Sediment supply explains long-term and large-scale patterns in saltmarsh lateral expansion and erosion

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Key Points:
- Sea level rise alone does not explain marsh lateral changes over the past 150 years
- Sediment flux is by far the strongest indicator of long-term lateral changes in salt marsh extent
- Small increases in fetch length may boost marsh expansion through stimulating wind-driven sediment transport onto marshes

Supporting Information:
- Supporting Information S1

Correspondence to:
C. J. T. Ladd,
c.ladd@bangor.ac.uk

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Sediment Supply Explains Long-Term and Large-Scale Patterns in Salt Marsh Lateral Expansion and Erosion

Cai J.T. Ladd[1,2], Mollie F. Duggan-Edwards[1], Tjeerd J. Bouma[3], Jordi F. Pagès[1,4,5], and Martin W. Skov[1]

[1]School of Ocean Sciences, Bangor University, Menai Bridge, UK, [2]Department of Geography, Swansea University, Swansea, UK, [3]Department of Estuarine and Delta Systems, Royal Netherlands Institute for Sea Research (NIOZ), Utrecht University, Yerseke, The Netherlands, [4]Departament de Biologia Evolutiva, Ecologia i Ciències Ambientals, Universitat de Barcelona, Barcelona, Spain, [5]Centre d'Estudis Avançats de Blanes (CEAB-CSIC), Blanes, Catalonia, Spain

Abstract Salt marshes often undergo rapid changes in lateral extent, the causes of which lack common explanation. We combine hydrological, sedimentological, and climatological data with analysis of historical maps and photographs to show that long-term patterns of lateral marsh change can be explained by large-scale variation in sediment supply and its wave-driven transport. Over 150 years, northern marshes in Great Britain expanded while most southern marshes eroded. The cause for this pattern was a north to south reduction in sediment flux and fetch-driven wave sediment resuspension and transport. Our study provides long-term and large-scale evidence that sediment supply is a critical regulator of lateral marsh dynamics. Current global declines in sediment flux to the coast are likely to diminish the resilience of salt marshes and other sedimentary ecosystems to sea level rise. Managing sediment supply is not common place but may be critical to mitigating coastal impacts from climate change.

Plain Language Summary Salt marshes are valuable ecosystems for human societies and are especially vulnerable to losses caused by human activity and climate change. Little is known about how the size of marshes has changed in response to disturbance over large- and long-term scales. We used historical maps and aerial photographs to capture 150 years of change in marsh area extent in 25 estuaries and ca. 100 marshes across Great Britain. We then related the rates of marsh change to existing data on hydrology, biology, climate, sediment supply, and other variables, to find out which elements best explained patterns of erosion and expansion for the period between 1967 and 2016. We found a shift from long-term marsh erosion in the southeast to long-term marsh expansion in the northwest of Great Britain. This pattern was explained by a south-to-north gradient of increasing sediment flux into marshes and wave fetch lengths which helps transport sediment onto marshes. Our study demonstrates how sediment supply should be monitored and managed to preserve salt marsh extent into the future.

1. Introduction

The threat of sea level rise has dominated theoretical and empirical salt marsh research for more than 30 years, from concerns that over 90% of global marshes could drown by 2100 (Crosby et al., 2016; Horton et al., 2018; Spencer et al., 2016; Valiela et al., 2018). Recent results show that marshes are adept at keeping pace with sea level rise, by growing vertically, when sediment is available to settle onto the marsh surface (Kirwan et al., 2016), an irony, given that fear of marsh loss by drowning has had an overriding influence on conservation policy since the 1970s (Hatvany et al., 2015). Despite the vertical resilience to sea level rise, there are many documented cases from Europe, North America, and Asia where marshes have undergone extensive lateral changes in cover, expanding or eroding hundreds of meters in just a few years (Yang et al., 2001; Lotze et al., 2006; Fagherazzi et al., 2013; Gunnell et al., 2013; Leonardi et al., 2016). This study heeds the call to investigate the drivers causing lateral marsh change (Kirwan et al., 2016; Kirwan, Temmerman, et al., 2016; Schuerch et al., 2018), shifting the current emphasis away from a predominant focus on vertical growth dynamics alone (Kirwan, Walters, et al., 2016; Mariotti & Fagherazzi, 2010). The causes for lateral marsh change need to be understood if natural coastal protection by marshes is to be effectively managed (Bouma et al., 2014; Ganju, 2019; Kirwan, Walters, et al., 2016).

Marsh loss by lateral retreat is thought to be the consequence of wind-wave attack (Marani et al., 2011; Mariotti & Carr, 2014; Mariotti & Fagherazzi, 2010, 2013). Sea level rise and increased severity of storm and river flooding, collectively act to raise water depths and wave/current scour over tidal flats, thereby increasing the likelihood of initiating lateral marsh erosion (Hu et al., 2015; Mariotti & Carr, 2014; Mariotti & Fagherazzi, 2010). Previous studies have indicated that sediment supply from marine or riverine sources can diminish this erosion risk if the replenishment of sediment is sufficiently large to cause tidal flats to elevate through accretion. For example, marshes in the macrotidal Bay of Fundy, Canada, are resilient to erosion because new sources of sediment from ice rafting are transported to the salt marsh edge by large-amplitude tides (van Proosdij et al., 2006). In contrast, some marshes in the microtidal Venice Lagoon, Italy, are erosion prone because of low river sediment supply, as well as limited tide-driven sediment mobilization and transport (Day et al., 1999; Fagherazzi et al., 2013; Marani et al., 2007). Along sediment starved coastlines, erosion of adjacent tidal flats can provide a local sediment source for marsh accretion (Schuerch et al., 2019), even if tidal flat loss eventually exposes marshes to long-term lateral erosion (Bouma et al., 2016). Marsh change is also associated with human activity. Land reclamation has reduced the extent of marshes globally (Gedan et al., 2009), while the introduction of invasive marsh building plants (*Spartina* species) has expanded marshes (Gedan et al., 2009; Ranwell, 1967). Large fluctuations in marsh cover have also been linked to changes in hydrology and sediment transport driven by coastal development and land use change (Yang et al., 2001).

While numerical models have pioneered the mechanistic understanding of lateral marsh dynamics (D'Alpaos & Marani, 2016; Hu et al., 2015; Kirwan, Walters, et al., 2016; Mariotti & Carr, 2014; Mariotti & Fagherazzi, 2010; Schuerch et al., 2018), empirical evidence has lagged behind and been limited to process-based studies (Feagin et al., 2009; Francalanci et al., 2013), isolated sites (Chauhan, 2009; Gunnell et al., 2013; McLoughlin et al., 2014), and single explanatory drivers of change (Gabler et al., 2017; Weston, 2013). We aimed to change this situation. Here, we ask which key climate, biotic, and anthropogenic drivers best explain long-term (150-year), large-scale (across Great Britain [GB]) lateral marsh change.

2. Methods

2.1. Study Sites

We measured change in salt marsh extent for 25 estuaries and embayments located in six regions across GB: the Solway, Morecambe, and Cardigan regions located along the west coast, and the Wash, Essex-Kent, and Solent regions along the east/southeast (Figure 1). In total, these estuaries occupied around 19,000 ha of salt marsh (~40% of the total marsh area in GB; Phelan et al., 2011; Haynes, 2016). Estuaries were shallow, generally well mixed with semidiurnal mesotidal to macrotidal ranges. Flood dominance was common along the west coast, the Wash region, and many of the Essex-Kent regions, whereas in the Solent region, all the estuaries were ebb dominant (Manning & Whitehouse, 2012). Typical estuary morphology ranged from bar-built to embayment/coastal plains (Pye & Blott, 2014). Relative sea level rise (RSLR) generally increases along an axis from the northwest to the southeast due to isostatic adjustment of the British Isles following deglaciation at the end of the Last Glacial Maximum (Bradley et al., 2009). Along a similar axis, tidal amplitude and estuary depth generally decrease, and sediment type changes from sand dominance to silt/clay dominance (Goudie, 2013). All regions have historically seen some sea wall construction, with extensive stepwise reclamation occurring in the Wash and the Essex-Kent regions (Davidson et al., 1991). Fluvial suspended sediment supply to the coastline across the United Kingdom has been historically low (Worrall et al., 2013).

2.2. Change in Salt Marsh Extent

We quantified salt marsh area for the entirety of each estuary approximately every 30 years between 1846 and 2016 using a combination of Ordnance Survey (OS) maps and aerial photographs. OS maps were accessed via the EDINA Digimap Resource Centre. Survey dates of maps were taken from Oliver (2013) and used as time stamps. For the Cardigan regions, aerial photographs were taken from the Royal Commission on Ancient Historical Monuments Wales. Photographs were scanned and georeferenced onto OS 1:25,000 rasters in the British National Grid projection. Pixel size corresponded to approximately 0.25×0.25 m in the field. Marsh extent measurements for the Solent and Essex-Kent regions, originally delineated from aerial photographs, were taken from Baily and Pearson (2007) and Cooper et al. (2001), respectively.

Marsh extent from OS maps and aerial photographs were delineated manually at a scale of 1:7,500 by placing vertices along the marsh edge approximately every 5 m. To account for boundary precision of the seaward

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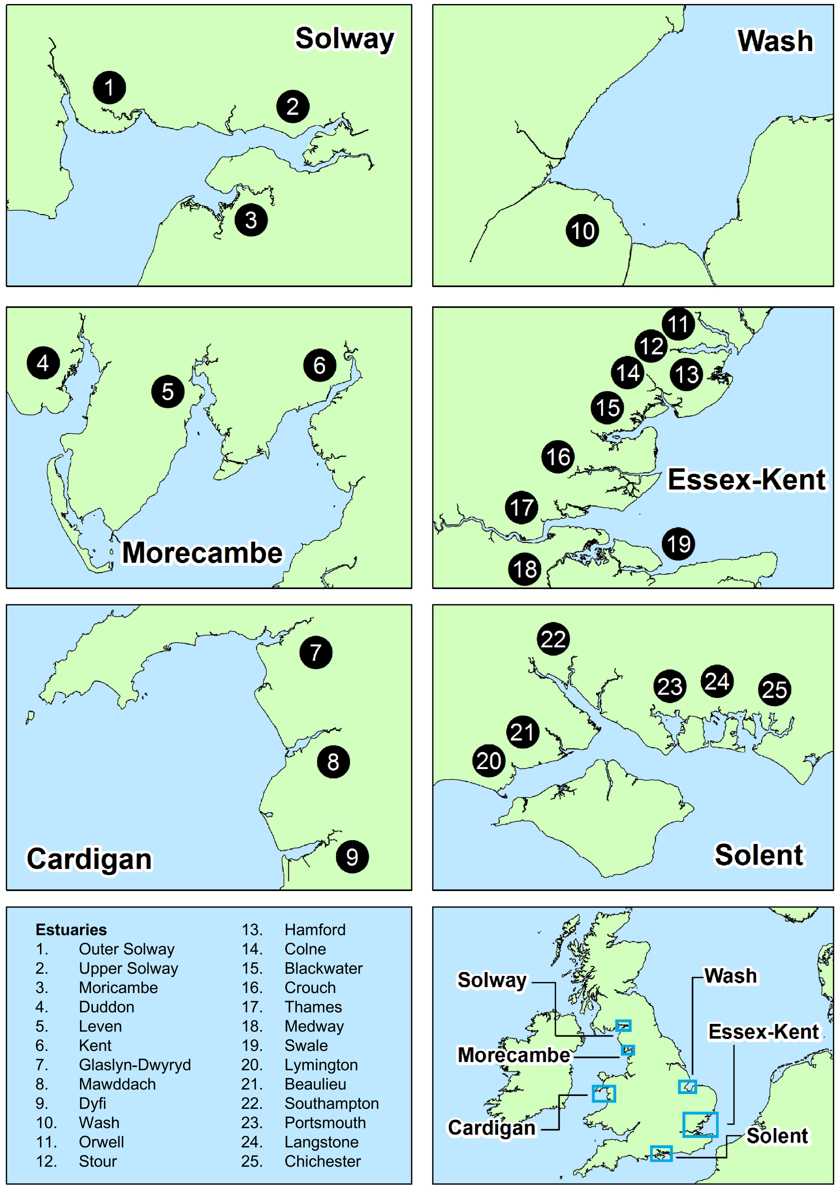

Figure 1. Estuaries examined within each region. A total of 25 estuaries separated into six regions across Great Britain.

marsh edge, visual comparisons between our georeferenced images to reference shapefiles (Haynes, 2016; Phelan et al., 2011) were carried out to ensure accuracy of the georeferencing procedure. We also looked for site-specific literature to verify whether observations of significant change in marsh extent could be considered "real" or were likely caused by differences in map surveyors' interpretation of where the marsh edge lay (see Supporting Information, Table S1). In the case of the Wash, large areas of marshland were reclaimed over the study period. To account for this, we calculated the area of reclaimed land and subtracted it from the marsh extent in the previous map revision. The new value was included as an additional measurement of marsh area between map revisions. See Text S1 for methods used to calculate an error term for each measure of marsh area.

A linear rate of salt marsh change per year was calculated for each estuary and used as the response variable in statistical modeling. Due to the highly nonlinear change of marsh extent in the Wash region, an average rate of marsh change was calculated following each reclamation phase. See Table S2 for the rates of marsh change and the dates over which this rate was taken. We also contrasted observed rates of lateral marsh

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Table 1
Rates of Lateral and Vertical Marsh Change Per Region

Region	Lateral expansion (ha/year)	Accretion balance (mm/year)
Solway	0.88 ± 1.17	15.41 ± 14.53 (Marshall, 1962)
Morecambe	2.94 ± 0.37	No data
Cardigan	2.31 ± 1.37	8.25 ± 4.06 (Kestner, 1975)
Wash	1.27 ± 0.00	46.17 ± 26.87 (Shi, 1993)
Essex-Kent	−6.42 ± 3.55	3.20 ± 3.56 (Cundy & Croudace, 1996)
Solent	−3.59 ± 1.65	2.91 ± 0.84 (van der Wal & Pye, 2004)

Note. Mean ± *SE* values per region for marsh lateral expansion rates, and the rate of marsh vertical accretion, minus the rate of relative sea level rise, to give the "accretion balance." Measures of vertical marsh accretion rates were unavailable for the Morecambe region.

change with published empirical measurements of vertical accretion on the nearby marsh surface. All accretion rates were measured in the low-marsh zone using Caesium radio-isotope dating, Sediment Elevation Tables or Marker Horizons (see references in Table 1). See Table S2 for dates over which accretion rates were measured.

2.3. Predictor Variables of Lateral Marsh Change

For each estuary, we collated data on key hydrological, sedimentological, and climatological variables known to structure salt marsh extent within estuaries. Annual net sediment flux per unit area of marsh was calculated by using the ratio of vegetated and unvegetated surfaces within each estuarine marsh complex (UVVR), which has been shown to be a proxy for external sediment supply (Ganju et al., 2017). See Text S2 for information on how net sediment flux was calculated and validated. Estimated bedload sediment flux volume (in or out of the estuary) was taken from HR Wallingford (2002), Brown and Davies (2010), Halcrow (2010), and NFDC (2017). Due to differences in the precision of modeled bedload sediment flux estimates between studies, all values were rounded to their nearest 10th value, representing a magnitude flux either into (positive) or out (negative) at the estuary mouth. Long-term tide gauge records were used to calculate the rate of RSLR for each estuary. Trends of RSLR are linear rates calculated from monthly averaged records with a minimum 30-year timespan (NOAA, 2019). Where nearby tide gauges were unavailable, we took the average RSLR rate from two nearest equidistant stations. Admiralty Tide Tables were used to determine the mean tidal range of each estuary, taken from Manning and Whitehouse (2012). Frequency of storm events was calculated using daily averaged wind speed data from the U.K. Met Office Integrated Data Archive System (Met Office, 2012). Stations were selected based on their proximity to each estuary. The temporal range for each station varied considerably, although at most limited to between 1957 and 2016. As a consequence, some stations nearby had low number of samples and were rejected for further analysis. The final representation of stations was limited to one per region, and storm events recorded by that station were assumed to be representative of all estuaries for the respective region. Prior to analysis, wind speed data were screened for quality and completeness (see Watson et al., 2015 for method). Frequency of storm events was then estimated from annual data sets as a count above an absolute threshold of 23 ms^{-1} ("strong gale" on the Beaufort scale), and rate of change in number of events per year was used in the statistical analysis. Prevailing wind directions within 10° compass bearing intervals of each station were also used to calculate fetch length of each estuary (the distance over which wave-generating winds blow). The Waves Toolbox for ArcGIS 10.1 (Rohweder et al., 2012) with an "SPM-Restricted" method was used to calculate fetch length every 200 m along the seaward marsh edge of each estuary (using a national marsh shapefile taken from Phelan et al., 2011 and Haynes, 2016). The median fetch lengths for each estuary were recorded. Rate change in river flood event frequencies were calculated using number of Peaks-Over-Threshold per water year data provided by the National River Flow Archive (Robson & Reed, 1999). Predictor variables, and the timescale over which they were measured, are noted in Table S2. Dates of *Spartina townsendii* and *Spartina anglica* (henceforth *Spartina spp*.) colonization (Figure 2; gray shading) were taken from Goodman et al. (1959), Hubbard and Stebbings (1967), and Harwood and Scott (1999). Information on significant infrastructure projects (Figure 2; arrows) were taken from Kestner (1962), Marshall (1962), and Burd (1992) for the Solway, Wash, and Essex-Kent regions.

2.4. Statistical Treatment

All statistical analyses were implemented in R. Predictor variables were checked for outliers and log or cube transformed to meet assumptions of normality and equal variance. Predictor variables were also checked for collinearity and dropped if variance inflation factors exceeded 3 (Zuur et al., 2009). To identify groupings across our study sites, we used pairwise Euclidean distances between all 25 estuaries and found six clearly defined regions (Figure 1). We then used region as a random variable to test for spatial autocorrelation but did not find a significant effect. A stepwise linear regression model was therefore used to select the minimal adequate model. See Text S3 for details on the full statistical analysis used.

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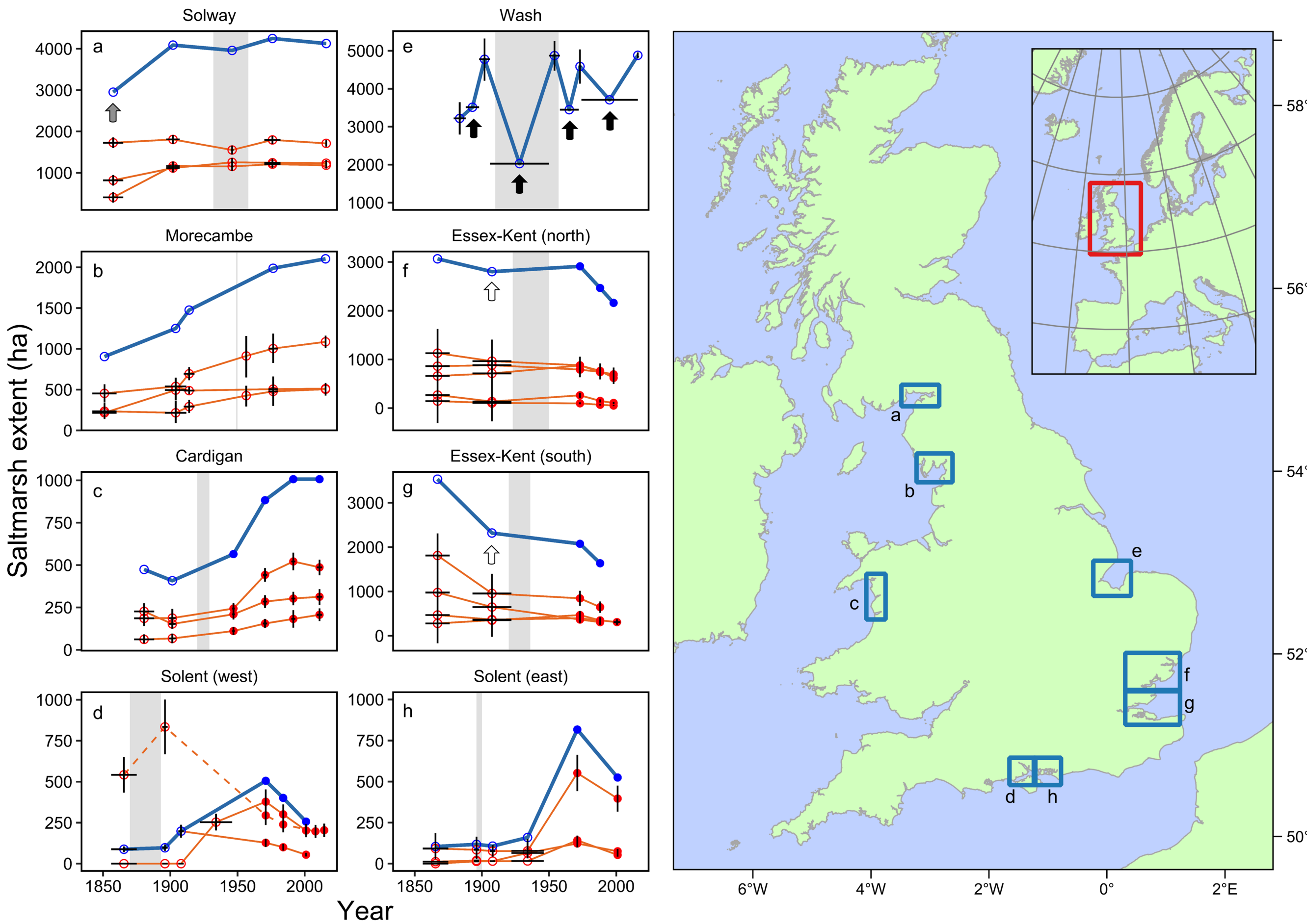

Figure 2. Change in estuarine-scale marsh extent across Great Britain. Regional- (blue line) and estuarine-scale (orange line) change in areal extent of salt marshes between 1846 and 2016 from photographs (filled circles) or maps (hollow circles). Arrows indicate occurrences of embankment (solid arrow), canalization (gray arrow), or collapse of sea walls after storms (hollow arrow). Gray shading indicates *Spartina spp.* colonization in each region. Vertical error bars indicate 95% confidence intervals in marsh area extent. Horizontal lines indicate the dates over which surveys of marsh extent were carried out. Essex-Kent and Solent regions have been subdivided for ease of presentation. Regional-scale marsh change (blue line) only includes marsh extent measures for all estuaries in a given region and year. Marsh change in Southampton estuary (panel d: dashed line) was excluded from the regional-scale marsh change line due to paucity of contiguous cover in salt marsh extent across multiple years.

3. Results and Discussion

Our analysis of marsh extent change revealed a stronger tendency for seaward lateral marsh expansion than for marsh erosion. Five of the six regions increased in marsh cover by 29% to 158% between 1846 and 2016 (Figures 2a–2e and 2h) and marshes overall expanded by 11%. Southeast Britain was the only region to consistently lose marsh cover (Figures 2f and 2g). The largest lateral expansion occurred in the south, where Solent marshes had grown 307% by the 1970s before declining to their current levels, 29% greater than in 1868 (Figures 2d and 2h). The northeastern Wash region lost large areas of salt marsh on four occasions due to land reclamation (Figure 2e; arrows); however, new marshes always expanded laterally on the seaward side of walls, leading to a 52% overall increase in marsh area.

Effects of *Spartina* colonization on long-term marsh change appeared to be limited. In estuaries where marsh areal extent had been increasing, trends of marsh expansion generally preceded the arrival of invasive *Spartina* (Figures 2a–2c; gray shading), with the exception of the Solent region (Figures 2d and 2h; gray shading), where *Spartina* invasion has been substantial (Hubbard, 1965). Causes for erosion post-1970 in the Solent are unclear (Baily & Pearson, 2007); however, studies have reported marsh loss through lateral marsh erosion which indicates that losses may be related to dynamics at the salt marsh-tidal flat interface

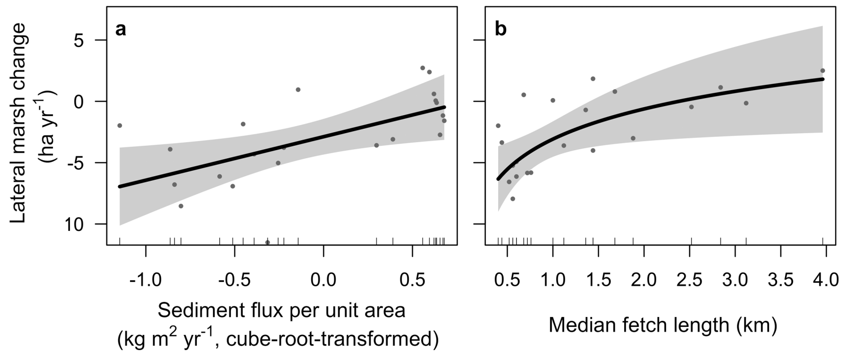

Figure 3. Relationships of estuarine-scale lateral marsh change with two significant predictor variables identified from a best fit linear regression model on data for 1967 to 2016 (n = 22): (a) sediment flux per unit area and (b) median fetch length. Data points represent distribution of standardized partial residuals. Solid lines represent model fit through the data, bounded by 95% confidence intervals (solid gray shading). Tick marks along the bottom of each plot denote deciles of the distribution of each predictor value.

(Johnson, 2000). In the Essex-Kent region, eroding marshes saw a prolonged period of little marsh change between 1900 and 1970 during which *Spartina* was first recorded and several sea walls were breached by storms (Figures 2f and 2g; gray bars and white arrows). Overall, coastal works also had little effect on long-term marsh change. In the Wash and Solway regions, marshes expanded despite losses through reclamation (Figure 2e; black arrows) and canalization (Figure 2a; gray arrows), respectively. The prevailing hydrological and sedimentological environment appeared to be conducive to achieving a new dynamic equilibrium in marsh extent (Kestner, 1975). Both the effects of the introduction of *Spartina* and coastal works appear to have only temporarily offset a long-term trend of marsh decline. We therefore conclude that long-term patterns of marsh lateral change were not driven by direct human impact alone.

We next considered which key drivers were responsible for lateral marsh change for the period between 1967 and 2016. Results from a stepwise linear regression model showed that sediment flux per unit area and median fetch length in combination best explained (62% of variation) the rate of marsh lateral change in estuaries across GB (Table S3). Marshes shifted from eroding to expanding when sediment flux and fetch length concurrently increased (Figure 3). Bedload sediment flux was retained in the best fit model but was not significant (Table S3).

From a range of key hydrological, sedimentological, and climatological variables known to influence lateral marsh dynamics, we find that sediment supply plays a crucial role in explaining large-scale, long-term trends of lateral marsh change (Figure 3a). While increases in fetch length are typically associated with marsh loss rather than expansion (Callaghan et al., 2010), the relatively sheltered mesotidal to macrotidal estuaries in our study had small fetch lengths (averaging 1.2 km) compared to the ~10-km threshold fetch lengths needed to trigger runaway marsh erosion along microtidal U.S. coastlines (Mariotti & Fagherazzi, 2013). Since wave action is also responsible for sediment resuspension and transport (Green & Coco, 2014), it is likely that moderate increases in fetch length enhance sediment transport to the coast, thereby facilitating marsh accretion (Figure 3b) as observed along other macrotidal coastlines (Pringle, 1995; van de Groot et al., 2011). Across GB, marshes with larger wave fetch lengths also tended to have longer foreshore widths (Taylor et al., 2004). The presence of a wide foreshore can attenuate incoming waves, reducing the potential for marsh edge erosion (Bouma et al., 2014 and references therein). Additional field-based measurements would be required to ascertain whether a shift from marsh erosion to expansion across GB is primarily influenced by increased wave-driven sediment transport to the coast or greater wave protection from wider foreshores. Nevertheless, our results provide empirical support for large-scale and long-term shifts in the lateral extent of marshes driven by sediment supply and transport, in agreement with numerical models (Mariotti & Fagherazzi, 2010).

