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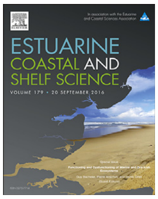

Salt marsh persistence is threatened by predicted sea-level rise

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ABSTRACT

Salt marshes buffer coastlines and provide critical ecosystem services from storm protection to food provision. Worldwide, these ecosystems are in danger of disappearing if they cannot increase elevation at rates that match sea-level rise. However, the magnitude of loss to be expected is not known. A synthesis of existing records of salt marsh elevation change was conducted in order to consider the likelihood of their future persistence. This analysis indicates that many salt marshes did not keep pace with sea-level rise in the past century and kept pace even less well over the past two decades. Salt marshes experiencing higher local sea-level rise rates were less likely to be keeping pace. These results suggest that sea-level rise will overwhelm most salt marshes' capacity to maintain elevation. Under the most optimistic IPCC emissions pathway, 60% of the salt marshes studied will be gaining elevation at a rate insufficient to keep pace with sea-level rise by 2100. Without mitigation of greenhouse gas emissions this potential loss could exceed 90%, which will have substantial ecological, economic, and human health consequences.

1. Introduction

Despite their ecological importance and economic value (Barbier et al., 2011), herbaceous salt marshes globally have been subjected to substantial human impacts and are rapidly losing area (Gedan et al., 2009; Kennish, 2001). While the impacts of many natural and anthropogenic stressors are understood, climate change now threatens salt marsh persistence in unprecedented ways (Craft et al., 2009). Salt marshes are built by salt- and inundation-tolerant plants that exist in a limited elevation range relative to mean sea level (Bertness and Ellison, 1987). Due to limits in the inundation tolerance of these plants, salt marshes must gain elevation (accrete) at a rate equal to or exceeding relative sea-level rise (SLR) to resist drowning and conversion to unvegetated mudflats (Redfield, 1965). Salt marsh ecosystems have previously survived substantial changes in sea level such as during past glaciations (Redfield, 1972). However, the persistence of these systems with SLR has relied on land being available that could be colonized by salt marsh plants as the sea level changed. Human modification and development of shorelines worldwide has limited the area available for upland migration by salt marshes as sea level rises, and coastal populations and development pressures continue to grow. Consequently, many salt marshes will be unable to migrate inland (Torio and Chmura, 2013). Understanding the likely fate of the current area of salt marshes is of critical importance.

Salt marsh elevation gain is driven by a combination of sediment deposition on the marsh surface and the accumulation of peat, which is controlled by belowground plant growth and decomposition (Redfield, 1965, 1972). As SLR rates increase (Stocker et al., 2013), it is not clear if sufficient elevation gain will be possible for salt marshes to keep up with those rates. Areal loss has already been predicted for salt marshes with low sediment supply under high SLR scenarios (Schile et al., 2014; Stralberg et al., 2011). In fact, sediment supply to many salt marshes is declining, accelerating the rate of loss (Weston, 2014). The potential risk for salt marshes with SLR may be further impacted by other elements of climate change

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such as storm frequency (Schuerch et al., 2013) and rising CO_2 and temperature (Charles and Dukes, 2009; Kirwan and Blum, 2011; Kirwan et al., 2009). In spite of the complexity of possible impacts, climate change and its effects (particularly SLR) are expected to decrease the potential for persistence of many salt marshes (Kirwan et al., 2010).

While anthropogenic increases in SLR have occurred over the past century, even more dramatic increases are expected by 2100 (Stocker et al., 2013). One of the Intergovernmental Panel on Climate Change (IPCC) representative concentration pathways (RCPs) with the highest CO_2 concentrations (RCP8.5) predicts a dramatic increase in sea level, corresponding with a SLR rate as high as 16 mm y^{-1} by the end of the century (Stocker et al., 2013). Even the most conservative pathway (RCP2.6) would still result in a rate of SLR of up to 7 mm y^{-1} (Stocker et al., 2013). While the potential for salt marsh loss with SLR is widely recognized (Kirwan et al., 2010; Kirwan and Megonigal, 2013; Morris et al., 2002; Orson et al., 1985; Reed, 1995), the extent and magnitude of loss to be expected is uncertain. Potential salt marsh responses can be evaluated now by taking advantage of existing long-term records of change in marsh elevation in response to SLR rates. In addition, local and regional variation in relative SLR rates (driven by isostatic rebound, groundwater withdrawal, ocean circulation, and other factors) provides an opportunity to explore accretion in salt marshes currently experiencing different SLR rates. Collectively, these existing records can provide a lens to explore how salt marshes have responded to recent sea level perturbations and how they might fare in the future.

