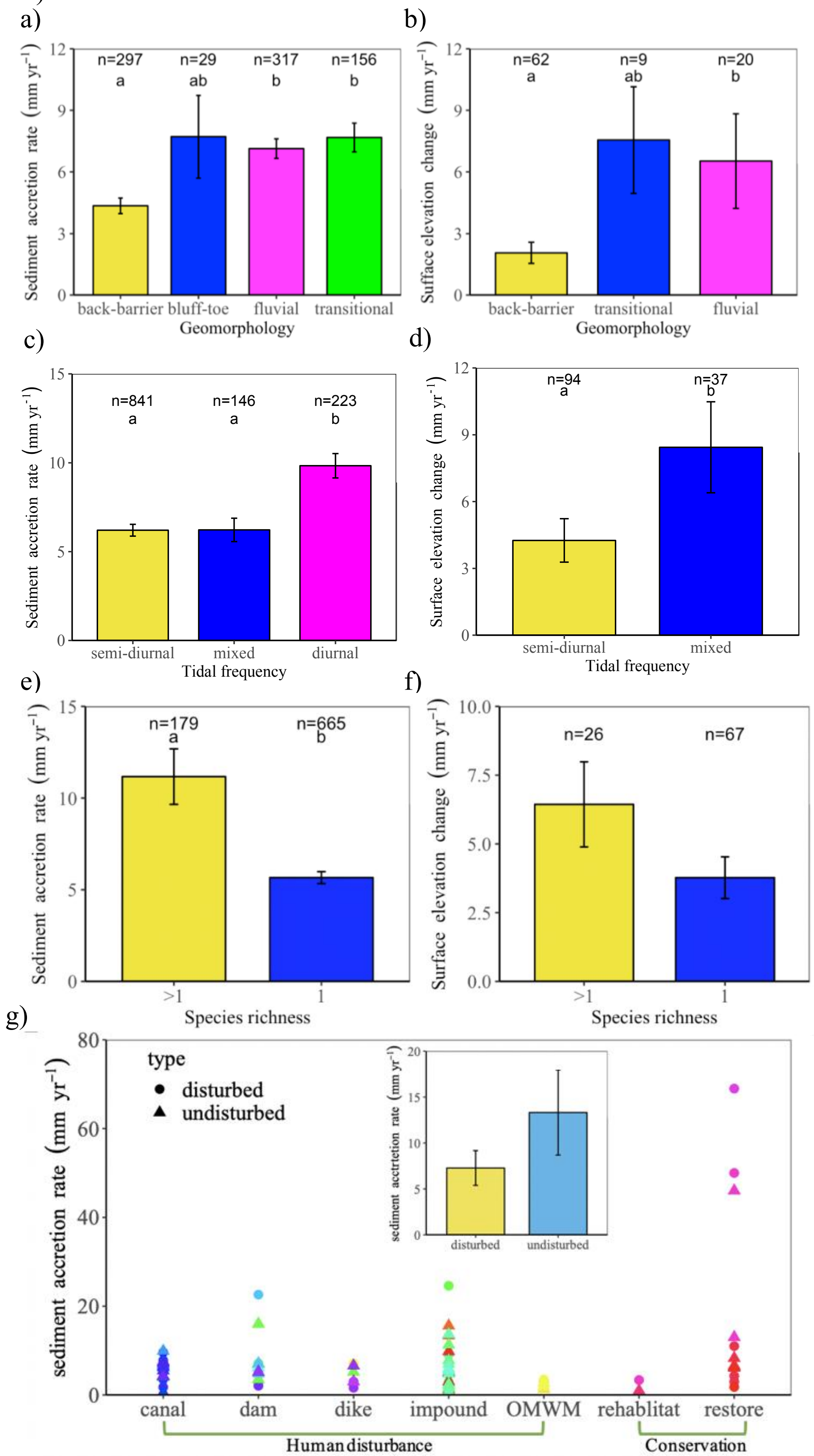

Fig. 5 Variation of sediment accretion rate and/or surface elevation change with natural and anthropogenic factors. (a) and (b), geomorphology; (c) and (d), tidal frequency; (e) and (f), species richness; (g) human activities. Human activities include human disturbance and conservation activities. OMWM denotes open marsh water management. Different sites in (g) are depicted by different colours. Significance values are given in the text.

