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Research Article

Long-term accretion rates in UK salt marshes derived from elevation difference between natural and reclaimed marshes

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ABSTRACT

The future of salt marshes depends in a large part on the balance between the future rate of marsh accretion and the future rate of sea-level rise (SLR). Current accretion rates can provide some insight into future resilience of salt marshes to SLR, but representative long-term rates across the complete salt marsh area are difficult to obtain. Here, we introduce a new method based on the elevation difference between a natural marsh and a neighbouring reclaimed marsh. The method, referred to as the 'reclaimed salt marsh method', was applied to 19 UK salt marshes and yielded a UK-averaged accretion rate of 4.5 mm/yr with considerable inter-site variability (0.68–7.88 mm/yr). Accretion rates were positively correlated with the mean spring tide range, with tide range explaining 37% of the inter-site variability in accretion rate. Observed accretion rates were found to be generally larger than that predicted for SLR according to RCP2.5, comparable to that predicted according to RCP4.5 and less than that predicted according to RCP8.5. However, future accretion rates are unlikely to remain the same. It is suggested that UK salt marshes in macrotidal settings are likely to be more resilient to SLR than those in micro- and meso-tidal settings. The reclaimed salt marsh method can be readily applied to other sites to obtain a global data base of marsh accretion rates.

1. Introduction

Salt marshes are intertidal coastal wetlands characterized by halophytic (salt-tolerant) vegetation that are regularly flooded by tides (Rogers and Woodroffe, 2014). They are mostly found in wave-sheltered settings, such as in estuaries, behind barrier systems and along semi-enclosed embayments (Allen, 2000), and support a wide variety of ecosystem services, including biodiversity (Jones et al., 2011), coastal erosion and flood prevention (Möller et al., 2014) and water quality improvement (Barbier et al., 2011). To keep their position within the tidal frame, salt marshes respond to sea-level rise (SLR) by gaining elevation through complex feedbacks between surface elevation, tidal flooding, sediment accretion and plant growth (Cahoon, 2006; Fagherazzi et al., 2012; Kirwan et al., 2016), thus exhibiting natural resilience (Masselink and Lazarus, 2019). Sedimentation processes in salt marshes are a function of numerous factors and processes, including SLR, marsh elevation, hydroperiod, vegetation, tides, storm activity, influx of allochtonous sediments and the in-marsh production of organic autochtonous sediments (Reed, 1990; Friedrichs and Perry, 2001; Passeri et al., 2015). Hydroperiod, which is the amount of time that the marsh is covered by the tide, is often considered the main physical control on salt marsh accretion (Pethick, 1981). However, sediment supply to the marsh, quantified by the suspended sediment concentration, is also a key factor (Weston, 2014). According to Boyd et al. (2017), sediment supply is more influential than the hydroperiod on 50–100-year accretion rates.

Salt marshes typically respond to SLR with increased accretion as higher sea levels result in the marsh being inundated for greater periods of time, thus increasing the hydroperiod and the period of sediment deposition (Friedrichs and Perry, 2001). Salt marshes also respond to SLR by migrating (transgressing) inland (Fagherazzi et al., 2019). There is no consensus in the literature with regards to the long-term persistence of salt marshes in the face of SLR (Schuerch et al., 2018). On the one hand, Crosby et al. (2016) suggests that even under the most conservative IPCC SLR projection, a majority of salt marshes (60%) will have insufficient accretion to compensate for SLR. On the other hand, Kirwan et al. (2016) consider marsh vulnerability to SLR to be over-estimated and indicate that estimates of critical rates of SLR for coastal salt marshes around the world indicate a relatively high resilience for many salt marsh sites. The effect of SLR on marsh survival is further

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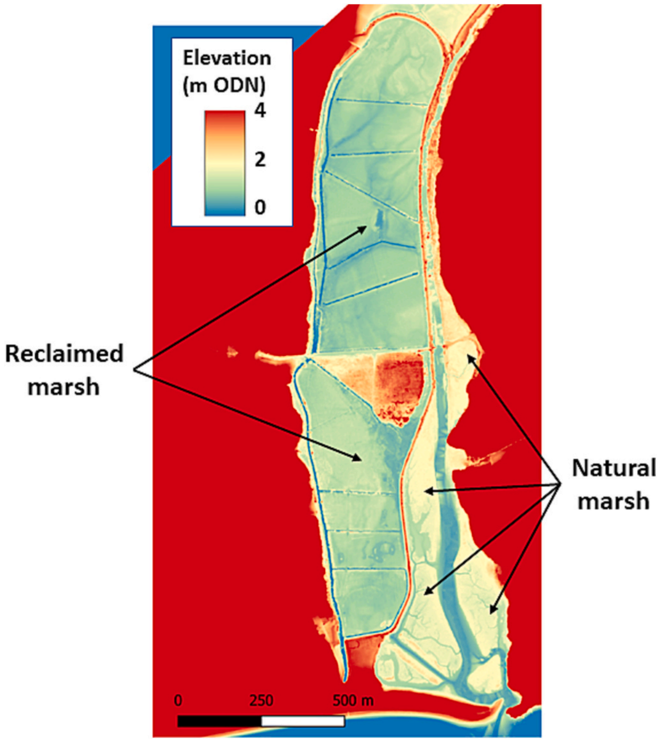

Fig. 1. Example Digital elevation model (DEM) of the Otter Estuary, SW England, showing the natural salt marsh in the eastern part of the estuary (yellow) having an overall higher elevation than the reclaimed salt marsh in the western part of the estuary (blue-green). LiDAR data from https://southwest.coastalmonitoring.org/. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

complicated by other variables that influence accretion rate, such as sediment supply (Ladd et al., 2019), tidal range (Kirwan et al., 2010), storms (Leonardi et al., 2018), tidal channel movements (Pye, 1995) and other site-specific factors (Reed, 1995). Furthermore, marsh response to SLR is not instantaneously and may lag by 20–30 years (Kirwan and Temmerman, 2009).

Current salt marsh accretion rates provide valuable insights into the potential for marshes to keep up with future SLR and a variety of methods are available for this purpose. Short-time (months–decades) measurements using reference layers (Stoddart et al., 1989; Wood et al., 1989; Bartholdy et al., 2004; Ma et al., 2014) or sedimentation plates/mats (Watson, *2004*) record the amount/rate of *sedimentation*, whereas deployment of pins/stakes (Ranwell, 1964), marsh elevation tables (Webb et al., 2013) or altimeters (Marion et al., 2009) record bed-level changes or *accretion*. Sedimentation rates are not affected by land-level change, but accretion rates are. Sediment cores and dating techniques are widely used for long-term (decades–centuries) sedimentation rates (Callaway et al., 1996; Adams et al., 2012). The main disadvantage of all these methods is that they provide spatially limited data and, as salt marsh accretion rates vary spatially across the salt marsh surface (e.g., Bartholdy et al., 2004), a large number of measurement stations or cores are required to provide a robust estimate of the marsh-averaged accretion rate. Here, we use the elevation difference between a natural marsh and a neighbouring reclaimed marsh, together with the date of reclamation, to estimate long-term and marsh-averaged accretion rates, referred to as the 'reclaimed salt marsh method'. The method will be discussed in more detail in Section 2.1.

The aim of this paper is to quantify long-term accretion rates for 19 UK salt marshes using the reclaimed salt marsh method. The accretion rates will be related to the mean spring tide range and the historic rate SLR, and will also be evaluated with respect to future rates of SLR (IPCC, 2014; IPCC, 2021). It will be demonstrated that the method yields robust salt marsh accretion rate estimates that are positively related to the mean spring tide range and unrelated to the historic SLR. The obtained accretion rates are larger than the predicted rate of SLR according to RCP2.5, similar to that predicted by RCP4.5 and less than that predicted by RCP8.5.

2. Methods

2.1. Reclaimed salt marsh method for deriving long-term vertical accretion rate

Salt marsh reclamation prevents the former salt marsh from being tidally inundated (Hobbs and Shennan, 1986), and sediment deposition and accretion will cease. Since the natural salt marsh will continue to flood and accrete, its elevation will progressively increase, while the elevation of the reclaimed salt marsh is assumed to remain the same (this assumption will be discussed later in the Discussion). The accretion rate of the natural salt marsh can be calculated by dividing the elevation offset between the natural and reclaimed salt marsh by the time since reclamation. The Digital Elevation Model (DEM) for the Otter Estuary, Devon, SW England, obtained from vegetation-filtered LiDAR data, shown in Fig. 1, illustrates the principle behind the reclaimed salt marsh method. The DEM demonstrates that the elevation of the reclaimed marsh is consistently lower than that of the natural marsh.

LiDAR data are used extensively in salt marsh research (e.g., Schmid et al., *2011*; Fernandez-Nunez et al., 2017), but the reclaimed salt marsh method is rarely exploited. Millard et al. (2013) calculated the elevation difference between a reclaimed and a natural marsh to determine restoration suitability, while Masselink et al. (2017) deployed the method to calculate an approximate accretion rate of 3 mm/yr for a salt marsh in the Avon Estuary, Devon, SW England. The method measures elevation change, which, unlike accretion, includes any subsidence (Nolte et al., 2013). Due to the proximity of the natural and reclaimed salt marsh for each site, regional subsidence effects, such as GIA (Bradley et al., 2011), have an equal effect on both and have no influence on the obtained accretion rate. Local subsidence can be an issue and is addressed in Section 4. The four main advantages of the reclaimed salt marsh method for deriving salt marsh accretion rates are: (1) it only requires LiDAR data and the reclamation date; (2) it is cheap and easy to implement; (3) considering most salt marsh reclamations in Great Britain happened in the past 300 years, long-term accretion rates are obtained; and (4) it yields accretion rates that are representative of the whole marsh.

2.2. Site selection

Not all salt marsh sites with reclamation are useful as accretion rates can only be measured if the reclamation date is known, preferably to the specific year, and reliable elevation data, preferably high-resolution LiDAR data, must be available. A total of 19 sites were selected in this study (Fig. 2.; Table 1).

