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Saltmarsh blue carbon accumulation rates and their relationship with sea-level rise on a multi-decadal timescale in northern England

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ABSTRACT

Saltmarshes are widely thought to sequester carbon at rates significantly exceeding those found in terrestrial environments. This ability arises from the in-situ production of plant biomass and the effective trapping and storage of both autochthonous and allochthonous organic carbon. The role saltmarshes play in climate change mitigation, through accumulating 'blue' carbon, depends on both the rate at which carbon accumulates within sediments and the rapidity with which carbon is remineralised. It has been hypothesised that carbon accumulation rates, in turn, depend on the local rate of relative sea-level rise, with faster sea-level rise providing more accommodation space for carbon storage. This relationship has been investigated over long (millennial) and short (decadal) timescales but without accounting for the impact of higher quantities of labile carbon in more recently deposited sediment. This study addresses these three key aspects in a saltmarsh sediment study from Lindisfarne National Nature Reserve (NNR), northern England, where there is a comparatively pristine marsh. We quantify rates of carbon accumulation by combining a Bayesian age-depth model based on ^{210}Pb and ^{137}Cs activities with centimetre-resolution organic carbon density measurements. We also use thermogravimetric analyses to determine the relative proportions of labile and recalcitrant organic matter and calculate the net recalcitrant organic matter accumulation rate. Results indicate that during the 20th century more carbon accumulated at the Lindisfarne NNR saltmarsh during decades with relatively high rates of sea-level rise. The post-depositional loss of labile carbon down the core results in a weaker though still significant relationship between recalcitrant organic matter accumulation and sea-level change. Thus, that increasing saltmarsh carbon accumulation is driven by higher rates of sea-level rise is demonstrated over recent multi-decadal timescales.

1. Introduction

Saltmarshes are highly valuable ecosystems that provide a range of services important for humans, wildlife and the environment (Barbier et al., 2011). Most relevant to this study is their ability to sequester large quantities of atmospheric carbon dioxide (Chmura et al., 2003; Macreadie et al., 2021). This is achieved through the input of organic matter (OM) from both the primary productivity of saltmarsh plants (autochthonous carbon) and from tidally delivered material (allochthonous carbon), coupled with the anaerobic conditions produced by frequent tidal inundation that lead to low decomposition rates (Mcleod et al., 2011; Saintilan et al., 2013). It has been estimated that carbon burial rates in saltmarshes are up to fifty times greater than those of terrestrial forests (Mcleod et al., 2011). This has led to the recent interest in saltmarshes as a nature-based solution to climate change, capable of storing large quantities of carbon for significant lengths of time (Lovelock and Duarte, 2019; Mason et al., 2022).

Despite the numerous benefits they provide, many saltmarshes have become degraded due to human activity and climate change (Pendleton et al., 2012; Mariotti and Carr, 2014; Lopes et al., 2021). Loss can occur

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via marsh fragmentation, creek widening, edge erosion, coastal eutrophication and coastal squeeze (Duran Vinent et al., 2021; Burns et al., 2021; Marani et al., 2011; Deegan et al., 2012; Doody, 2004). One cause for great concern is the potential for rapid rates of sea-level rise (Church and White, 2011) to submerge these ecosystems (Reed, 1995; FitzGerald et al., 2008; Kirwan and Megonigal, 2013; Horton et al., 2018). However, it has been demonstrated that many marshes are in fact increasing their elevation through vertical accretion at rates similar to or above the rate of sea-level rise (Kirwan et al., 2016). The ability of marshes to gain elevation is dependent upon the space available for mineral and organic matter accumulation, known as accommodation space (Jervey, 1988; Muto and Steel, 2000; Kirwan and Guntenspergen, 2010; Rogers et al., 2019; Rogers, 2021). Accommodation space is filled by the accretion of mineral sediment (French, 1993; Allen, 1995) and the accumulation of OM (Orson et al., 1985; Nyman et al., 1993). Higher rates of sea-level rise result in increased delivery of mineral sediment and can therefore lead to an equilibrium between sea-level rise and saltmarsh mineral accretion (French, 1993). Vegetation can also contribute to the trapping of mineral sediment (e.g., Ranwell, 1964; Gleason et al., 1979; Li and Yang, 2009; Mudd et al., 2010; Kirwan and Guntenspergen, 2012). Furthermore, for certain plant species, it has been demonstrated that an optimum level of sea-level rise exists at which productivity (and thus OM production) is maximised (Morris et al., 2002; Mudd et al., 2009), meaning that marshes experiencing this optimum receive a greater input of OM to further aid with elevation gain. However, differences in factors such as mineral sediment and OM supply and rate of sea-level rise create spatial variation in the responses of saltmarshes to rising sea-levels.

Owing to the established relationship between more frequent tidal inundation and plant productivity, marshes in areas undergoing sea-level rise are likely to have increased OM accumulation rates. The intrinsic link between OM and carbon (C; Craft et al., 1991) suggests that enhanced OM accumulation driven by sea-level rise could also increase the C sequestration capacity of saltmarshes. In a large-scale review of existing data, Rogers et al. (2019) showed that saltmarshes on coastlines experiencing faster rates of sea-level rise over the past few millennia do in fact have higher soil C concentrations than those experiencing slower rates. In line with these results, modelling approaches have also predicted that an increase in sea-level rise will result in higher rates of C sequestration (Wang et al., 2021), although some predict this will eventually diminish if the rate of sea-level rise exceeds the ability of saltmarshes to keep pace (Kirwan and Mudd, 2012; Horton et al., 2018). Other studies have found that the relationship between carbon accumulation and sea-level rise exists on decadal timescales (Choi and Wang, 2004; Breithaupt et al., 2018; McTigue et al., 2019; Herbert et al., 2021; Miller et al., 2022). Although some of these studies acknowledged that higher carbon accumulation rates in younger sediment is primarily due to less OM having been degraded and removed, they did not attempt to quantify the relationship between sea-level rise and the OM that is more resistant to remineralisation.

It has also been suggested that higher rates of RSL rise aid OM accumulation by slowing decomposition rates (e.g., Davidson and Janssens, 2006); however, several studies have now shown that sea level has a negligible impact upon the decomposition rate of newly deposited OM (Kirwan et al., 2013; Janousek et al., 2017; Mueller et al., 2018). Despite this, decomposition is still an important process in determining the quantity of OM, and therefore C, stored in saltmarsh sediments for the long term (Valiela et al., 1985). Also important is the chemical composition of the OM, which comprises molecules that range in terms of degradability. At one end of the scale are simple labile molecules that are easily broken down and, at the other, lie more complex recalcitrant and refractory compounds, which are relatively unreactive and difficult to degrade (Sollins et al., 1996; Lützow et al., 2006; Arndt et al., 2013). In deep layers of saltmarsh sediment, the pool of C resistant to decay is larger because most labile organic carbon (OC) has been broken down and sufficient time has passed for the stabilisation of OM via various physical processes to occur. In this study, the chemical lability of the OM is considered. This is additional to what is usually included in studies of blue carbon, which raises the question of whether efforts should be made to incorporate this aspect of ecosystem functioning into future work.

This study aims to investigate the link between OC and OM sequestration and sea-level rise at a much greater temporal scale than previously attempted by examining the rates of these variables associated with each centimetre of sediment in a core from a Northumbrian (United Kingdom) saltmarsh. Placing the focus upon a young marsh that has only been accreting saltmarsh sediment for ~70 years allows this study to investigate the relationship between carbon accumulation and sea level on a multi-decadal timescale. It is hypothesised that years when the area experienced higher rates of sea-level rise will be represented in the core by sections of sediment with higher rates of OC accumulation. Further to this, the contributions of labile and recalcitrant OM to saltmarsh sequestration rates are considered, the expectation being that levels of recalcitrant OM will remain correlated with the rate of sea-level rise while labile organic matter content decreases down the core as it is degraded.

2. Study area

The study area is Lindisfarne National Nature Reserve (NNR), situated approximately 16 km to the south of Berwick-upon-Tweed in Northumberland, northern England (Fig. 1a). The site comprises 3500 ha of sand dunes, saltmarshes and mudflats (Natural England, 2014). Saltmarshes make up 247 ha of the total area (Environment Agency, 2022). Separated from the mainland by a tidal causeway is the island of Lindisfarne, also known as Holy Island.

Based on the deployment of a water-level logger from 10/03/22 to 20/04/22, we estimate a mesotidal mean tidal range of 2.74 m, with a mean tide level of 0.33 m above geodetic datum (UK Ordnance Datum, OD) and a highest astronomical tide of 3.07 m OD (Gore et al., 2023).

Within Lindisfarne NNR, the Snook saltmarsh is the area of focus for this study. This site is located adjacent to the causeway leading from the mainland to Holy Island (Fig. 1b). The saltmarsh displays clear zonation of plant species in high, mid and low marsh zones; the high marsh has a preponderance of *Armeria maritima* and *Puccinellia maritima*, both of which continue in high proportions into the mid marsh but with increasing levels of *Atriplex portulacoides*. The low marsh plant community is dominated by *Spartina anglica* and *Salicornia europaea*. No erosional features, such as marsh cliffs, are present at its seaward edge. Furthermore, the marsh first appears on maps in the ~1960s and continues to expand from this point, indicating that the marsh is actively accreting (Ordnance Survey, 1965). This suggests the marsh is successfully keeping pace with sea-level rise and so further demonstrates the suitability of the area for conducting this sediment study.

3. Materials and methods

3.1. Sampling

We mapped and assessed the consistency of the stratigraphy of the Snook saltmarsh using three transects of hand-driven 3 cm-diameter gouge cores (Fig. 1c). To ensure all major marsh zones were encountered, two transects ran perpendicular to the shore while the third transect ran diagonally to the shore and intersected the first two (Ladd et al., 2022; Smeaton et al., 2023). All cores were described using the Troels-Smith classification system (Troels-Smith, 1955). The stratigraphic survey allowed us to identify the location with the thickest sequence of organic sediment, which had the greatest potential to provide a long record of the interplay between sea-level change and carbon accumulation. Core LI21/20 (6 cm diameter; 40 cm length), was recovered from the high marsh (55.6810, −1.8434; 2.56 m OD), using a 5 cm diameter gouge corer. The stratigraphic survey also enabled us to confirm the lateral continuity of the organic saltmarsh sediment,

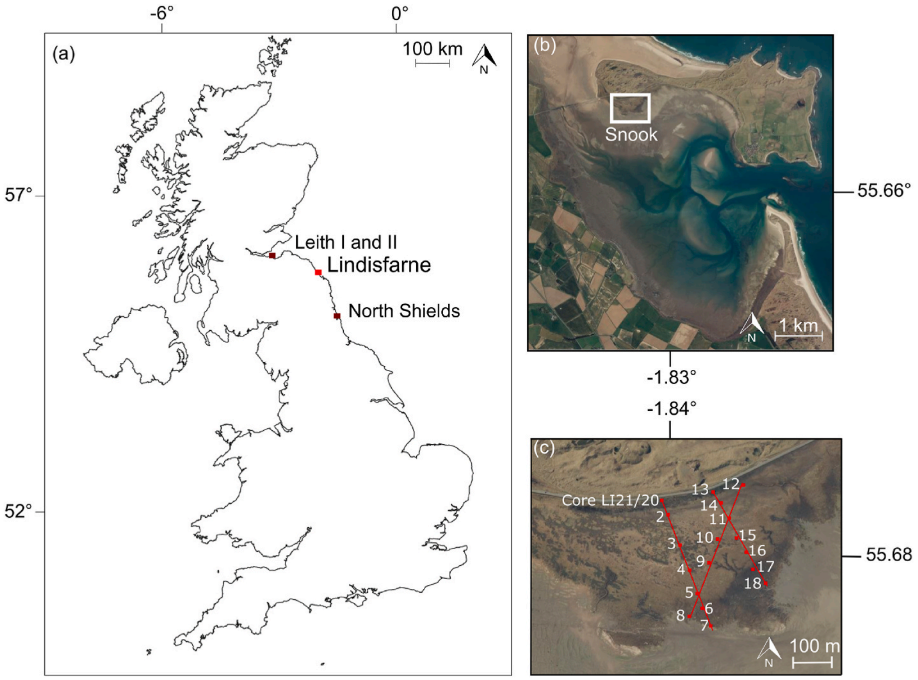

Fig. 1. Locations of (**a**) Lindisfarne NNR, the North Shields tide gauge and Leith I and II tide gauges used to assess the rates of sea-level rise experiences by the area; (**b**) the Snook saltmarsh on Holy Island within Lindisfarne NNR; and (**c**) coring locations on the marsh. The sampled core, LI21/20 is indicated.

providing greater confidence that the master core was representative of the wider high marsh environment at the Snook saltmarsh. In high marsh environments, vertical accommodation space is created by sea-level rise, while in lower marsh areas vertical accretion mainly results from sediment infill (Gehrels, 2000). Therefore, high marshes are more suitable to establish the relationship between sea-level rise and OC accumulation as the rate of sea-level rise is the limiting factor for the rate of sediment accumulation. The core was collected in April 2021 (22/04/21) and stored at less than 4°C prior to elemental and thermogravimetric analyses.

3.2. *Carbon analysis*

Core LI21/20 was sampled at a 1 cm resolution and the OC content and dry bulk density of each sample determined. OC content was quantified following standard methods (Verardo et al., 1990; Nieuwenhuize et al., 1994). Briefly, 10 mg of each sample were placed in silver capsules and acidified with HCl (10%) to remove carbonates ($CaCO_3$). The samples were dried overnight at 50 °C before being sealed. To quantify OC, a Thermo Flash EA 1112 NC elemental analyser was used. Dry bulk density was calculated by dividing the dry mass of the sample by the volume prior to drying (Dadey et al., 1992). OC density (g cm^{-3}) was calculated by multiplying the dry bulk density (g cm^{-3}) by the organic carbon content (%; Howard et al., 2014).

3.3. *Thermogravimetric analysis*

Thermogravimetric analysis (TGA) followed the protocol described by Smeaton and Austin (2022). Briefly, milled samples were placed in a Mettler Toledo TGA2 and heated from 40 °C up to 1000 °C under a constant stream of N_2. The temperature ranges were 200°C–400 °C for labile and 400°C–650 °C recalcitrant organic matter (OM). Labile and recalcitrant OM densities were calculated in the same way as OC density, detailed above.

3.4. *Radiometric dating*

Wet subsampling was employed and levels of unsupported ^{210}Pb and ^{137}Cs were determined in each centimetre down the core until a depth of 20 cm, after which two more measurements were made at 25 cm and 30 cm depths. Radionuclide samples were analysed by gamma spectrometry at the Consolidated Radio-isotope Facility (CoRIF), University of Plymouth.

The age-depth model generated using this data was developed in the R package *rplum*, version 0.3.0 (Blaauw et al., 2023). Using *rplum* negates the need to select an equilibrium depth and does not require that the whole core be sampled, meaning that missing data does not become problematic (Aquino-López et al., 2018). Furthermore, *rplum* allows for the simultaneous integration of other chronohorizons, including the ^{137}Cs data used here, without the need to remodel the outputs of traditional ^{210}Pb-only models. This age-depth model not only provided the ages of the sediment but also the sediment accretion rates (mm yr^{-1}), which were used to calculate the OC, recalcitrant OM and labile OM accumulation rates (g m^{-2} yr^{-1}) by multiplying the SAR values of each centimetre by the corresponding OC/recalcitrant OM/labile OM density (g cm^{-3}).

3.5. *Relative sea-level rise*

The OC and OM accumulation rates are compared with rates of sea-level change calculated using nearby tide gauge data to determine the effect of rising RSL on these variables through time. The tide-gauge data used for this purpose is from North Shields, the tide gauge closest to the study area (77 km to the south; Fig. 1a). The Leith tide gauges (92 km to the northwest; Fig. 1a), show a similar record to North Shields for the overlapping period (see section 4.5), justifying this interpolation to the core location. Trends in sea level were obtained with a Gaussian process regression (cf. Rasmussen and Williams, 2006; Cahill et al., 2015) using the annual North Shields tide gauge dataset. We assume a linear trend mean and Matérn covariance functions, with hyperparameters for each function (i.e., intercept and gradient, and amplitude, length-scale and order parameter, respectively) determined from the data by maximising the likelihood of a given set of observations (i.e., minimizing the negative log likelihood) using the bound-constrained limited memory BFGS optimization (‘L-BFGS-B’) algorithm. The Gaussian process function is then constructed from these ‘optimal’ hyperparameters and evaluated at 1-year intervals. Rates of sea-level rise are the first derivative of the recovered sea-level reconstruction, and average rates for each dated interval are a Gaussian weighted mean based upon the age estimates (and uncertainty) from the *rplum* age model. Regression analyses were performed to evaluate whether sea-level rise influences carbon accumulation rates. Model residuals were visually inspected using diagnostic plots and normality was confirmed.

4. Results

4.1. Stratigraphy

The Snook saltmarsh shows a relatively consistent pattern of stratigraphy across all three transects of narrow diameter gouge cores (Figs. 1 and 2). Along the first transect (numbered 1–7 on Fig. 2a) these cores generally consist of a layer of coarse sand (14–30 cm thick), usually mid-grey in colour, which, at lower elevations, is overlain by mid-grey organic silt (8–30 cm thick), often containing rootlets. Higher up the marsh, the sand layers in most cores are overlain by mid-brown silty herbaceous peat (9–20 cm thick; Fig. 2a). In the middle marsh zone, all three layers, sand, silt and peat, are present (Fig. 2b). The cores of the second transect (13–18 on Fig. 2b) show a similar pattern to those of the first except for the presence of an underlying shell hash layer (16–24 cm thick) and the fact that the sand becomes finer at the lower elevations (Fig. 2b). Cores from the third transect (12-8 on Fig. 2c) again exhibit the pattern of coarse sand (15–21 cm thick), overlain by organic silt (4–31 cm thick) and silty herbaceous peat (10–20 cm thick), except in the lowest elevation core, which contains coarse sand topped only by a layer of organic silt (Fig. 2c). The ‘master’ core recovered from the high marsh zone at the landward end of the first transect using a wide diameter gouge corer, core LI21/20, consists of a 2 cm-thick layer of coarse sand with an overlying 18 cm-thick layer of silty sand. There is a gradual transition to an 8 cm thick layer of humified peat, which is topped by an 8 cm-thick layer of fibrous peat. (Fig. 2d).

4.2. Carbon and bulk density analysis of core LI21/20

From the bottom of the core until a depth of 15.5 cm, OC content is very low, ranging from 0.21 to 0.44 % (Fig. 3a). At 15.5 cm, a large jump in OC occurs and this increase then continues steadily up the core, starting at 12 % and ending at 28 % in the uppermost sample. (Fig. 3a). Labile and recalcitrant OM content both follow a similar pattern; levels are consistently low (both <1 %) until a substantial increase is seen at 16.5 cm depth (Fig. 3b and c). Across the peat section, labile OM content increases from 9.79 % to 26.64 % (Fig. 3b); this increase is less linear than that seen in OC content (Fig. 3a). Conversely, recalcitrant OM content remains at a similar level throughout the peat section, with a mean of 8.05 ± 0.73 %. The large increases in OC and OM content are at the transition from mineral to organic sediment in the core (Fig. 2a).

Bulk density in the lower half of the core, comprising mineral sediment, has highly variable values, with a peak of 1.53 g cm^{-3} at 31.5 cm and a low of 0.25 g cm^{-3} in the lowest sample (Fig. 3d). This latter value

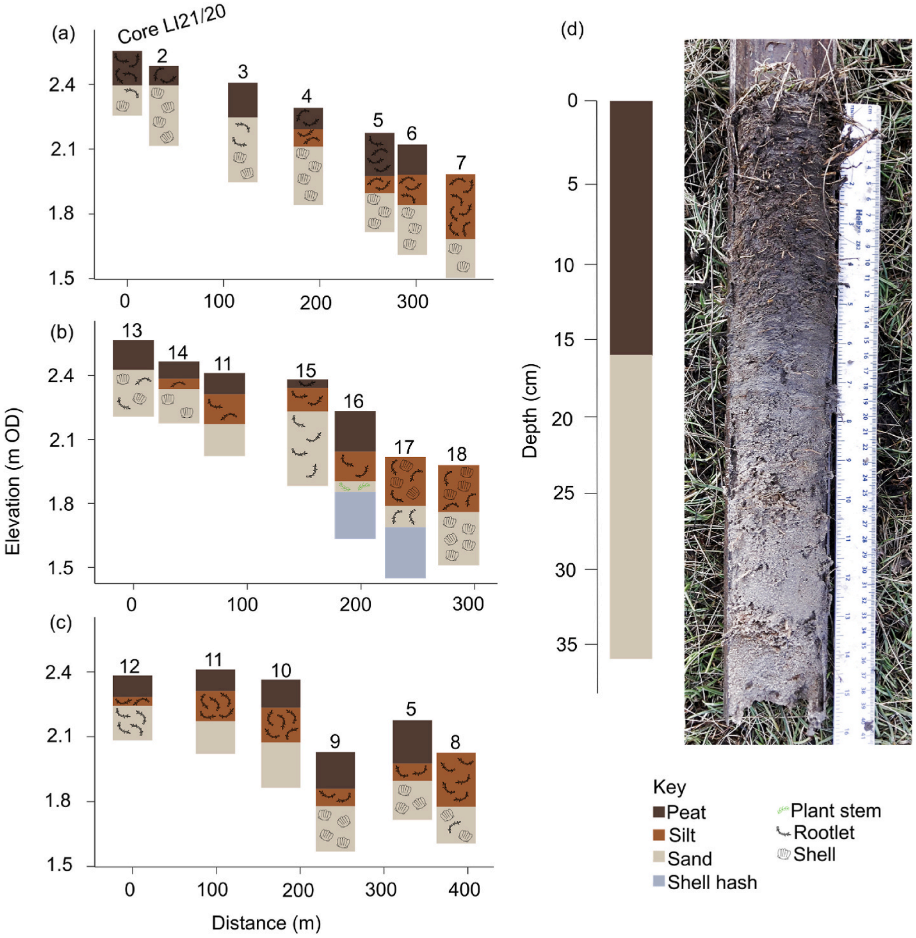

Fig. 2. Stratigraphy of the Snook marsh. Specifically, (**a-c**) the three transects of cores taken across the marsh and (**d**) simplified stratigraphy and photograph of core LI21/20. The labels at the top of each bar correspond to those in Fig. 1c.

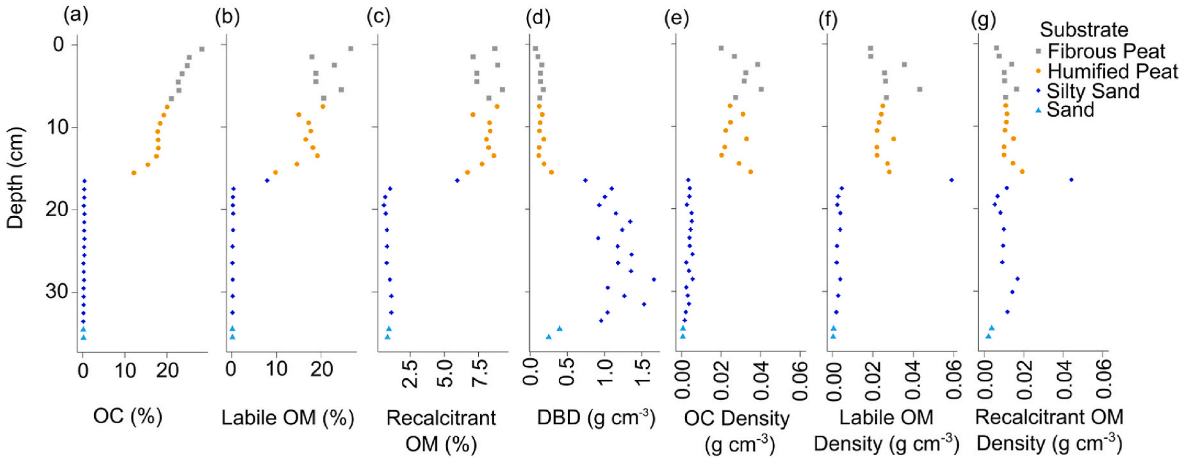

Fig. 3. Content of core LI21/20. Levels of (**a**) organic carbon (OC), (**b**) labile organic matter (OM), (**c**) recalcitrant OM and (**d**) dry bulk density (DBD) are shown, which are in turn used to calculate (**e**) OC density, (**f**) labile OM density and (**g**) recalcitrant OM density.

is similar to the bulk density of the organic segment of the core, where values remain very stable throughout with a mean of 0.18 ± 0.15 g cm^{-3} (Fig. 3d).

The OC density (the product of bulk density and OC content) of the sand section of the core ranges from 0.0055 to 0.0005 g cm^{-3} (Fig. 3e). The lowermost peat sample has a relatively high OC density of 0.035 g cm^{-3} (Fig. 3e). Subsequently, there is a sharp drop in OC density and a low of 0.020 g cm^{-3} is reached at 12.5 cm depth. Density values then vary widely but reach a high of 0.040 g cm^{-3} at a depth of 4.5 cm (Fig. 3e). From this point, values tend to decrease, and OC density is lower (0.020 g cm^{-3}) at the very top of the core (Fig. 3e). Labile OM density closely follows the trends in OC density across the core. In the mineral sediment unit, density is low in all except the uppermost sample; this outlier has a value of 0.059 g cm^{-3} (the highest seen throughout the entire core) while the remainder range between 0.0004 and 0.005 g cm^{-3}. In the organic unit, labile OM density is generally an order of magnitude greater, and peaks appear at similar points to those in OC density (e.g., at 3, 6 and 12 cm depth). The pattern of recalcitrant OM density differs markedly from those of both OC and labile OM density. Along the entire length of the core, values remain relatively consistent (mean is 0.012 ± 0.007 g cm^{-3}). Here too, however, there is particularly high OC density in the uppermost sand sample (0.044 g cm^{-3}).

4.3. Age-depth model and sediment accretion rates

^{210}Pb and ^{137}Cs data were used to create an age-depth model (Fig. 4a) in *rplum* (Blaauw et al., 2023). The Sellafield ^{137}Cs discharge peak (modelled as 1980 ± 5 years, Tsompanoglou et al., 2011; Swindles et al., 2018) is visible at a depth of 14.5 cm (Fig. 4b) and total ^{210}Pb activities decline from the surface and reach supported ^{210}Pb levels (<10 Bq kg^{-1}) at a depth of 19.5 cm (Fig. 4c). The age model provides 2 σ uncertainties of less than 20 years above a depth of around 13.5 cm, below which point, they increase down the core to 49 years at 18.5 cm depth and 58 years at the base of the core (Fig. 4a).

Sediment accretion rates (SAR) were also obtained from the *rplum* model (Fig. 4d). The lowermost centimetre of sediment has an accretion rate of 1.50 ± 3.17 mm yr^{-1} and SAR stays at a similar level until around 15.5 cm (Fig. 4d). Above this, SAR gradually increases from 1.98 ± 1.52 mm yr^{-1} to a rate of 5.86 ± 2.67 mm yr^{-1} in the top centimetre of the core (Fig. 4d). The point at which SAR starts to increase coincides with the transition from sand to peat (Fig. 2a).

4.4. Carbon and organic matter accumulation rates

Sediment accumulation rates (SAR) were used with the OC and OM density values to calculate the OC, labile OM and recalcitrant OM

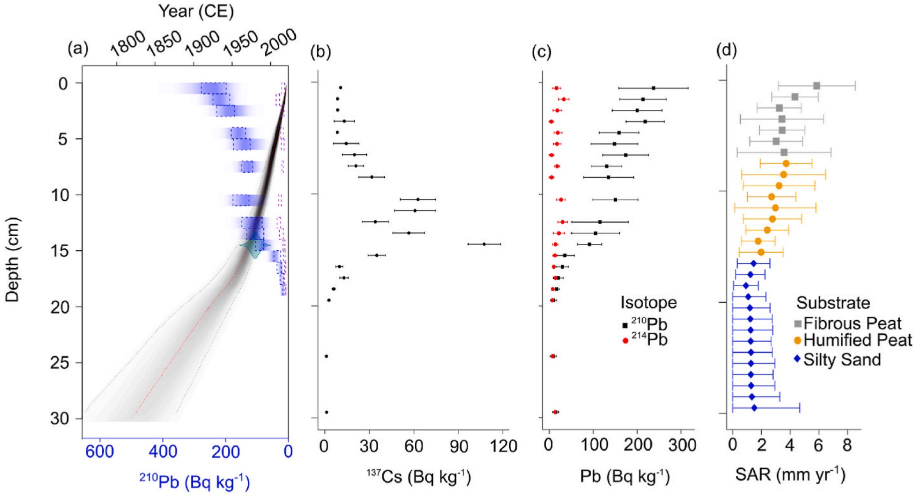

Fig. 4. (**a**) The Bayesian age-depth model for core LI21/20 with the blue shaded areas representing the total ^{210}Pb level, the model itself represented by the black shaded area and the ^{137}Cs peak shown as a calendar date (1980 ± 5) at 14.5 cm depth. The model was generated using (**b**) ^{137}Cs and (**c**) ^{210}Pb data with the package *rplum* (Blaauw et al., 2023); (**d**) sediment accretion rates (SAR) were obtained from this model. Error bars are ±2 σ.

accumulation rates (Fig. 5). The carbon accumulation rate (CAR) increases up the core and shows a dramatic increase consistent with the transition from mineral sediment to peat. In the mineral section, CAR never exceeds 7.5 g m^{-2} yr^{-1}; after the transition to peat, CAR values fluctuate from 48.7 ± 30.1 to 124.9 ± 59.1 g m^{-2} yr^{-1}. The mean CAR of the Snook saltmarsh, taken as the mean CAR of the peat section of core LI20/21, is 91.6 ± 59.4 g m^{-2} yr^{-1}.

The labile organic matter accumulation rates change similarly to CAR across the core (i.e., increasing from the bottom of the core; Fig. 5a). Excluding the outlier value discussed above, values are low in the sand section (ranging between 2.6 ± 2.4 and 5.7 ± 4.7 g m^{-2} yr^{-1}). Accumulation rates then increase through the peat section from 48.4 ± 32.1 g m^{-2} yr^{-1} to 130.6 ± 79.4 g m^{-2} yr^{-1} in the uppermost centimetre; the mean labile OM accumulation rate of the peat section is 83.3 ± 54.1 g m^{-2} yr^{-1}. Recalcitrant organic matter accumulation rates remain relatively stable throughout (Fig. 5c); values are slightly lower in the mineral section (5.8 ± 6.5–14.0 ± 11.6 g m^{-2} yr^{-1}, excluding the outlier with a value of 64.2 ± 50.0 g m^{-2} yr^{-1}) than in the peat (24.0 ± 14.8–49.3 ± 29.9 g m^{-2} yr^{-1}). The mean recalcitrant OM accumulation rate of the peat section is 35.9 ± 23.8 g m^{-2} yr^{-1}.

4.5. *Relative sea-level rise*

The North Shields and Leith tide gauges (locations in Fig. 1a) record an increase in relative sea-level (RSL) up to the present day. In North Shields, the tide gauge has recorded ca. 0.2 m of relative sea-level rise between 1896 and 2017 (Fig. 6a). The Leith recordings began later, in 1956, but the RSL trend since has been similar to the North Shields record (Fig. 6a). Both tide gauges are highly consistent in their records (Fig. 6a) which leads to the expectation that a similar sea-level trend was experienced in Lindisfarne NNR, which lies between them (Fig. 1a). As it provides a longer and more complete record, we focus analyses on the North Shields data.

The rates of sea-level change at North Shields increase rapidly from the time at which the sediment at 19.5 cm (age range: 1893.4–1951.8 CE) depth in core LI21/20 was being deposited, from 2.07 ± 0.90 mm yr^{-1} to 2.30 ± 0.68 mm yr^{-1} during the period represented by 18.5 cm depth (age range: 1910.6–1959.7; Fig. 6b). The rate then falls sharply to 1.22 ± 0.27 mm yr^{-1} at 13.5 cm (age range: 1964.8–1985.2) before rising consistently throughout the rest of the core (Fig. 6b). The most recent value (0.5 cm depth; age range: 2020.4–2020.1) reaches a high of 2.90 mm yr^{-1} (Fig. 6b).

4.6. *Carbon sequestration and sea-level rise*

Regression indicates that rates of RSL explain a significant portion of the variation in CAR in the peat section (the unit relating to saltmarsh sedimentation) of the Lindisfarne NNR core (ANOVA: $F = 54.6000$; *d.f.* = 1,14; p = 3.41 x 10-5; Fig. 7). Rates of RSL change also explain a significant portion of the variation in recalcitrant OM accumulation, although this relationship is weaker (ANOVA: $F = 5.6350$; *d.f.* = 1, 14; $p = 0.0493$; Fig. 7). We do not analyse the relationship between RSL rates and labile OM accumulation rates because this fraction of OM is broken down over time and therefore is expected to be reduced in deeper, older layers of the core. The results of these analyses support the hypothesis that increased rates of sea-level rise result in higher blue carbon accumulation rates.

Additionally, the Lindisfarne NNR core displays a significant positive relationship between the rates of RSL rise and sediment accretion (ANOVA: $F = 6.7930$; *d.f.* = 1,14; $p = 0.0179$; Fig. S1). Conversely, between OC density and the rate of RSL rise no significant relationship is detected (ANOVA: $F = 0.2828$; *d.f.* = 1,14; $p = 0.6010$; Fig. S2).

5. Discussion

The significant relationship detected between OC accumulation and the rate of RSL rise is further evidence to show that sea-level rise can enhance CAR over relatively short (multi-decadal) timescales. When recalcitrant OM accumulation rate is used in the analysis instead of CAR, this significant relationship is weakened though maintained, suggesting

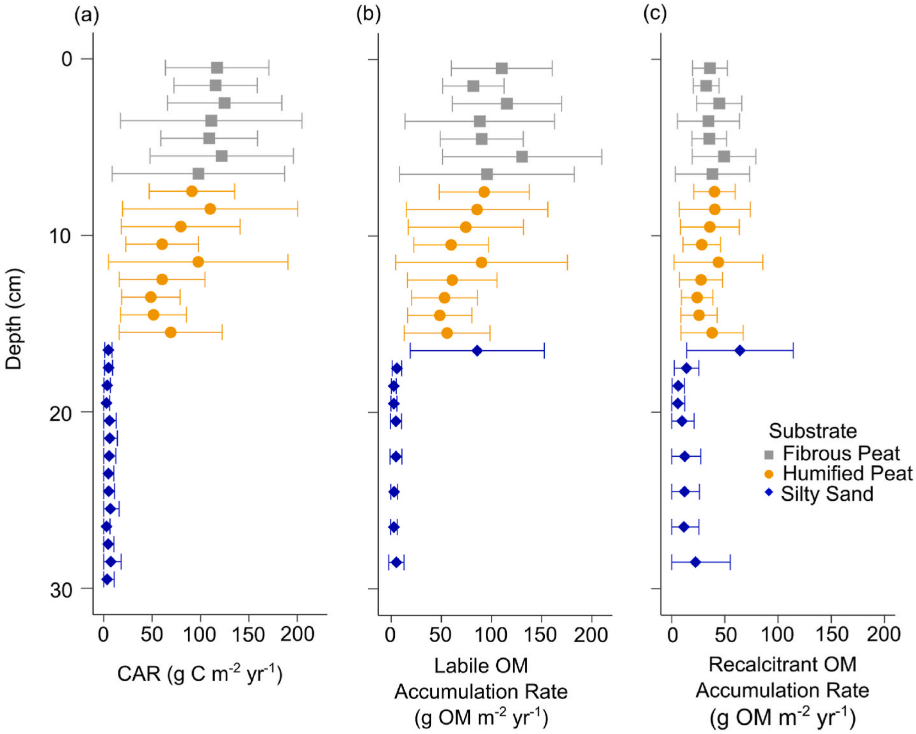

Fig. 5. Accumulation rates of core LI21/20. Sediment accretion rates (Fig. 4d) are multiplied with the density values (Fig. 3) to calculate (**a**) carbon accumulation rate (CAR), (**b**) labile organic matter (OM) accumulation rate, and (**c**) recalcitrant OM accumulation rate. Error bars are ±2 σ.

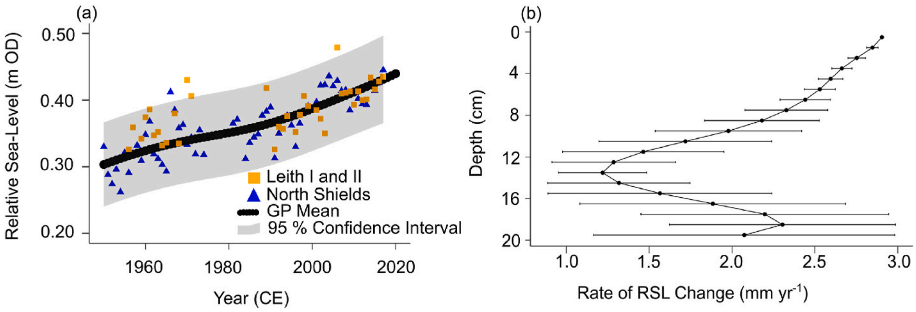

Fig. 6. Tide gauge data recorded at North Shields and Leith (see Fig. 1 for locations). The records show (**a**) rising sea levels and the Gaussian Process (GP) mean used to calculate (**b**) the rates of RSL change for the time periods represented by each centimetre of sediment in core LI21/20. Error bars are ±2 σ.

that the effect is, to an extent, independent of labile OM remineralisation. In this section, we discuss how assessing the recalcitrant and labile OM densities and accumulation rates leads to questions about how much of the OM deposited on the marsh is sequestered for meaningful lengths of time and helps to highlight the relatively underappreciated potential of unvegetated tidal flats as blue carbon stores.

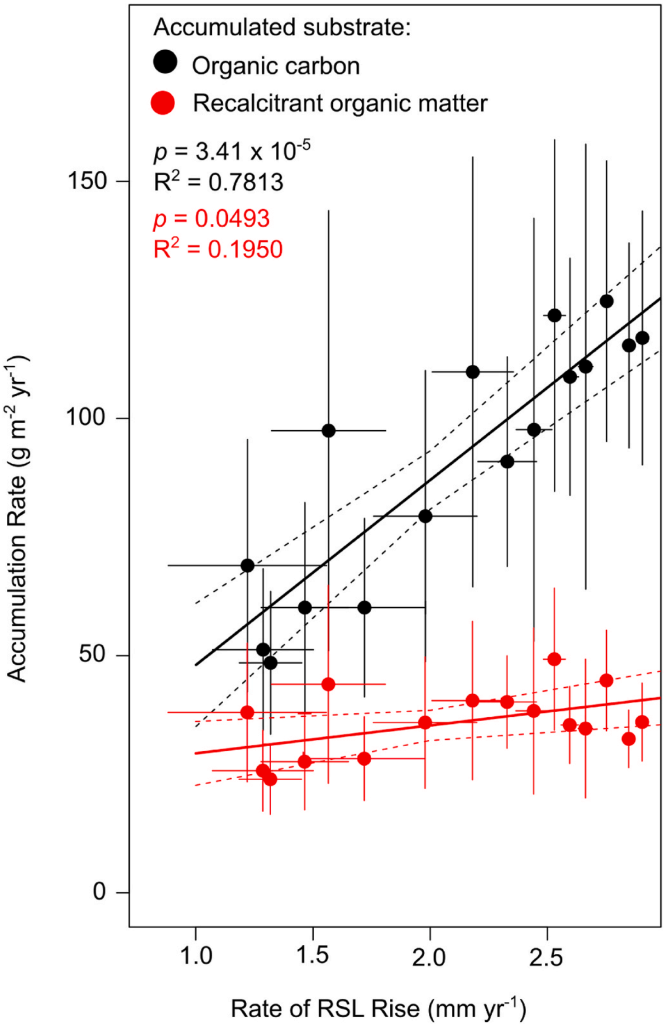

Fig. 7. Regression analysis of the contribution of sea-level rise to increased CAR (shown in black) and increased recalcitrant organic matter accumulation rates (shown in red). This analysis was performed using only samples from the peat section of core LI21/20 as this is representative of a saltmarsh ecosystem. Error bars are ± 1σ.

5.1. Sea-level rise and blue-carbon accumulation

Investigating the effect of sea-level rise on saltmarsh OC accumulation globally, Rogers et al. (2019) identified a link between regions characterised by millennial-scale sea-level rise and higher OC concentrations in the uppermost metre. The Snook saltmarsh is around 70 years old, and our study provides further evidence to demonstrate the existence of a relationship between carbon accumulation and sea level on a multi-decadal timescale. This relationship appears to hold for rates of a few millimetres per year and carbon accumulation may be further enhanced by more rapid rates of sea-level rise (Rogers et al., 2019); however, at a critical threshold, marshes will be unable to keep up with excessively high rates of rise (Kirwan and Megonigal, 2013; Horton et al., 2018).

It is worth noting that the rates of RSL rise have fluctuated during the period of sediment accumulation (Fig. 6b) and so are not directly correlated with increasing CAR. However, the strong significant relationship between CAR and RSL rise is confounded somewhat by the fact that labile OC is removed from the sediment over time. Labile OC is the fraction of soil C susceptible to short-term turnover via microbial decomposition (Zhang et al., 2020); therefore, lower down the core (and thus further back through time) the labile fraction of the OC stock is more likely to have been remineralised. Owing to this, the periods of time represented by sediment towards the bottom of the core when sea-level rise was less rapid also necessarily have lower CAR. This problem is overcome by considering recalcitrant OM accumulation rates. The weaker positive relationship found between recalcitrant OM accumulation and RSL rise suggests that the loss of labile OM does influence the CAR regression analysis. The importance of considering OC density change down the core has been highlighted previously by Mueller et al. (2019) – OC density levels often do not stabilise (i.e., no longer decrease) until 20–40 cm depths. However, the fact that the relationship between the rate of RSL rise and recalcitrant OM accumulation is still significant lends further credence to the hypothesised enhancement of saltmarsh OC accumulation in response to higher rates of sea-level rise.

5.2. Drivers of increased carbon accumulation

Sea-level rise creates accommodation space for mineral and organic matter accumulation, which are driven by different processes (Rogers et al., 2019). Studies conducted in organogenic US marshes have attributed the increase in OC accumulation caused by sea-level rise to the vertical accretion of OM as plant productivity increases (e.g., Kirwan and Guntenspergen, 2012; Gonneea et al., 2019). Evidence of the impact of sea-level rise on UK saltmarsh plant species is far more limited. One study has demonstrated, using a greenhouse experiment, that flooding increases the biomass of *Aster tripolium* (Lenssen et al., 1995). It has also been shown that *S. anglica* has become increasingly dominant at higher elevations in North West European saltmarshes in response to sea-level rise over the last ~30 years (Granse et al., 2021). This is driven by the ability of this plant to withstand waterlogged conditions by efficiently oxidising the surrounding sediment (Holmer et al., 2002) but it remains unclear whether this translates into enhanced OC accumulation, as is the case with invasive *Spartina alterniflora* in China (Qi and Chmura, 2023). Another process that can lead to enhanced OM accumulation, therefore, is the shifting of plant communities across marsh surfaces over time (Gonneea et al., 2019). The global study by Rogers et al. (2019) showed that a rapid sea-level rise is needed to create the accommodation space required for substantial increases in OM input; under slowly rising or falling sea levels, mineral sedimentation is expected to dominate. Mineral sediment trapping can be enhanced by plant growth either through increasing the plant stems available for particle capture and/or reducing the turbulent kinetic energy of the tides, leading to the settling of sediment (Mudd et al., 2010). Alternatively, it has been demonstrated that sea-level rise can directly increase mineral sedimentation due to longer inundation frequencies (Marion et al., 2009). To unpick the drivers of the relationship detected in this study, therefore, a consideration of local factors is required.

Further regression analyses were conducted to investigate the drivers behind the main result and a significant positive relationship between the rates of RSL rise and sediment accretion was detected (Fig. S1). This could suggest that increased sedimentation is the main driver of the relationships shown in Fig. 7, given that CAR and recalcitrant OM accumulation rate are both calculated using SAR. It cannot be conclusively determined, however, whether this higher SAR is caused directly by sea-level rise increasing inundation frequency and period or is a result of enhanced plant productivity increasing organic inputs and aiding with sediment trapping. As no significant relationship was found between OC density and rate of RSL rise (Fig. S2), increased inundation combined with sediment trapping, rather than enhanced *in-situ* organic sediment production, may be more important in driving higher sediment accumulation rates during periods of faster sea-level rise. It is important to note that other potential drivers exist that were not tested as a part of this study. For example, increasing temperatures and precipitation levels have been shown to enhance OC accumulation in other blue carbon ecosystems (Wang et al., 2021). Therefore, factors other than sea-level rise could be controlling OC accumulation rates.

5.3. Labile and recalcitrant organic matter

Despite the focus of this study being the impact of RSL rise on saltmarsh blue carbon accumulation rates, the data collected and analysed for this purpose can also be used to reflect upon a wider issue within blue carbon science. It is already known that a portion of OM is broken down and released back to the environment, thus not contributing to long term OC stocks and climate mitigation efforts (Belshe et al., 2019). This point is reiterated by the data of this study; both OC and labile OM follow a similar pattern of decreasing content (%), density and accumulation rates down the length of core LI21/20 (Fig. 3e and f). Conversely, recalcitrant OM density maintains a similar level throughout the core (Fig. 3g), including in the sand section.

The convention in blue carbon science is, nevertheless, to measure OC – be this using loss on ignition or elemental analysis techniques – in cores of sediment taken from sites of interest and to use the resulting data to calculate stocks and accumulation rates (Howard et al., 2014; Ouyang and Lee, 2014). However, consideration is rarely given to the decomposition and loss of OC through time. The common method of estimating carbon accumulation rate is to multiply age-depth model derived sediment accretion rates by OC densities (this study; Chmura et al., 2003; Ouyang and Lee, 2014). However, as stated by Van de Broek et al. (2018) and Belshe et al. (2019), depending on which part of the core is used for this purpose, this could result in overestimations. For example, recent studies have calculated rapid rates of carbon accumulation in newly restored saltmarshes (Wollenberg et al., 2018; Mossman et al., 2022) but using the OC content of the upper 0–30 cm of sediment for this purpose results only in estimates of how much OC is deposited and not an understanding of how much is buried for a meaningful period of time (Williamson and Gattuso, 2022). Furthermore, the immediate accommodation space created by restoration is often quickly filled by OC-rich sediment from adjacent environments (Saintilan et al., 2013), as opposed to by the autochthonous OM of in-situ saltmarsh plants. Whether this initial influx of OM is stored for a meaningful length of time is unknown but allochthonous material was shown to be the most recalcitrant in a natural marsh (Saintilan et al., 2013; Van de Broek et al., 2018). However, allochthonous OM is not counted as a part of carbon crediting schemes as there is no way of determining whether this material would have been deposited and buried in a different ecosystem had restoration not occurred (Windham-Myers et al., 2018). In the case of this study, the loss of labile OC has a large influence on the statistical analysis performed using the traditional CAR data and further consideration was required before a conclusion about the influence of RSL rise on OC accumulation rates could be reached.

Applying TGA to bulk soil samples can have complications because of the mixture of organic and mineral matter they contain; however, the main issues arise when the mineral sediment is the portion of interest because the exothermic peaks of the organic component can mask the endothermic peaks of the mineral fraction (Plante et al., 2009). In the case of this study, only the OM was of interest meaning this was less of a problem and further precaution was taken by clipping the temperature range to 200–650 °C to minimise the interference from absorbed water and non-organic materials (Smeaton and Austin, 2022). Therefore, confidence can be placed in the ability of this TGA to estimate the OM content of the samples and, by extension, due to the close linkage between OM and OC (Craft et al., 1991; Smeaton et al., 2022), their OC content.

Chemical lability alone does not necessarily mean the OM will be degraded and released back into the atmosphere (Kleber et al., 2011; Schmidt et al., 2011). Physical processes, such as the formation of soil aggregates and interactions with soil minerals, can result in chemically labile organic matter being “protected” from microbial decomposition (Sollins et al., 1996; Eusterhues et al., 2003). Furthermore, environmental drivers, microbial ecology and enzyme kinetics all have important roles to play in determining which molecules are degraded, and do not always necessarily favour those that are chemically labile (Kleber, 2010). This nuance cannot be captured by TGA but, for the purposes of this study, we consider this approximation to be appropriate as it has been used in this manner by other studies (e.g., Lopez-Capel et al., 2005; Capel et al., 2006; Smeaton and Austin, 2022). Further support is given to this method by the significant correlation detected between depth and labile OM content ($r = -0.72$; $t = -3.84$; $d.f. = 14$, $p = 0.002$; Fig. 3b) but not between depth and recalcitrant OM content ($r = -0.17$; $t = -0.64$; $d.f. = 14$, $p = 0.53$; Fig. 3c). This suggests that the OM classed as ‘labile’ in TGA is in fact lost down the core while the recalcitrant material remains resistant to decomposition.

5.4. Implications for saltmarsh management

While saltmarshes provide a wide range of ecosystem services, much of the current academic and policy focus is on their role as blue carbon stores, leading to the development of, for example, a UK Saltmarsh Carbon Code that would allow saltmarsh carbon to be traded as carbon offsets (Mason et al., 2022). While this code is still in development, its realisation would likely rapidly increase the funding available for saltmarsh conservation and restoration projects. Our findings provide several key implications for the formulation and management of such projects. We have demonstrated that, for rates of sea-level rise of a few millimetres per year, there is a strong positive correlation between the rate of sea-level rise and the rate of carbon accumulation. Saltmarsh conservation and restoration projects should therefore consider projected future sea-level rise and the potential for higher sea-level rates to enhance carbon accumulation. The likelihood for the breakdown of this relationship at higher rates of sea-level rise (Kirwan and Megonigal, 2013; Horton et al., 2018), as anticipated around the UK later this century, should not be overlooked.

As discussed in section 5.3, our results highlight the significance of the loss of labile carbon from saltmarsh sediments over decadal timescales, reducing saltmarshes' net benefit to atmospheric CO_2 reduction. Where saltmarshes are conserved or restored for their carbon sequestration benefits, due consideration must be given to the residence time of carbon within the system. While the recalcitrant OM accumulation rates estimated for the sand section of the core are slightly lower than those in the peat (Fig. 5c), they still indicate that unvegetated tidal flats may also play a considerable role in long-term OC sequestration, especially given their larger spatial extent (Foster et al., 2013). Consequently, we suggest that the role of tidal flats in storing blue carbon may currently be relatively underappreciated in comparison to saltmarshes and other vegetated intertidal habitats. Further investigation of tidal flat carbon stocks may therefore be warranted, and this result highlights the importance of conserving these habitats, as well as the more vaunted blue carbon ecosystems.

6. Conclusions

In this study we show that higher rates of sea-level rise contribute to increased organic carbon accumulation and storage in saltmarsh sediments at Lindisfarne NNR on a multi-decadal timescale. The relationship between rates of sea-level rise and recalcitrant organic matter accumulation, while weaker than the relationship between sea-level rise and organic carbon accumulation, should be focused upon. This is due to the high probability of labile organic carbon loss contributing to the more strongly significant relationship between carbon accumulation rates and sea-level rise. It is shown that higher sedimentation rates in response to sea-level rise are a key driver of the demonstrated relationship. These results support the hypothesis that higher rates of sea-level rise into the 21st century will enhance carbon accumulation in saltmarshes; however, if rates of sea-level rise exceed the ability of the marsh to keep pace, marshes will be submerged and may become sources rather than sinks of carbon. While we have demonstrated the link between sea-level rise and organic carbon accumulation over a period of ~70 years, the range of rates of sea-level rise over this period in Lindisfarne NNR was limited to between 1.2 and 2.9 mm yr^{-1}. This analysis should therefore be repeated at a range of different sites with different recent sea-level histories to further investigate the existence of this relationship on a multi-decadal timescale.

The emphasis placed here on the importance of differentiating between the accumulation of labile and recalcitrant organic matter in turn raises broader questions about the generally accepted methodology for calculating organic carbon accumulation rates in blue carbon ecosystems. If organic carbon data from the upper sediment layers are used, overestimation of stocks and accumulation rates, and thus of climate change mitigation benefit, are likely.

CRediT authorship contribution statement

Catrina Gore: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **W. Roland Gehrels:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Craig Smeaton:** Writing – review & editing, Methodology. **Luke Andrews:** Writing – review & editing, Investigation. **Lucy McMahon:** Writing – review & editing, Investigation. **Fiona Hibbert:** Writing – review & editing, Methodology, Formal analysis. **William E.N. Austin:** Writing – review & editing, Funding acquisition. **Stefanie Nolte:** Writing – review & editing. **Ed Garrett:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

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

The datasets used in this study can be found in an online repository (figshare): http://doi.org/10.6084/m9.figshare.23815941.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecss.2024.108665.

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