3.2 Temporal changes in sediment accretion rates

Sediment accretion rates fluctuate over different time scales, ranging from sub-decadal to centennial scales. There is significant difference in sediment accretion rates between decadal and sub-decadal scales (Supplementary Information Fig. S5, 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. 5g, 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. Among sites affected by human disturbances, impoundment is the most frequently reported activity. SAR at impounded sites are significantly higher than those of natural sites (Fig. 5g, paired t test, $t=-2.1$, $p=0.047$, $df=23$).

3.4 The resilience of tidal marshes to SLR

Significant relationships exist between tidal marsh SEC and RSLR under SLR scenarios of SLR RCP2.6 (R^2=0.33, p<0.05, F test), RCP4.5 (R^2=0.21, p<0.05, F test) and RCP8.5 (R^2=0.34, p<0.05, F test) (Fig. 6). These relationships are significant to estimating global SEC since we cannot collect SEC from all the tidal marshes while global RSLR data are available at relatively high precisions. The relationships were incorporated into the modelling framework (Fig. 2) to simulate the response of tidal marshes to SLR. We 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. 7). 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 through nature-based adaptation solutions. Globally, under human adaptation scenario 1, tidal marsh areal change fluctuates between -7% and -5.3% for RCP2.6, and between 58.2% and 62.7% for RCP8.5. Under scenario 2, tidal marsh areal change fluctuates between -24.4% and -7% for RCP2.6, and between 36.3% and 58.2% for RCP8.5. Scenario 3 would see tidal marsh areal change fluctuate between -30.8% and -24.4% for RCP2.6, and between 14.1% and 36.3% for RCP8.5.

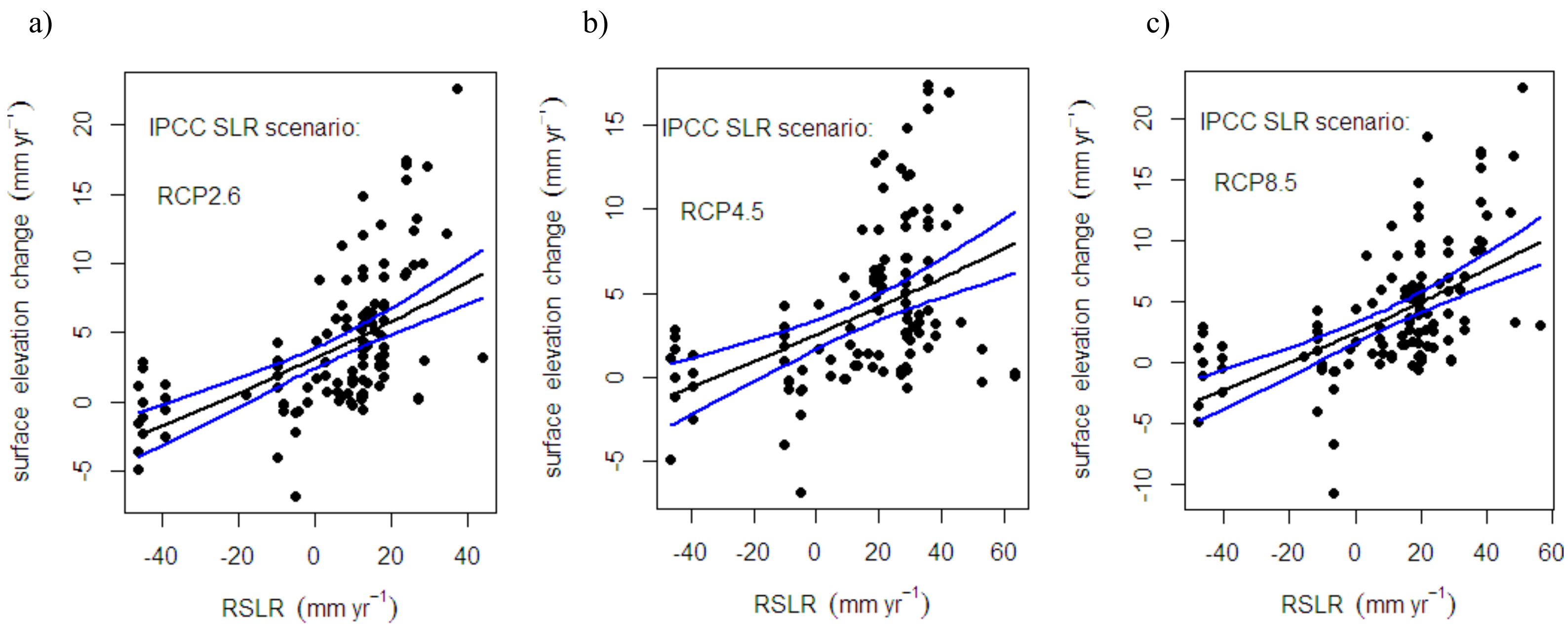

Fig. 6 The relationships between tidal marsh surface elevation change and relative sea level rise under different scenarios of future sea level rise. SEC is estimated by RSLR under IPCC SLR scenarios of a) RCP 2.6 as $SEC=10^{0.001\pm0.0002RSLR+1.635\pm0.004}-40$ ($R^2=0.33$, $p<0.05$, F test), b) RCP4.5 as $SEC=10^{0.001\pm0.0002RSLR+1.629\pm0.004}-40$ ($R^2=0.21$, $p<0.05$, F test), and c) RCP 8.5 as $SEC=10^{0.001\pm0.0002RSLR+1.627\pm0.004}-40$ ($R^2=0.34$, $p<0.05$, F test). RSLR denotes relative sea level rise. IPCC denotes International Panel on Climate Change.