2.3. Data sources

LiDAR elevation data were obtained from the SW Regional Monitoring Programme (SWRMP) for sites in SW England (https://southwest.coastalmonitoring.org/), while Digimap was used for other sites (EDINA, 2021). SWRMP LiDAR data are generally collected during low spring tide (to optimise intertidal cover) during winter (to minimise vegetation). For Digimap LiDAR data, the collection conditions are not always clear; therefore, SWRMP data have been used over Digimap data where possible. For each site, reclamation dates have been obtained and specific data sources are listed in Table 1. The rate of SLR over the last 200 years has been sourced from Hogarth et al. (2021), who split SLR into clusters across Great Britain, and each site was allocated the rate of SLR closest to the cluster. The rate of SLR was adjusted for GIA effects

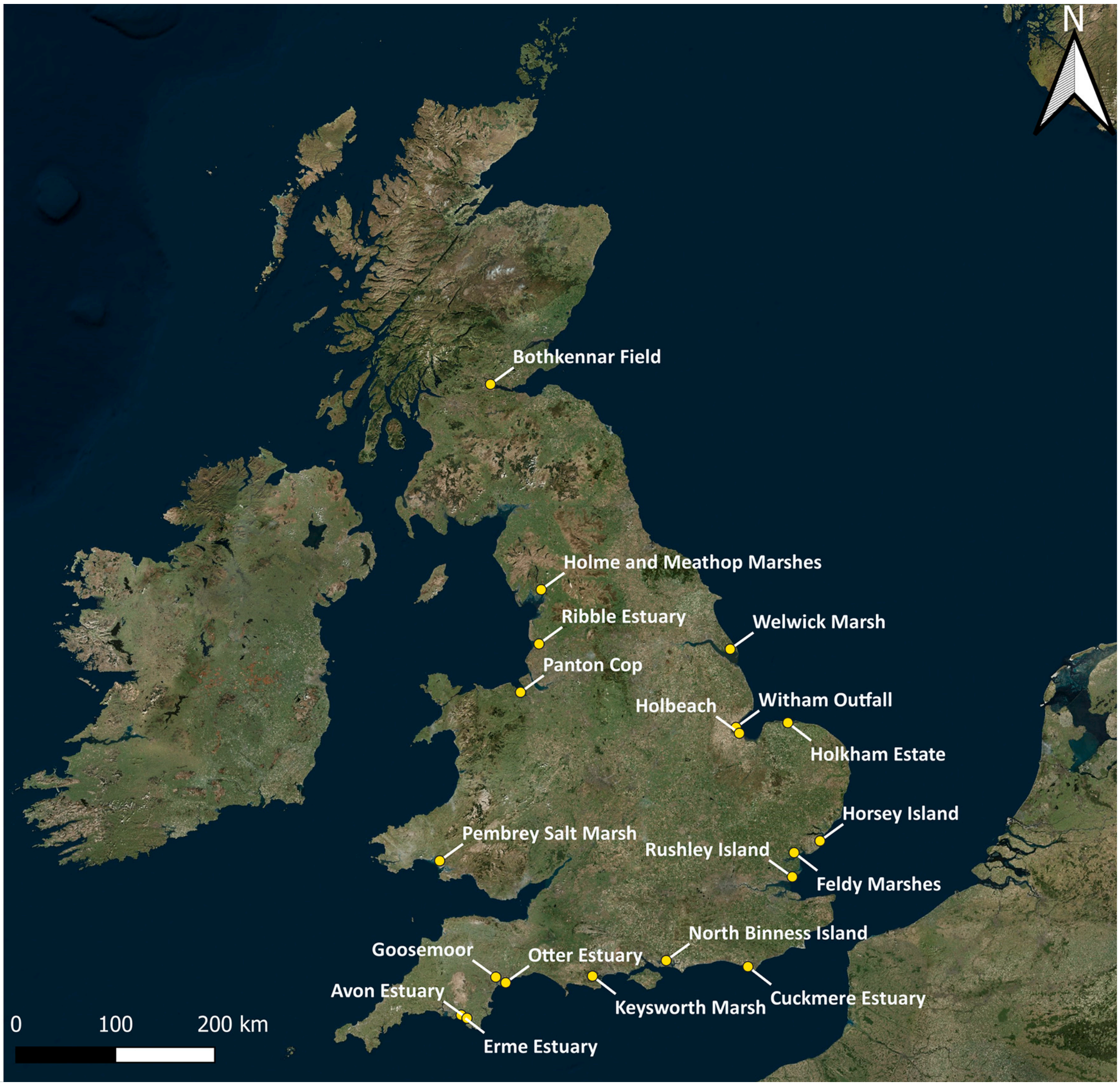

Fig. 2. Map of UK with location of studied salt marshes (Source: Googlemap).

using the methodology provided by Hogarth et al. (2021). The UK Climate Projections (UKCP) database (Fung et al., 2018) was used to obtain local predictions of future SLR up to 2100 with a 12-km resolution. As UKCP has not yet produced regionalised SSP-based projections from the 6th IPCC report (IPCC, 2021), emission pathways RCP2.6, RCP4.5 and RCP8.5 from the 5th IPCC report (IPCC, 2014) were chosen to examine marsh survival under a range of scenarios. Tidal range data (mean spring tide range MSTR, mean high water spring MHWS) were derived from Admiralty Tide Tables.

2.4. DEM creation and manipulation

QGIS, a free and open-source (QGIS, 2021) GIS program, was used to create the Digital Elevation Models (DEMs). These were created by filtering out unnecessary data tiles and then mosaicking the remaining tiles using the "Merge" tool, before altering the image colouration to focus on the heights of the marshes. To calculate accretion rate and perform other spatial analyses, the "Add polygon" feature tool was used to demarcate boundaries containing the natural and reclaimed salt marshes. For natural salt marshes, which often have irregular boundaries and areas of high and low elevation that are not related to the marsh itself, using only a polygon would lead to the inclusion of non-marsh elevation data. To mitigate this, an elevation mask is created within these polygons by using the "reclassify by table" tool to define an elevation range for the marsh that is informed by both the DEM and aerial photography. The "raster calculator" tool turns this reclassification into a mask layer, and the "clip raster by mask layer" tool matches the DEM raster to the boundaries of the mask layer, providing a DEM which only displays elevation data within the defined range. Fig. 3 illustrates the three main stages of this process for the natural salt marsh region of Feldy Marshes, SE England.

Once the natural and reclaimed salt marsh regions were clipped by the polygon and elevation masks, the "zonal statistics" tool was used to calculate the mean elevation (and associated standard deviation). It is well known that accretion rate varies spatially within a salt marsh, for example, as a function of distance towards a creek or the distance towards the edge of the salt marsh (Bartholdy et al., 2010). This spatial variability is subsumed in the mean accretion rate and is reflected in the associated standard deviation. Using these techniques, the DEM of the Otter estuary in Fig. 1 produces a natural marsh elevation and a reclaimed marsh elevation of 1.833 and 1.091 m ODN, respectively (ODN is Ordnance Datum Newlyn and represents mean sea level + 0.2 m in the UK). Dividing the difference by the number of years since reclamation (205 yrs) gives an accretion rate of 3.62 mm/yr. There are two sources of uncertainty associated with computing the mean marsh elevation (for both reclaimed and natural salt marsh). Firstly, the mean

Table 1
Information on salt marsh sites used in this study. Reclamation dates have been sourced from a variety of sources, mostly gray literature. Easting and Northing represent WGS84 coordinates, MSR is mean spring tide range, ODN is Ordnance Datum Newlyn and represents mean sea level + 0.2 m in the UK, and SLR is sea-level rise.

Site name	Easting	Northing	Reclamation date with reference	Region	MSR (m)	Spring tide level (m ODN)	SLR over past 200 years (mm/yr)
Avon Estuary	268,363	46,437	1760 (Masselink et al., 2017)	SW England	4.6	2.5	1.76
Bothkennar Field	292,074	686,226	1784 (Barras and Paul, 2000)	Scotland	5.2	2.8	1.09
Cuckmere Estuary	551,657	98,473	1846 (Brew and Williams, *2003*)	SE England	6.0	3.2	2.17
Erme Estuary	262,467	49,693	1800 (White, 2015)	SW England	4.6	2.5	1.76
Feldy Marshes	598,163	213,553	1810 (Gascoyne and Medlycott, *2014*)	SE England	4.7	2.6	2.00
Goosemoor	297,430	87,969	1840s (White, 2015)	SW England	3.8	2.1	1.68
Holbeach	542,947	334,014	1948 (Kestner, 1962)	East England	6.8	3.6	1.74
Holkham Estate	591,902	344,667	1859 (Natural England, 2009)	East England	6.4	3.4	2.20
Holme and Meathop Marshes	343,178	478,946	1857 (Gray, 1972)	NW England	9.5	5.0	1.26
Horsey Island	624,266	225,357	1665 (Thomson et al., 2011)	SE England	3.8	2.1	1.66
Keysworth Marsh	394,902	88,959	1805 (Hubbard and Stebbings, 1968)	SE England	1.65	1.0	1.68
North Binness Island	469,236	104,646	1773 (Bryant, 1967)	SE England	4.0	2.2	1.22
Otter Estuary	307,461	82,279	1812 (LORP, 2023)	SW England	4.1	2.3	1.68
Panton Cop	322,388	375,394	1892 (Halcrow, *2013*)	Wales	7.6	4.0	1.34
Pembrey Salt Marsh	240,891	205,293	1852 (Ludlow, 1991)	Wales	7.5	4.0	2.08
Ribble Estuary	341,007	424,194	1980 (Holden, 2008)	NW England	8.0	4.2	1.34
Rushley Island	596,378	189,101	1782 (Fautley and Garon, 2004)	SE England	4.8	2.6	2.00
Welwick Marsh	533,736	418,935	Various 1870 (Andrews et al., 2008)	Yorkshire and Humber	6.4	3.4	1.74
Witham Outfall	539,645	339,933	1942 (Hobbs and Shennan, *1986*)	East England	6.8	3.6	1.74

marsh elevation has an associated standard deviation due to the spatial variability in marsh elevation. Secondly, there is an error associated with the LiDAR elevations which is estimated at 0.15 m (Environment Agency, 2021), although this may be a conservative value considering the difficulty associated with filtering out the salt marsh vegetation. Only the second source of uncertainty is considered as it presents an error, whereas the first source is a measure of spatial variability. The LiDAR error is propagated when computing the accretion rated as follows (Valiente et al., 2019):

$$error\ in\ accretion\ rate\ (m\ per\ year) = \frac{\sqrt{0.15^2 + 0.15^2}}{\Delta t} = \frac{0.21}{\Delta t} \quad (1)$$

where Δt is the time interval between the reclamation date and the LiDAR data collection date. For the Otter Estuary, the accretion rate is 3.62 +/− 1.03 mm/yr.

3. Results

Table 2 lists the computed salt marsh accretion rates with associated LiDAR uncertainties, as well as projected rates of SLR for the three different emission scenarios. The average accretion rate across all the sites is 4.5 mm/yr which is significantly more that the average rate of SLR over the past 200 years of 1.7 mm/yr (Table 1). The site-averaged accretion rate is also larger than the SLR rate projected according to RCP2.6 (3.8 mm/yr), but less than that projected according to RCP4.5 (5.7 mm/yr) and RCP8.5 (10.5 mm/yr).

For six of the sites, salt marsh accretion estimates are available from other studies, and these can be compared with the results obtained with the reclaimed salt marsh method. For Keysworth Marsh, the LiDAR-derived accretion rate of 2.33 mm/yr is smaller than the 5 mm/yr derived by Bird and Ranwell (1964) from erosion pins. The LiDAR-derived accretion rate at Holkham of 7.13 mm/yr is larger than the value of 2.7–3.9 mm/yr derived by Callaway et al. (1996) from analysis of sediment cores. The results for the four remaining sites are similar. Accretion rates at the Avon (2.81 mm/yr) are comparable to Blake et al. (2007) based on core analysis (2.09–3.14 mm/yr); at Witham Outfall (4.84 mm/yr) they are comparable to Brown et al. (2007) from surface elevation table (4.93 mm/yr); at Horsey Island (2.49 mm/yr) they are comparable to Rampling (2000) based on sedimentation plate (1.4–3.5 mm/yr); and at Feldy Marshes (5.58 mm/yr) they are comparable to Adams et al. (2012) from core analysis (5.4 mm/yr).

Salt marshes are generally restricted to a relatively narrow tidal elevation band, from mean high water neap to mean high water spring (Wolters et al., 2005). Tidal levels are not available for all study sites, as many of them are located at the back of estuaries; therefore, the mean natural and reclaimed salt marsh elevation derived from the LiDAR data is compared to the open-coast mean spring tide level at each site (Fig. 4). The average elevation of the natural salt marsh surface is located around the mean spring tidal level and a very strong linear relationship between the marsh elevation and the spring tide level is apparent (Fig. 4a). Not surprisingly, the reclaimed marsh elevation also shows a similarly strong relationship with the mean spring tide level, but, for the vast majority of the sites, the spring high tide level is significantly higher than the marsh elevation (Fig. 4b), reflecting that, since reclamation, accretion has ceased whilst spring high tide level has continued to rise.

The long-term salt marsh accretion rate increases significantly (p = 0.01) with the mean spring tide range (Fig. 5a). There is no significant correlation, however, between accretion rate and the rate of SLR over the past 200 years (Fig. 5b), although it should be noted that the range of rate of SLR represented by the data set is limited (1.09–2.20 mm/yr; Table 1).

The current long-term salt marsh accretion rates are further compared with future predictions of the rate of SLR (Table 2; Fig. 6). Observed long-term accretion rates are generally larger than that predicted according to RCP2.5, comparable to that predicted according to RCP4.5 and less than that predicted according to RCP8.5. Notably, only the Erme Estuary was characterized by accretion rate less than the long-term rate of SLR, and for six of the salt marshes (Cuckmere Estuary, Holbeach, Holkham Estate, Holme & Meathrop Marshes, Pembrey Salt Marsh and Welwick Marsh), the current accretion rate exceeded the projected rate of SLR according to RCP4.5.

4. Discussion

Long-term salt marsh accretion rates were estimated from the elevation difference between a natural marsh and a neighbouring

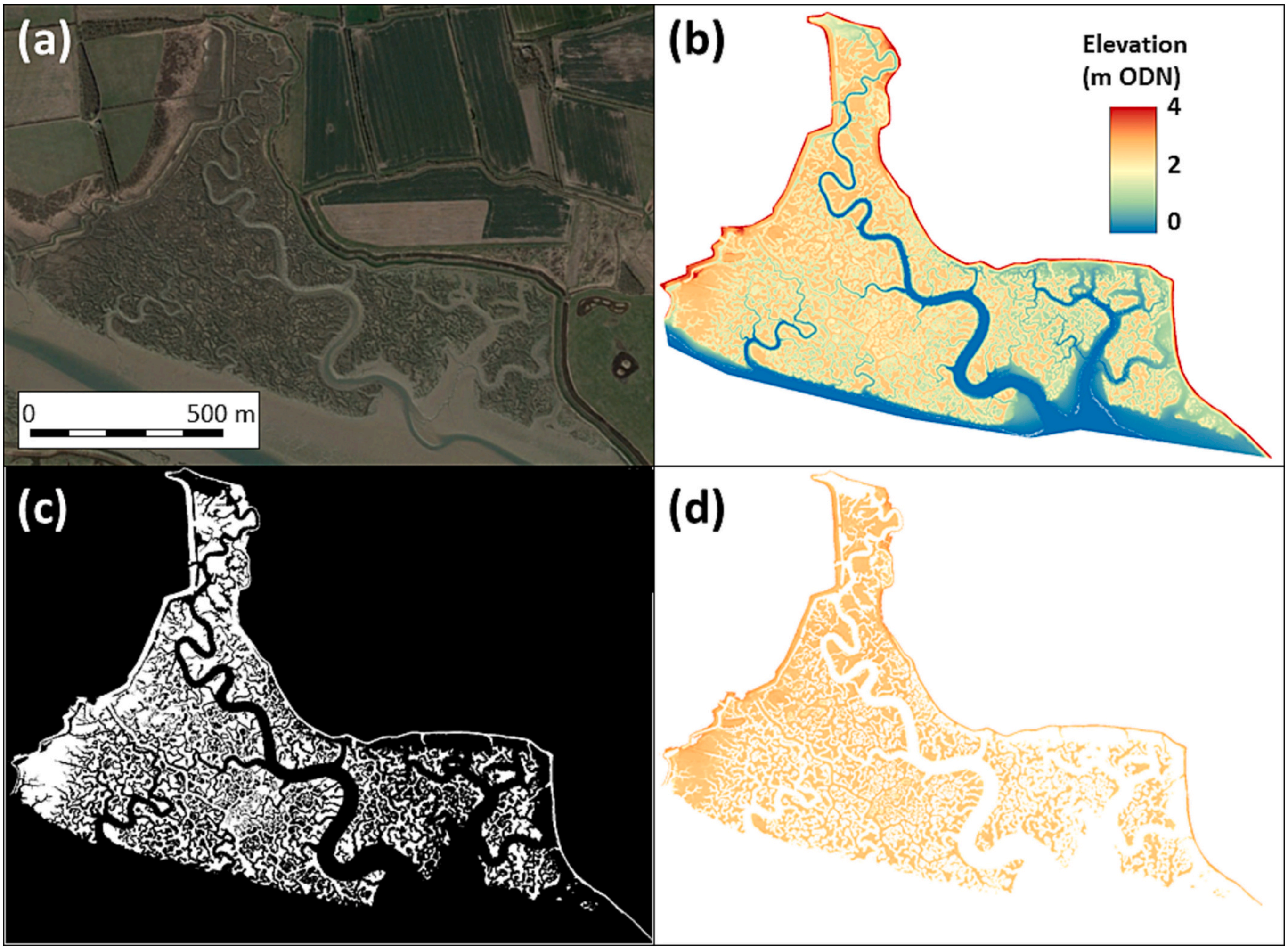

Fig. 3. (a) aerial photography of Feldy Marshes, SE England, with (b) DEM after being clipped by a polygon; (c) elevation mask, where white areas are kept, and black areas are removed; and (d) DEM after being clipped by both a polygon and an elevation mask. Aerial photograph from GoogleEarth and LiDAR data from EDINA (2021).

reclaimed marsh, referred to as the 'reclaimed salt marsh method', for 19 UK salt marshes. The method only requires LiDAR data and the reclamation date, and is cheap and easy to implement. Considering most salt marsh reclamations in Great Britain happened in the past 300 years, long-term accretion rates can be derived using this method. A further key advantage is that it yields accretion rates that are representative of the whole salt marsh, as opposed to methods that involve coring, stakes, elevation table, sedimentation plates or marker horizons. A key disadvantage is that the method relies on accurate elevation data, but the LiDAR error reduces rapidly for increased time span since reclamation (Eq. (1)). When the method is applied to a site with a 100-year reclamation, the error is 2.1 mm/yr; but, for a 200-year old reclamation site, the error is 1.05 mm/y. Derivation of DEMs using UAVs can significantly reduce the error. Another disadvantage is that a reclaimed salt marsh must also be present, which limits the applicability of this method to salt marsh settings that are human-altered.

A potentially more serious issue could be local subsidence, such as due to the loss of organic matter through soil oxidation, soil compaction and dewatering (French, *2006b*), that can lower the elevation of reclaimed marshes, potentially resulting in an overestimation of the accretion rate. Dewatering will occur in reclaimed soils due to drainage and a lack of regular saltwater input (Portnoy, 1999). This may contribute to compaction, reducing soil volume (Portnoy and Giblin, 1997), leading to subsidence. A lack of saltwater also aerates the soil, which increases the decomposition of organic matter, further reducing volume (Portnoy, 1999). In agricultural reclamations, the weight of livestock and farm machinery can compact the soil (Spencer and Harvey, 2012) and it is possible that accumulation of organic matter could also raise the surface of a reclaimed marsh in a manner different from that of a natural salt marsh. Furthermore, a conversion to arable land can be accompanied by intentional surface flattening and infilling of former channels, reducing surface elevation (Dixon et al., 2008). Unfortunately, there is no literature on the scale of the post-reclamation subsidence and its role is therefore not considered.

Tidal range, as a principal component of the hydroperiod, is a well-recognised critical influence on accretion rate (Reed, 1990; Friedrichs and Perry, 2001; Rogers and Woodroffe, 2014). Hence, the statistically significant positive correlation between mean spring tide range and accretion rate affirms the role of the hydroperiod at these sites. It also supports the notion that salt marshes in macrotidal regimes are more resilient to high rates of sea level rise and/or reduced sediment supply (French, *2006a*; Townend et al., 2011; Kirwan et al., 2010; Kirwan et al., 2010) than those in microtidal regimes. Mean spring tide range explains 37% of the variability in salt marsh accretion rate, indicating there are other factors involved in determining accretion rates, including storms (Schuerch et al., 2013), sediment supply (Boyd et al., 2017), vegetation density (Gleason et al., 1979), wind-wave climate (van der Wal and Pye, 2004) and human activities and structures (Mattheus et al., 2010). While investigating these other factors was outside the scope of this study, it is expected that the influence of each of these factors will naturally vary

Table 2
Mean natural and reclaimed marsh elevation with standard deviation associated with spatial variability, marsh accretion rate with LiDAR uncertainty, and projected rates of SLR for different emission scenarios for all salt marsh sites used in this study. ODN is Ordnance Datum Newlyn and represents mean sea level + 0.2 m in the UK, SD is the standard deviation, SLR is sea-level rise and RCP refers to the Representative Concentration Pathways.

Site Name	Natural marsh elevation (m ODN)	Natural marsh elevation (SD)	Reclaimed marsh elevation (m ODN)	Reclaimed marsh elevation (SD)	Accretion rate ± LIDAR error (mm/year)	SLR projection for 2100 (RCP2.6) (mm/year)	SLR projection for 2100 (RCP4.5) (mm/year)	SLR projection for 2100 (RCP8.5) (mm/year)
Avon Estuary	1.69	0.24	1.00	0.11	2.81 ± 0.86	4.20	6.03	11.10
Bothkennar Field	3.04	0.32	2.57	0.14	2.15 ± 0.97	2.06	5.72	8.14
Cuckmere Estuary	3.20	0.23	2.18	0.20	6.15 ± 1.28	4.02	5.86	10.97
Erme Estuary	1.74	0.18	1.60	0.20	0.68 ± 1.06	4.20	6.03	11.10
Feldy Marshes	2.54	0.23	1.39	0.45	5.58 ± 1.02	4.08	5.89	10.95
Goosemoor	2.02	0.20	1.39	0.33	4.14 ± 1.38	4.11	5.94	10.99
Holbeach	3.38	0.30	2.84	0.24	7.88 ± 3.07	3.99	5.78	10.69
Holkham Estate	2.87	0.19	1.75	0.55	7.13 ± 1.35	3.99	5.70	10.69
Holme & Meathop Marshes	5.53	0.21	4.42	0.38	6.89 ± 1.33	2.89	5.61	9.29
Horsey Island	2.04	0.15	1.16	0.14	2.49 ± 0.60	4.09	5.91	10.96
Keysworth Marsh	0.82	0.09	0.34	0.20	2.33 ± 1.04	4.07	5.54	10.97
North Binness Island	1.84	0.29	0.78	0.57	4.52 ± 0.91	4.04	5.86	10.94
Otter Estuary	1.83	0.15	1.09	0.26	3.62 ± 1.03	4.10	5.93	10.98
Panton Cop	4.57	0.10	4.02	0.28	4.58 ± 1.75	3.19	5.72	9.68
Pembrey Salt Marsh	3.90	0.16	3.04	0.20	5.36 ± 1.33	3.81	4.94	10.53
Ribble Estuary	4.56	0.16	4.38	0.17	4.83 ± 5.73	3.10	4.84	9.56
Rushley Island	2.72	0.22	1.44	0.14	5.39 ± 0.90	4.06	5.88	10.94
Welwick Marsh	3.30	0.16	2.35	0.18	6.64 ± 1.48	3.95	4.62	10.57
Witham Outfall	3.44	0.12	3.08	0.19	4.84 ± 2.87	3.99	5.78	10.69

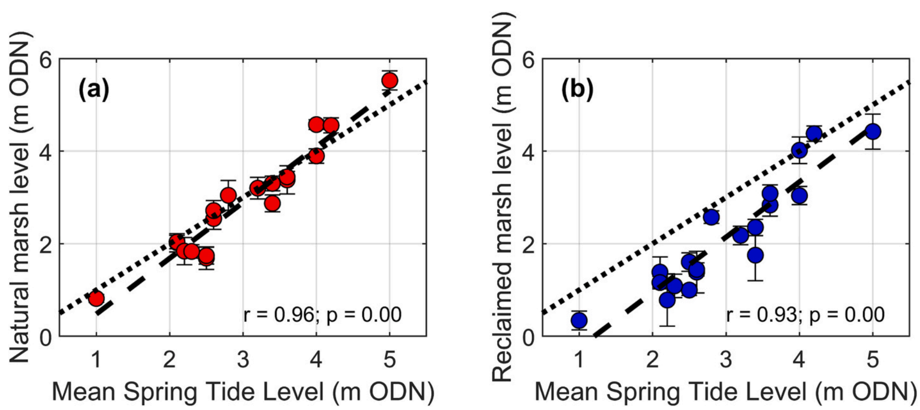

Fig. 4. Scatter graphs of (a) mean natural marsh elevation versus mean spring tide level, and (b) mean reclaimed marsh elevation versus mean spring tide level. Vertical lines reflect the spatial variability of the marsh elevation (standard deviation associated with the mean). The dashed lines represent the lines of best fit and the dotted lines represent a 1:1 relation. Pearson *r* and associated *p*-value are printed in the lower-right-hand corner of the plots.

per site. For example, as study sites are drawn from around the UK, they represent different wave climates and storm surge regimes.

Except for the Erme Estuary, the long-term accretion rates for all studied UK salt marshes exceed the long-term rate of SLR. This is what should be expected from healthy-functioning salt marshes, but appears to contrast with the reported general loss of UK salt marsh habitat (Hughes and Paramor, 2004) and widespread erosion of UK salt marshes (Harmsworth and Long, 1986; van der Wal and Pye, 2004). The former process is largely attributable to coastal squeeze (Doody, 2013; Pontee, 2013) and the latter generally occurs at the marsh edge, at the transition with tidal flats; both processes can occur independent of accretion at the top of the marsh surface. For example, Oenema and DeLaune (1988) found that sediment accumulation in accreting marshes in the Eastern Scheldt, SW Netherlands, exceeded the loss of sediment by retreat of the

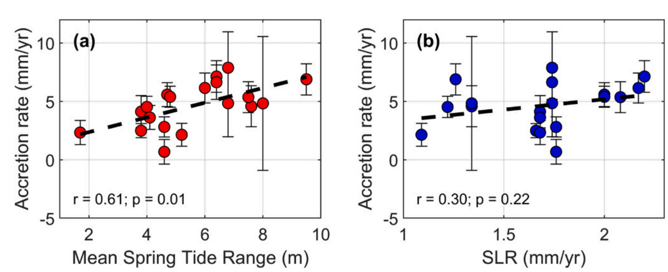

Fig. 5. Scatter graphs of salt marsh accretion rate versus (a) mean spring tide range and (b) rate of SLR over the last 200 years. Vertical lines are the uncertainty associated with the LiDAR error and the dashed lines represent the lines of best fit. Pearson *r* and associated *p*-value are printed in the lower-left-hand corner of the plots.

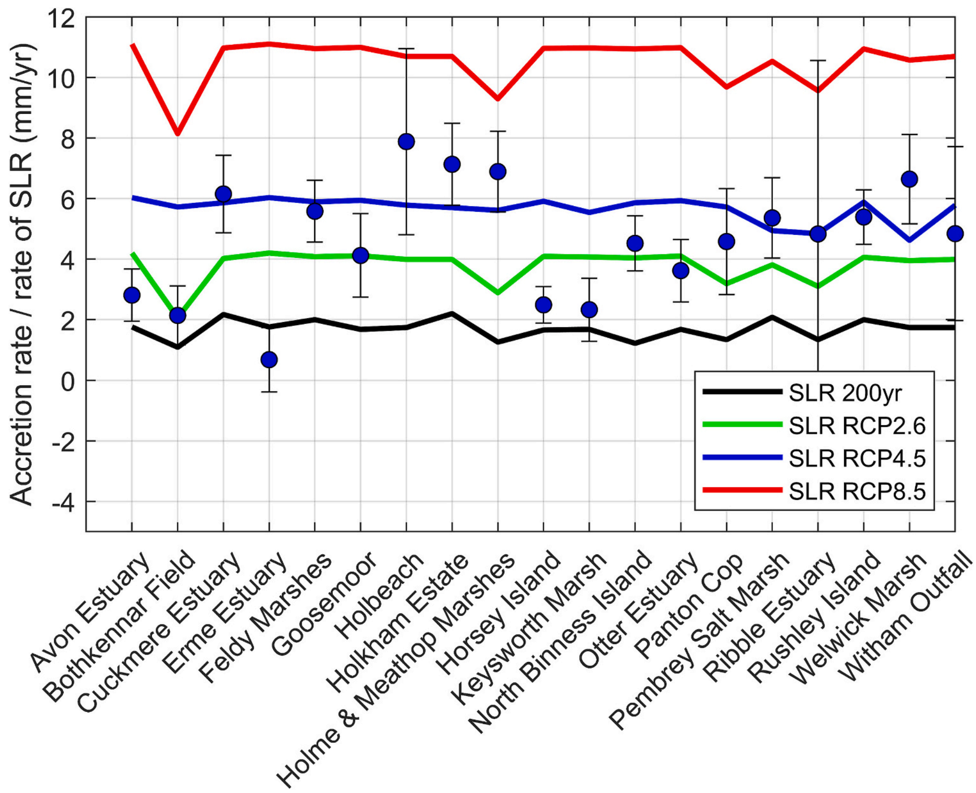

Fig. 6. Comparison of salt marsh accretion rate and rate of sea-level rise for historic (200 yr) and IPCC projections.

marsh cliffs, by a factor of 10–20. The reclaimed salt marsh method deployed here filters out the marsh edge and creeks; hence, only the top surface of the marsh is considered. Moreover, the accretion rate averaged over the complete marsh region is computed, thus including both upper and lower marsh regions. It is well known that accretion rates across the lower marsh are significantly larger than that across the upper marsh (French and Spencer, 1993), a clear influence of hydroperiod, and marsh-averaged accretion rates are likely biased towards the lower marsh values.

The future of salt marsh environments depends on the balance between the vertical accretion rate and the rate of SLR (Reed, 1995; Cahoon, 2006; Fagherazzi et al., 2012; Kirwan et al., 2016). There is no clear consensus as to whether salt marshes are sufficiently resilient and will be able to keep up with rising sea level (Day et al., 2007; Kirwan et al., 2016), but sediment supply is widely acknowledged as playing a key role (Boyd et al., 2017). For most of the studied UK salt marshes, the current long-term rate of accretion is less than that predicted according to RCP4.5 and RCP8.5 (IPCC, 2014); however, these rates are expected to increase with increasing hydroperiod due to SLR (Friedrichs and Perry, 2001; Van Wijnen and Bakker, 2001; Fagherazzi et al., 2012). The current accretion rates do, however, provide some insight into the potential resilience of UK salt marshes, and it can be concluded that the marshes in macrotidal environments are likely to be more resilient than those in micro- and meso-tidal settings.

5. Conclusion

Long-term salt marsh accretion rates were estimated from the elevation difference between a natural marsh and a neighbouring reclaimed marsh, referred to as the reclaimed salt marsh method, for 19 UK salt marshes. The accretion rate averaged across all sites was 4.5 mm/yr, but there was a considerable inter-site variability, with accretion rates increasing with the mean spring tide range. Observed long-term accretion rates are generally larger than SLR rates predicted according to RCP2.5, comparable to that predicted according to RCP4.5 and less than that predicted according to RCP8.5. It is suggested that UK salt marshes in macrotidal settings are most resilient to SLR. The reclaimed salt marsh method can be readily applied to other sites to obtain a global data base of marsh accretion rates.

CRediT authorship contribution statement

Gerd Masselink: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Supervision, Writing – original draft. **Robert B. Jones:** Formal analysis, Writing – review & editing.

Declaration of Competing Interest

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

Data availability

LiDAR elevation data are available through the SW Regional Monitoring Programme (SWRMP) for sites in SW England (https://southwest.coastalmonitoring.org/), while Digimap was used for other sites (EDINA, 2021).

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