While patterns in salt marsh carbon sequestration have been examined (Chmura et al., 2003) and accretion data have been used to assess salt marsh carbon storage (Ouyang and Lee, 2014), few syntheses of accretion rates relative to SLR and marsh persistence have been conducted (Kirwan et al., 2016). Here, an analysis of salt marsh elevation change was conducted to investigate where and when salt marsh drowning (i.e., elevation gain rate less than the rate of SLR) has occurred and what future losses might be expected. Using a standard meta-analytic approach, data on rates of local SLR and salt marsh elevation change were compiled from 142 records from 54 publications (Table S1) to provide a perspective on future herbaceous, temperate-zone salt marsh loss under multiple SLR scenarios. Mangroves and other ecosystem types were not included in the analysis. We examined accretion rates observed in the field using long-term averages (data from ^{210}Pb and ^{137}Cs radiometric dating (Appleby, 2008), average record length of 47.9 ± 3.1 years) and recent records (data from surface elevation tables (Cahoon et al., 2002), average record length of 5.2 ± 0.3 years). We considered these records both together and separately for the low marsh (flooded daily by tides) and the higher marsh (flooded less frequently), as controls on elevation change can differ between these zones (e.g., due to sediment capture, Fig. S1).

2. Methods

2.1. Literature search and article inclusion criteria

We surveyed the literature for papers reporting salt marsh accretion rates using radiometric, surface elevation table, or sediment deposition methods using systematic review and meta-analysis guidelines (Moher et al., 2009). We searched the literature using the National Park Service IRMA and the ISI Web of Science databases for articles related to salt marsh elevation change to include in this study (cutoff date: June 6, 2013), using combinations of relevant key words (Table S2). After removing duplicates, there were 2400 results for WOS and 1540 results for NPS. We conducted preliminary filtering of the papers by reading the titles and abstracts of each article, retaining all papers with topics that were not obviously irrelevant. We also excluded papers that were written in languages other than English or where only the abstract was published. Modeling or laboratory studies without field data were excluded. A total of 468 relevant articles were identified, and the full text each of those was obtained, read and searched for data on salt marsh accretion rates and SLR. Our secondary filtering excluded papers that did not specify at a minimum the accretion rate, methods used, study duration, and in which marsh habitat the data were collected (low or high elevation marsh zones). Papers with surface elevation table or radiometric dating data records of less than 3 years were also excluded.

2.2. Data collection

We extracted data from the final pool of relevant studies as defined above. We aggregated the data from these papers, capturing for each marsh the study location, the mean accretion rate for each marsh, the timing and duration of the study, the local reported SLR rate, the marsh habitat, the tidal range, dominant vegetation species and other site characteristics as available. If the study was conducted at an elevation above the low marsh but not explicitly in the high marsh (i.e., in the mid-marsh), it was classified as from the high marsh zone for our analyses. Overall mean accretion rates for each site were either provided directly in the text, figures or captions, or were calculated by us when raw data or replicates were provided. We treated data from one marsh habitat at one study time as a single observation. For example, if low and high marsh data were provided for one site in one study, each was included separately in our study. If one study reported two accretion rates in the low marsh covering the same time period, then we took the mean of those values and treated the mean as a single observation. If SLR was provided as a total amount of rise spanning a range of dates, we divided that total by the number of years to calculate the SLR rate.

We collected accretion data calculated using three method types: (1) radiometric dating, (2) surface elevation tables and (3) marker horizons. Radiometric dating methods typically used deep marsh sediment cores that were sampled at regular intervals down the core and then ^{210}Pb, ^{137}Cs or both were quantified in each sample to calculate age of the core with depth. Surface elevation tables record elevation change using surface elevation measurements relative to a deep benchmark over multiple years, similarly integrating elevation change across both the surface and subsurface marsh. Marker horizon data measures the deposition of sediment on the marsh surface as measured over a material applied to the top layer of sediment, typically feldspar or glitter. Data from the first two method types were compared to SLR, as they are measures of elevation change, while the marker horizon data were used only as context for the other data since they do not include sub-surface and organic contributions to elevation change. It is possible that differences in the frequency and time since the occurrence of episodic events (e.g., hurricanes) could impact our interpretation of accretion rates and balances across our sites. However, we did not find a relationship between accretion rate (with a log (x+1) transformation applied for normality) and study length ($n = 97$; $y = 0.00036x + 0.71$, $P = 0.68$, $R^2 = 0.0018$) using linear regression. We also observed no relationship between accretion balance and tidal range for the different temporal scales in the low marsh (long-term: $n = 8$; recent: $n = 3$) and high marsh (long-term: $n = 32$; recent: $n = 7$).

2.3. Data analysis

We calculated accretion balance for each marsh as the mean accretion rate minus the local SLR rate as reported by that paper. We did not calculate an accretion balance for marshes for which only accretion rate was reported (without local SLR), though we did include those accretion rates in other data presentations (Figs. 1 and 2, Fig. S2) that did not include SLR data. Both SLR and accretion data were provided for 84 sites (as determined by radiometric dating and/or surface elevation table data). We compared the accretion rates by method and habitat type to the local SLR rates as provided in each paper, and compared all of the reported accretion rates to predicted future rates of SLR. The data included in our study were not equally available globally and reflect a geographic bias toward the northern Atlantic. Care should be taken in applying these results beyond the geographic scope of our work. Accretion rates less than zero are indicative of erosion.

We tested for relationships between accretion balance and SLR rate and tidal range using linear regression. We tested for differences in mean accretion balance between marsh habitat (low or high), study method (radiometric dating or surface elevation table), and vegetation (single species or multiple species) using t-tests. All statistical analyses were conducted in JMP (JMP, Version 10, SAS Institute Inc., Cary, NC, 1989–2007). The mean accretion balance for each marsh was mapped using Geographic Information Systems (ESRI ArcMap, version 10.2.2) to show the trends and variation in current marsh persistence across regions, with the background world map provided by the Global Self-consistent, Hierarchical, High-resolution Geography Database. Version 2.3.0. Paul Wessel, SOEST, University of Hawai'i, Honolulu, HI. Walter H. F. Smith, NOAA Geosciences Lab, National Ocean Service, Silver Spring, MD (accessed May 29, 2014).

Because the SLR data reported in the papers came from a variety of sources, we confirmed that the rates of SLR reported in the papers were consistent with other SLR records by comparing the papers' reported records to an existing long-term SLR rate dataset from the Permanent Service for Mean Sea Level [PSMSL] (Anonymous, 2014; Holgate et al., 2013). The PSMSL mean SLR rate data from all available stations were imported into a Geographic Information Systems (ESRI ArcMap, version 10.2.2) map to determine the nearest PSMSL station to each study site. We then compared the PSMSL long-term SLR rate record for the nearest station to the SLR rate reported for each paper. The average difference between the PSMSL and papers' reported rates was only 1.4 ± 0.1 mm y^{-1}, and there was a significant linear relationship between the reported rate of SLR and the PSMSL rate for the nearest station ($n = 84$; $y = 0.62x + 0.76$, $P = 0.0001$, $R^2 = 0.46$; square-root ($x+1$) transformation applied for normality). There was also a linear relationship (Fig. S3) between accretion balance calculated using the papers' reported SLR rates and the accretion balance calculated using the PSMSL rates ($n = 84$; $y = 0.88x + 0.25$, $P = 0.0001$, $R^2 = 0.78$). Based on these calculations using an external SLR data source, we concluded that use of the papers' reported rates was appropriate.

3. Results

The plant species composition of the marshes studied was reported in 70 of the records analyzed. Of these, 33 records were from plots containing only *Spartina alterniflora*, 16 were from plots containing only *S. patens*, and the remaining papers were from plots containing one or several of 21 species (Table S3). For these papers where plant species composition was reported, there was no difference in accretion rate or accretion balance observed between plots with one species ($n = 57$) versus multiple species ($n = 13$).

Salt marsh accretion varied among sites, but generally corresponded to rates that would be insufficient to keep pace with expected SLR rates. Recent rates of accretion ranged from −0.3–16 mm y^{-1}, but most were on the lower end of this range. More than 2/3 of the combined long- and short-term records had accretion rates less than 5 mm y^{-1} (Fig. 1a). Similar results were found when considering each data type independently (Fig. S2). Considering four different RCP scenarios, we expect that 60–91% of salt marshes studied will not be keeping pace with predicted SLR by the end of this century (Fig. 2). Predicted salt marsh loss varied among regions, but our ability to interpret this variation is limited by the small number of records in some regions and the lack of data available for others (Fig. 2).

Evidence of salt marshes' capacity to keep pace with SLR can be further examined by considering changes in ‘accretion balance’, which is the observed accretion rate subtracted from the local SLR rate. Accretion balance calculations indicate that insufficient accretion is occurring at many salt marshes to keep up with rates of SLR observed to date (Figs. 1b and 3). Among the nine salt marshes observed to have the highest rates of local SLR, eight are already not keeping pace, at an average rate of elevation loss of 3.9 ± 1.1 mm y^{-1} (Fig. 4). Examination of average accretion rates across salt marshes allows us to contrast different types of evidence from different time scales. On multi-decade timescales (based on radiometric dating records), on average the marsh accretion balance has been positive (i.e., salt marshes were accreting faster than SLR) in both the high and low marsh habitats, with accretion rates averaging 1.2 ± 0.38 mm y^{-1} greater than the rate of SLR (Fig. 5). However, more recent multi-year timescales (based on surface elevation table records) show accretion rates on average only 0.53 ± 1.3 mm y^{-1} greater than SLR (for the low and high marsh habitats combined), but less than SLR in low-marsh habitats (Fig. 5).

4. Discussion

The accretion rates observed in this study (Fig. 1a) are low relative to rates of SLR that are expected to occur by the end of this century (Stocker et al., 2013). Consequently, if recent rates of salt marsh elevation gain are maintained, then the majority of herbaceous salt marshes studied will begin to drown (Fig. 2). This would be true even with the most conservative RCP, whereas the most extreme RCP would correspond with drowning in 91% of salt marshes studied assuming their current accretion rates (Fig. 2). Insufficient accretion to keep pace with even present-day rates of SLR is widespread (Fig. 3). Still, it is conceivable that salt marshes might keep better pace in the future if ecogeomorphic feedbacks exist in which increasing SLR rates result in greater salt marsh accretion rates; this adaptive capacity could occur, for example, if increasing inundation leads to increases in sediment deposition (Cahoon and Reed, 1995) and plant productivity (Morris et al., 2002). We evaluated this possibility by examining elevation change with respect to local variation in the current rates of SLR, which can vary due to local factors including prevailing winds, ocean currents, gravitational forces, and isostatic conditions. We found no evidence for such a capacity to sufficiently respond to increased rates of SLR; the salt marshes in our study experiencing higher SLR rates were almost all already drowning (Fig. 4). Indeed, recent models predict a shift from positive to negative salt marsh organic matter accumulation at SLR rates of 4–4.5 mm y^{-1}, and based on those predictions this shift will occur after the year 2075 (Kirwan and Mudd, 2012). However, other studies suggest that for some sites this drowning will be compensated for by increased accretion with increased flooding frequency due in part to increased sediment deposition (Kirwan et al., 2010; Morris et al., 2002). However, for sediment-starved marshes where accretion is driven primarily by belowground biomass accumulation and at extreme rates of inundation any submergence-driven increase in accretion will likely be overwhelmed.

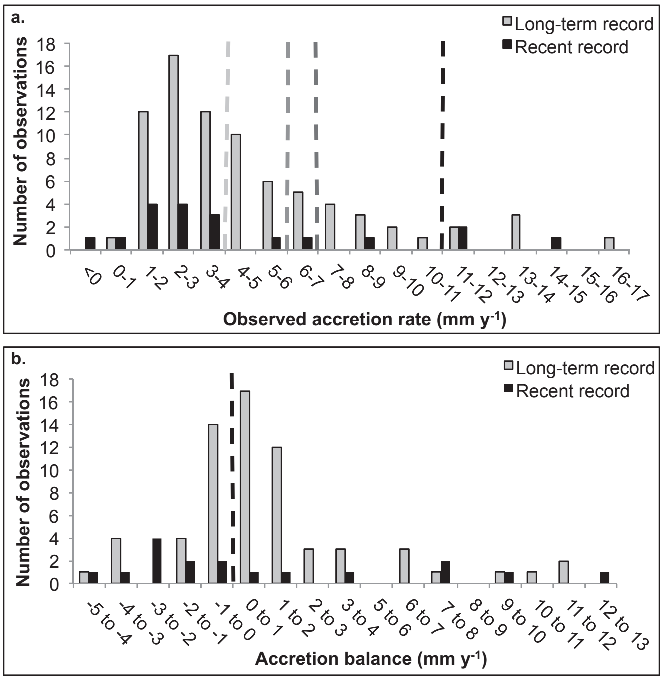

Fig. 1. (a) Histogram of recently observed accretion rates from saltmarshes worldwide, grouped by multi-decade, radiometric records (grey bars) and multi-year, surface elevation table records (black bars). Dashed lines indicate predicted rates of sea-level rise (rounded to the nearest whole number) under multiple representative concentration pathways (RCP2.6 in light grey, RCP4.5 in medium grey, RCP6.0 in dark grey and RCP8.5 in black) for the end of this century (2081–2100 (Stocker et al., 2013)). Median values for the range associated with each RCP are used. (b) Histogram of accretion balances (accretion rate − sea-level rise rate) for the same categories. Dashed black line shown at zero, such that observations to the left of the line represent salt marshes that are not keeping pace.

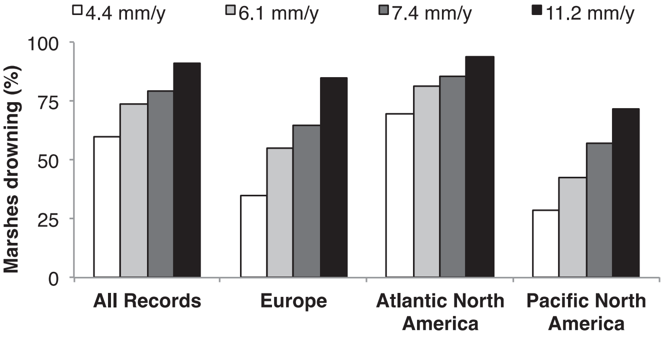

Fig. 2. Percentage of marshes drowning under predicted rates of sea-level rise based on the average of current accretion rates by region (All records, n = 98; Europe, n = 20; Atl. N. America, n = 69; Pac. N. America, n = 7; Australia, n = 2). Drowning is shown for multiple IPCC scenarios (RCP2.6 shown in white at 4.4 mm y^{-1}, RCP4.5 shown in light grey at 6.1 mm y^{-1}, RCP6.0 shown in dark grey at 7.4 mm y^{-1}, and RCP8.5 shown in black at 11.2 mm y^{-1}, from left to right) for the end of this century (2081–2100). Two records from Australia not shown separately were included in the presentation of all records.

Differences in accretion balance between long-term and short-term records suggest that a tipping point may have already been reached. On longer timescales salt marshes have been keeping pace; however, recent records show a lower accretion balance, and even that a negative accretion balance has already been reached for low-marsh habitats (Fig. 5). While some of the differences between long and short-term records might be due to the methods used (i.e., radiometric dating vs. surface elevation tables), the direction of the change is consistent with differences observed for two salt marsh areas where both types of data are available. In both cases, the long-term accretion rates were higher than the short-term, more recent rates (Roman et al., 2007). In the first case, the long-term rate was 2.2 mm y^{-1} while the corresponding recent rate was 2.08 mm y^{-1}. In the second case, the long-term rate was 4.2 mm y^{-1} while the corresponding recent rate was 2.04 mm y^{-1} (Roman et al., 2007). While other explanations are possible, the shift in accretion balance between long and short-term records is consistent with the interpretation of increased salt marsh drowning due to increasing SLR rates over the past several decades. However, additional research is needed on the comparability of these methods of accretion measurement.

The severity of the impact of SLR on salt marsh loss will depend upon a balancing of driving factors. For example, tidal range may impact the vulnerability of a given site; microtidal salt marshes may be more sensitive to rising sea level than macrotidal sites (Friedrichs and Perry, 2001; Kirwan and Guntenspergen, 2010). Alteration of sediment supply to salt marshes through damming and land-use or hydrological modifications can also decrease accretion (Weston, 2014). Increasing storm frequency may lessen the risk for some sites by increasing sediment supply and thus elevation gain through sedimentation (Schuerch et al., 2013), however storms can also cause substantial erosion especially along the salt marsh seaward edge. Other effects of climate change may also influence salt marshes' capacity to keep pace, but sometimes in opposing ways. For example, rising CO_2 and temperatures could increase plant growth, which could help to increase salt marsh elevation (Charles and Dukes, 2009; Kirwan et al., 2009). However, rising temperatures will also increase belowground decomposition, which would decrease salt marsh elevation (Kirwan and Blum, 2011). These changes will be further complicated by shifting plant phenology, which may impact above and belowground growth allocation (and thus accretion) (Crosby et al., 2015).

Our findings suggest by the end of this century that 60–91% of the salt marshes studied could be losing the race against IPCC-predicted rates of SLR. Some studies predict increases in sea level greater than IPCC scenarios (Jevrejeva et al., 2010; Vermeer and Rahmstorf, 2009), suggesting that these high levels of predicted salt marsh drowning may even be conservative. It is important to note, however, that these estimates do not consider current elevation capital of the salt marshes studied (Cahoon and Guntenspergen, 2010); some sites may have a higher-elevation starting point than others and thus will persist longer under unsustainable accretion rates before they are lost. Once the accretion rate of a given marsh is exceeded by the SLR rate, the time required for that marsh to drown completely could take decades or longer and will depend on local factors including the starting elevation and elevation range of the marsh, species composition, as well as the degree to which it is constrained from upland migration.

There are strategies that if enacted could help to preserve the spatial extent or in-place accretion rate of salt marshes. Allowing salt marshes to expand inland to higher elevations, by preserving terrestrial migratory space, could help to counter some marsh loss, but this is only feasible currently in places that lack a developed infrastructure and where the upland slopes gradually. Avoiding additional decreases in salt marsh sediment supply (Weston, 2014) by reconnecting them with their upland sediment sources (e.g., dam and impoundment removals) also may mitigate the rate of drowning for sediment-starved systems. While the net impact of nutrients on salt marshes is debated, decreasing eutrophication may also help decrease habitat loss (Deegan et al., 2012). Finally, reducing greenhouse gas emissions to be consistent with IPCC scenario RCP2.6 instead of RCP8.5 could potentially save 30% of the

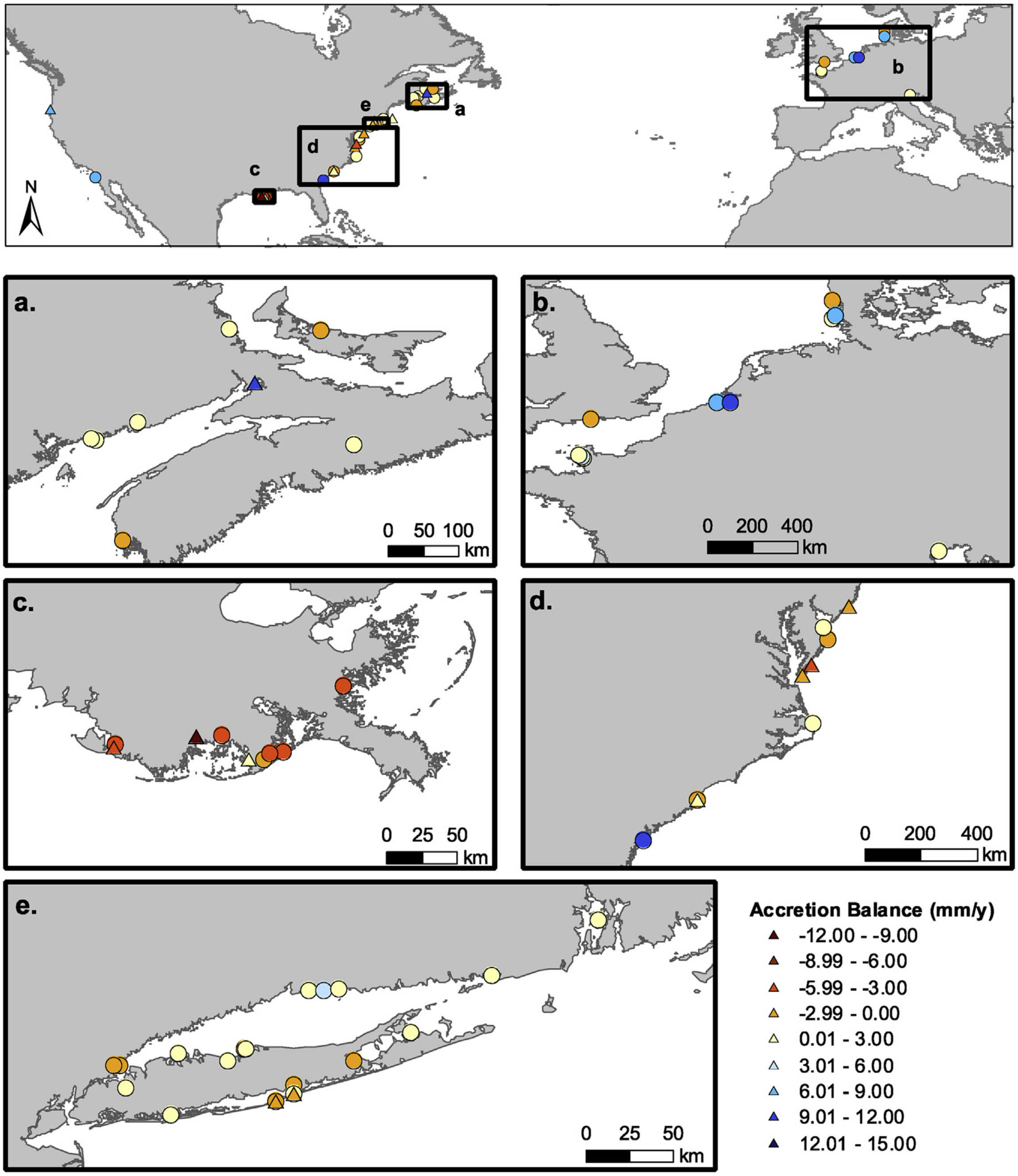

Fig. 3. Accretion balance (reported accretion rate minus local sea-level rise rate) data for salt marshes in the U.S. and Europe, with insets of (a) the Bay of Fundy and adjacent areas (Canada), (b) the North Sea and adjacent areas (Europe), (c) the Gulf coast of Louisiana (U.S.), (d) the mid-Atlantic and adjacent areas (U.S.), and (e) Long Island Sound (U.S.). Accretion balance is indicated by symbol color and method is indicated by shape (circles represent radiometric dating data and triangles represent surface elevation table data).

salt marshes studied from being at risk to drowning by the end of this century.

However, even if all of these strategies are enacted, many salt marshes are already at risk. The loss of these ecosystems is likely to have cascading effects on the health of people and other species and ecosystems (Barbier et al., 2011; Shepard et al., 2011). For example, due to the physical protection provided by salt marshes, coastal communities should expect increased storm impacts. Furthermore, the loss of salt marshes expected with SLR will contribute to global carbon cycling and further drive climate change because these ecosystems serve as significant carbon sinks (Chmura et al., 2003). In fact, salt marshes have higher carbon accumulation rates per unit area than mangroves, seagrass beds, or terrestrial forests (Ouyang and Lee, 2014), thus making the mitigation of their loss all the more critical. As the value of salt marshes to people becomes increasingly understood and acknowledged, the potential loss of these systems within this century will present exceptional management challenges.

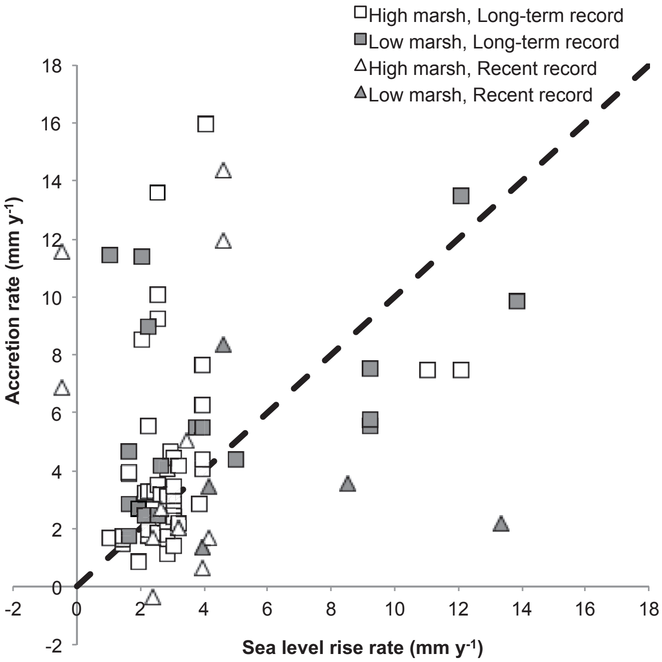

Fig. 4. Accretion rates for the long-term (squares) and recent (triangles) records in the low (grey) and high (white) marsh experiencing different local sea-level rise rates. The black dashed line shows the line of equality between sea-level rise and accretion rates. Points falling below the line indicate marshes where accretion rate is not keeping pace with sea-level rise.

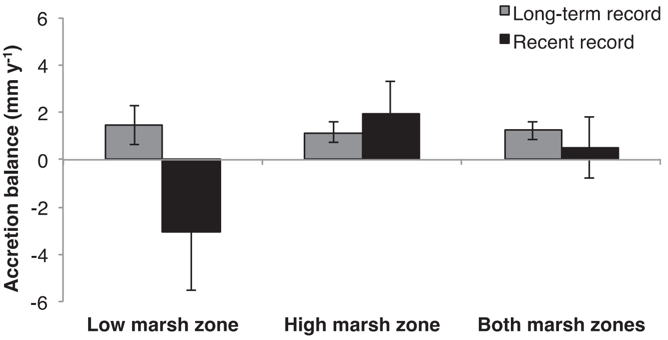

Fig. 5. Accretion balance in the low marsh (long-term: n = 24, recent: n = 5), high marsh (long-term: n = 55, recent: n = 14), and aggregated across both (long-term: n = 79, recent: n = 19). Long-term and recent records were significantly different for only the low marsh (*t*-test, $P = 0.026$). Error bars represent standard error.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.ecss.2016.08.018.

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