Global declines in sediment supply to the coast could lead to large-scale marsh loss through lateral erosion, as observed along the eastern U.S. coast (Weston, 2013). A spatial shift over the 1967–2013 period, from marsh complexes with a positive sediment flux to marshes that have been exporting sediment (Figure 3a), implies that there might have been differences in sediment availability across GB. There is no evidence that fluvial suspended sediment flux to the U.K. coast has changed since 1974 (Worrall et al., 2013) and there is also no indication that marine sediment sources have depleted over the past 50 years (Halcrow, 2010; HR Wallingford, 2002; NFDC, 2017). Intertidal flats, which can provide a local sediment source for marsh accretion (Mariotti & Carr, 2014; Schuerch et al., 2019), have reduced in size across GB since 1843 (Pontee, 2011; Taylor et al., 2004). More severe reductions in tidal flat widths along south and eastern England (Taylor et al., 2004) may have impaired their capacity to supply marshes with enough sediment to keep pace with sea level rise, exposing the marsh edge to long-term lateral erosion (Figures 2d and 2f–2h). Estuaries with a greater capacity for sediment remobilization and transport by wave action (Figure 3b) may have allowed marshes to continue to expand at the expense of tidal flat erosion (Figures 2a–2c and 2e). Without increases in sediment supply to the coast, trends of lateral marsh erosion are likely to continue (Figures 2d and 2f–2h) and may reverse trends of marsh expansion currently observed in the northern regions of GB (Figures 2a–2c and 2e).

Given that studies of marsh stability have tended to focus on whether or not vertical growth is equal to or greater than local sea level rise (Crosby et al., 2016; Horton et al., 2018; Kirwan, Temmerman, et al., 2016; Schuerch et al., 2018; Spencer et al., 2016; Valiela et al., 2018), we also compared our rates of lateral marsh change with the rates of vertical marsh accretion (references within Table 1) versus RSLR for each region. We found that all marshes had a positive accretion balance (Table 1). Marshes can erode at their flanks but still accrete with RSLR, because lateral erosion provides a sediment source for vertical accretion (Mariotti & Carr, 2014). Coupled lateral and vertical marsh dynamics may therefore better predict salt marsh resilience than comparing marsh vertical growth against RSLR alone (Gonneea et al., 2019; Kirwan, Temmerman, et al., 2016; Kirwan, Walters, et al., 2016; Mariotti & Carr, 2014).

Schemes involving managed realignment of the coastline with engineering solutions to control sediment supply and tidal inundation can be used to build large-scale and long-term marsh resilience in historically eroding systems including San Francisco Bay, USA (Stralberg et al., 2011), and the Scheldt estuary, Netherlands (Vandenbruwaene et al., 2011). Despite such large investments into the restoration of salt marsh flood protection, the monitoring of short-term sediment dynamics at the marsh edges (Bouma et al., 2016) and profile changes of tidal flats (Murray et al., 2014; Pontee, 2011; Taylor et al., 2004) is rarely done. This hampers the ability to predict whether marsh restoration schemes are likely to succeed or fail. Having shed light on the key drivers of long-term salt marsh lateral change, researchers should now capitalize on advances in satellite remote sensing (Dorji et al., 2016) and innovative and inexpensive instruments to quantify the short-term sediment dynamics at the coast (Hu et al., 2015) to evaluate coastal resilience against human- and environment-induced change at a global scale. The evidence presented here contributes to an emerging emphasis on investigating the causes for spatial shifts in coastal systems, including mudflats (Murray et al., 2014), seagrass beds (Suykerbuyk et al., 2015), and mangroves (Gabler et al., 2017). Though important, a shift away from a focus on sea level rise alone to consider also the influences of other anthropogenic and macroclimatic drivers of coastline change should be a priority.

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