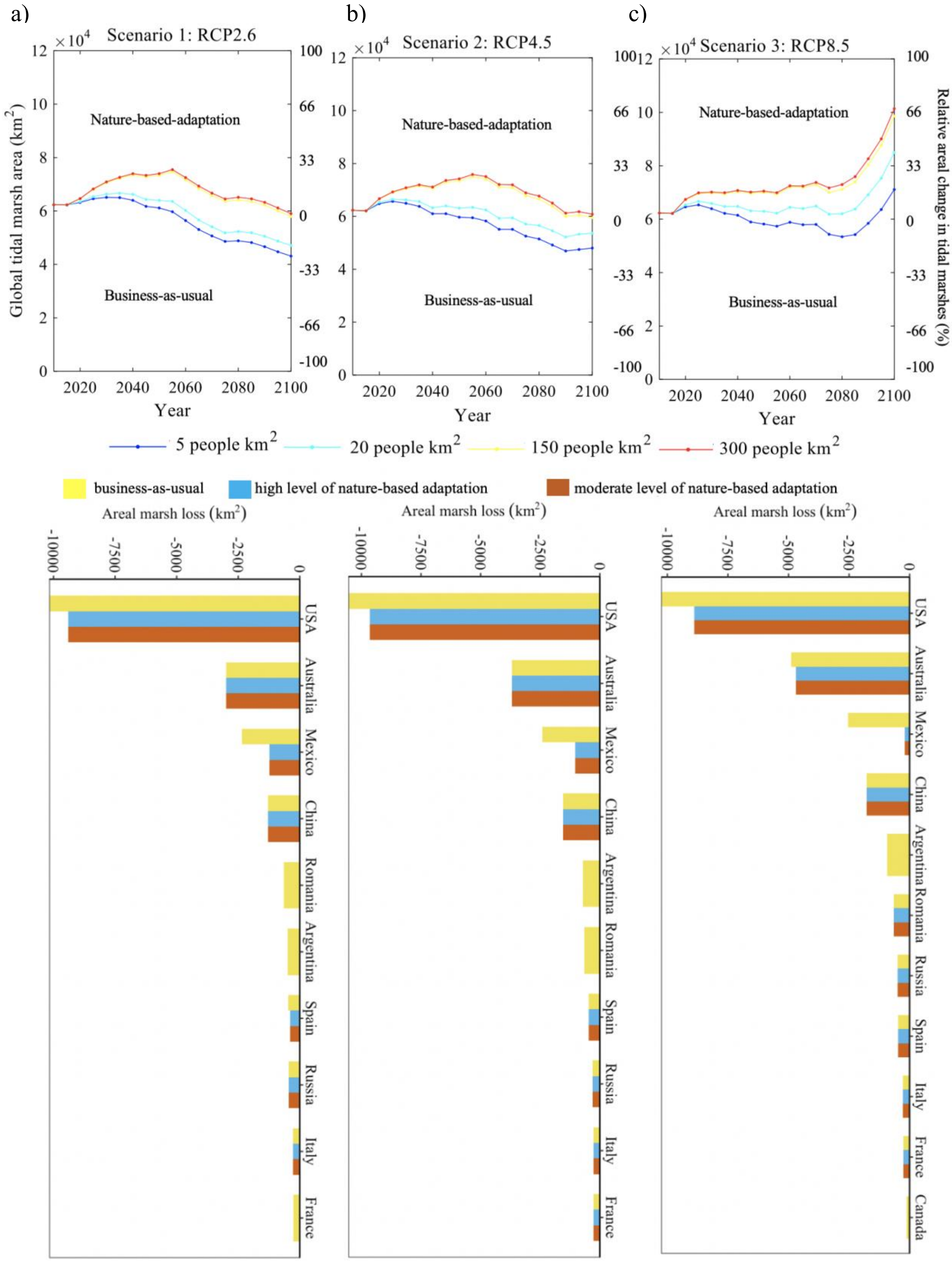

Fig. 7 Changes in global tidal marsh area under different scenarios of sea level rise and thresholds of coastal population density. The projections are made on three SLR scenarios:

(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.

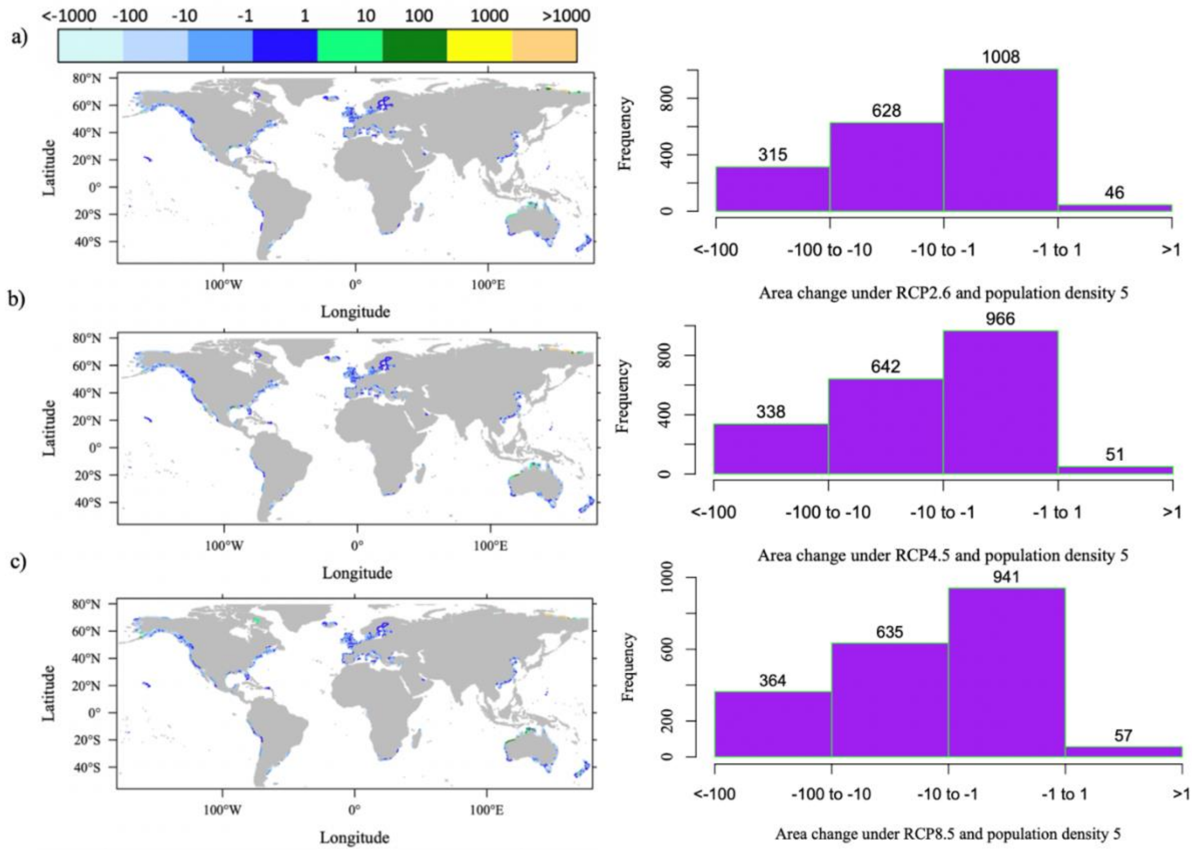

Fig. 8 Frequency of absolute changes in tidal marsh area by 2100 under different scenarios of sea level rise and coastal population density of 5 people km^{-2}. Net wetland area change is estimated under different IPCC SLR scenarios of (a) RCP 2.6; (b) RCP 4.5; and (c) RCP 8.5.

We further evaluated the resilience of tidal marshes to SLR by estimating spatially-explicit tidal marsh area changes by 2100 under different RCP scenarios (Fig. 8). At the lower boundary of the business-as-usual scenario (5 people km^{-2}), we estimated the hotspots of tidal marsh loss (>100 km^2) would account for 66.8%, 67% and 68.2% 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 Russia, Italy and France) (Fig. 7).

4 Discussion

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), as major storm surges can erode tidal marsh edges and surfaces (Nyman et al., 1993). 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. 5a). 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), including the upper intertidal region where sediment accretion is most significant and noticeable, and larger accommodation space available for increasing elevation. Further, smaller tidal range means lower tidal energy, which limits inorganic sediment input from marine sources, whereas macro-tides generate strong currents, which resuspend nearshore sediments and transport them onto tidal marsh surfaces (Hensel et al., 1999). Thus, macrotidal marshes (tidal range> 4m) are more resilient to changes in the rate of relative SLR (RSLR) than microtidal marshes (tidal range< 2m) [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, changes with latitude (Kirwan et al., 2009). Both tidal marsh plant 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). 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. Plant types with different morphology and complexity may enhance the retention of sediments. 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). Some human activities (e.g. disturbance) have negative effects on SAR whereas others (e.g. restoration) do not.

Our results forecast that the areal extents of tidal marshes all decline (-30.8% to -7%) in the lowest SLR scenario but all increase (14.1% to 62.7%) 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). 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.

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. The previous projection was criticized for estimating the adaptation ability of coastal wetlands to SLR using a wetland adaptation score defined in terms of sediment surplus or deficit, which is mistakenly represented by suspended sediment concentration (Törnqvist et al., 2019). Tidal marshes are highly efficient in sequestering CO_2 from the atmosphere and accumulate carbon in sediments for millennial (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. This means that tidal marshes will contribute to the climate neutral target and 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 2.8-3.5% lower, accounting for 64-64.7% of total marsh areal losses under different SLR scenarios (Supplementary Material Fig. S6). This finding highlights the effectiveness of nature-based adaption for shrinking hotspots of tidal marsh loss.

Our method cannot precisely account for the fate of tidal marshes, since 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. We 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. However, our mathematical 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.

Data availability

The satellite data that support the findings of this study are downloaded from http://hermes.acri.fr/index.php?class=archive (total suspended matter) and https://www.metoffice.gov.uk/hadobs/hadisst/ (sea ice), https://www.esrl.noaa.gov/psd/data/gridded/data.gpcc.html and http://catalogue.ceda.ac.uk/uuid/3f8944800cc48e1cbc29a5ee12d8542d (precipitation). Satellite and literature data are available in 'figshare' with the identifier doi: 10.6084/m9.figshare.7545212 or upon reasonable request sent to the corresponding author. Computer code is available from Xiaoguang Ouyang upon reasonable request.

Supplementary Material

Fig. S1

Fig. S2

Fig. S3

Fig. S4

Fig. S5

Fig. S6

Table S1

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Declaration of 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: