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# Organic carbon accumulation in British saltmarshes

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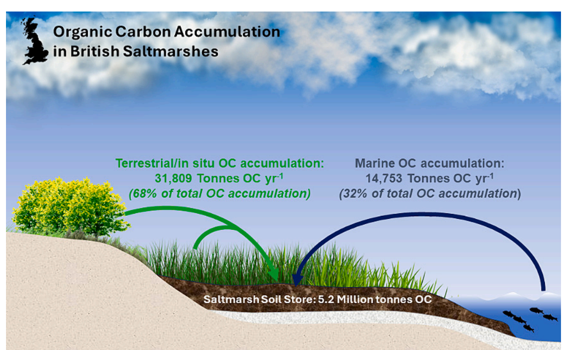
## HIGHLIGHTS

- We conducted the first national saltmarsh OC accumulation assessment for Great Britian.
- On average Great Britain saltmarshes accumulate 110.88 ± 43.12 g C $m^{-2}$ $yr^{-1}$.
- Annually, 46,563 ± 4353 t of OC accumulate in Great Britian's saltmarshes.
- The rate at which these saltmarshes accumulate OC is lower than previous estimates.
- The low accumulation rates highlight the need to protect the OC locked in the soil.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Saltmarshes are a crucial component of the coastal carbon (C) system and provide a natural climate regulation service through the accumulation and long-term storage of organic carbon (OC) in their soils. These coastal ecosystems are under growing pressure from a changing climate and increasing anthropogenic disturbance. To manage and protect these ecosystems for C and to allow their inclusion in emissions and natural-capital accounting, as well as carbon markets, accurate and reliable estimates of OC accumulation are required. However, globally, such data are rare or of varying quality. Here, we quantify sedimentation rates and OC densities for 21 saltmarshes in Great Britain (GB). We estimate that, on average, saltmarshes accumulate OC at a rate of 110.88 ± 43.12 g C $m^{-2}$ $yr^{-1}$. This is considerably less than widely applied global saltmarsh averages. It is therefore highly likely that the contribution of northern European saltmarshes to global saltmarsh OC accumulation has been significantly overestimated. Taking account of the climatic, geomorphological, oceanographic, and ecological characteristics of all GB saltmarshes and the areal extent of different saltmarsh zones, we estimate that

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the 451.65 $km^2$ of GB saltmarsh accumulates 46,563 ± 4353 t of OC annually. These low OC accumulation rates underline the importance of the 5.20 ± 0.65 million tonnes of OC already stored in these vulnerable coastal ecosystems. Going forward the protection and preservation of the existing stores of OC in GB saltmarshes must be a priority for the UK as this will provide climate benefits through avoided emissions several times more significant than the annual accumulation of OC in these ecosystems.

## 1. Introduction

Blue Carbon ecosystems such as saltmarshes are natural carbon (C) stores, accumulating organic carbon (OC) in their soils and storing it for decades to millennia (Mcleod et al., 2011; Duarte et al., 2013; Saintilan et al., 2013). Globally, saltmarshes are estimated to store 0.4–6.5 Gt of OC (Mcleod et al., 2011; Duarte et al., 2013; Temmink et al., 2022). It is estimated that annually a further 167–245 g C $m^{-2}$ $yr^{-1}$ accumulates within saltmarshes resulting in an additional 10–53.65 Mt. of OC entering these ecosystems each year worldwide (Chmura et al., 2003; Ouyang and Lee, 2014; Wang et al., 2021). The ability of saltmarshes to rapidly accumulate and store OC means these blue carbon habitats have the potential to be a key nature-based solution in mitigating climate change through the additional accumulation and long-term storage of OC (Intergovernmental Panel on Climate Change (IPCC), 2019), while also providing a range of other key ecosystem services including enhanced water quality, coastal protection, and biodiversity gain (Temmerman et al., 2013). Yet saltmarshes and other blue carbon ecosystems are under threat, with global annual losses of saltmarsh extent averaging 0.28 % between 2000 and 2019 (Campbell et al., 2022).

Establishing the rate at which saltmarshes accumulate OC is crucial for quantifying the past, present, and potential future benefit of these ecosystems to climate change mitigation. Furthermore, without robust estimations of saltmarsh OC accumulation rates (OCAR), their inclusion into climate frameworks (e.g., United Nations Framework Convention on Climate Change) and C markets (Friess et al., 2022) will be challenging. To date, national OC accumulation estimates are rare (e.g., Macreadie et al., 2017; Miller et al., 2023), with most nations relying on global averages (Chmura et al., 2003; Ouyang and Lee, 2014) to estimate the quantity of OC accumulating in their saltmarshes. The large data compilations that these global estimates are based upon potentially bias the global mean OCAR value towards well-studied areas such as the OC-rich saltmarshes of North America (Chmura et al., 2003; Ouyang and Lee, 2014). Together, spatial clustering and variability in the quality of the data within these global data compilations likely result in the global mean OCAR being an overestimation, thereby limiting the applicability of these values in many regions. Refined approaches to systematically quantifying accumulation rates at national and regional scales are therefore required.

As with many nations, there are growing ambitions for the United Kingdom (UK) to include saltmarsh ecosystems in national emission reporting (UK Climate Change Committee, 2022; Burden and Clilverd, 2021), natural capital accounting (Hooper et al., 2019) and C markets (Mason et al., 2022). Nevertheless, OC accumulation data for GB saltmarshes are spatially poorly resolved with the majority of the data originating in Scotland (Miller et al., 2023) and Essex (Burden et al., 2019), with little elsewhere. Here, we build on recent assessments of the stock and accumulation rates of OC in Scottish saltmarshes (Miller et al., 2023) and the OC stock held in British saltmarshes (Smeaton et al., 2022a, 2023) by providing a comprehensive assessment of OC accumulation in British saltmarshes. We estimate the total quantity of OC accumulating across all British saltmarshes annually and determine the source of that OC. In doing so, this study contributes to understanding and exploring the climate regulation potential of saltmarshes. The OC accumulation estimates allow comparisons with other global systems, enable the development of GB-specific policy and management approaches to prioritise saltmarsh conservation, restoration, and management for OC storage, and provide a foundation to discuss the appropriate inclusion of saltmarsh habitat in national emission reporting and C markets.

## 2. Methods

### 2.1. Study area

Saltmarsh ecosystems occupy 451.65 $km^2$ of the coastline of GB, with ~74 % of the total area of GB saltmarsh located in England, and Wales and Scotland each accounting for ~13 % (Haynes, 2016; Natural Resources Wales, 2016; Environment Agency, 2023). The diverse nature of the British coastline results in the development of six main types of saltmarshes (Haynes, 2016): estuarine, embayment, back-barrier, and fringing (fluvial) marshes are found throughout GB, while loch-head are exclusively found in Scotland and perched marshes occur in Scotland and Wales. The vegetation composition of saltmarshes varies throughout GB, but in general these marshes are dominated by *Puccinellia maritima* and *Festuca rubra* communities (Adam, 1978; Burd, 1989; Haynes, 2016). Additionally, Smeaton et al. (2023) classified the saltmarshes by bringing together a range of variables (climatic, geomorphological, oceanographic, ecological) for each of GB's 448 mapped saltmarshes (Fig. 1A) with a k-medoids cluster analysis based upon the partitioning around medoids (PAM) algorithm (Kaufman and Rousseeuw, 1990) to cluster (*group*) saltmarshes with similar characteristics. This approach groups the British saltmarshes into eight clusters (Fig. 1B).

To assess rates of OC accumulation, we integrate data from a total of 21 saltmarshes located around the coasts of England, Scotland, and Wales (Fig. 1A), including five sites previously sampled by Miller et al. (2023). Of the five sites sampled by Miller et al. (2023) additional samples were collected from three sites (Fig. 1A). The 21 saltmarshes sampled within this study cover all eight groups as classified by the cluster analysis (Smeaton et al., 2023) and are in-turn considered representative of the entire GB saltmarsh habitat (Fig. 1B; Supplementary Table 1).

Together, the sampled saltmarshes occupy an area of 80.02 $km^2$, equivalent to 18 % of the areal extent of saltmarsh in GB (Haynes, 2016; Natural Resources Wales, 2016; Environment Agency, 2023).

### 2.2. Sample collection

At each of the 16 study sites, we used prior knowledge of type, thickness, and relative position of sedimentary layers underlying the vegetated saltmarsh derived from three transects of equally spaced narrow diameter (3 cm) gouge cores ($n = 15–18$) from across each site, as reported by Smeaton et al. (2023). Representative large diameter (master) cores were collected using a Russian corer or wide (6 cm diameter) gouge corer for radionuclide dating and geochemical analyses. In addition to the 16 newly sampled sites, three sites from Miller et al. (2023) were revisited with an additional master core being collected at the Tay, Skinflats and Wigtown (Fig. 1A). In total 27 new master cores were collected from sites around GB (Fig. 1A) which is further supplemented with data from seven cores in Scotland (Miller et al., 2023; Supplementary Table 2).

These 34 master cores were collected from the high and mid-low marsh zones as defined following the modified EUNIS scheme which classifies the saltmarsh into different zones using vegetation communities (Environment Agency, 2023). Together, these two saltmarsh zones represent ~77 % of all GB saltmarsh. High marsh was not present at some sites; in these cases, cores were collected from the seaward edge and the rear of the mid-low marsh zone, this marsh configuration accounted for 10 of the sites. Due to restricted access, only one master core was collected at some sites (e.g., Morrich More). Supplementary Table 2 provides sampling information for the 21 saltmarshes; supplementary figs. 1–21 and Supplementary Table 3 display the core locations. The use of gouge and Russian corers results in negligible soil compaction (Smeaton et al., 2020). We described the sedimentary sequence in each master core following Troels-Smith (1955) and further classified sediments into basal sediments, which accumulate prior to saltmarsh colonisation (e.g., intertidal flat), and saltmarsh soils, following the approach of Miller et al. (2023) and Smeaton et al. (2023). This classification is primarily based on the proportion of organic sediment (see Fig. 3 in Smeaton et al. (2023)). The position and elevation of all cores was recorded using differential GPS, with an average precision of 2 cm. Master cores were recovered whole and stored at <4 °C prior to analysis. Sample collection was undertaken between November 2018 and July 2021.

### 2.3. Geochemical analysis

The master cores were sliced at 1 cm depth intervals, resulting in a total of 1575 samples of known volume. The samples were freeze dried to assure sample integrity prior to subsequent analyses. