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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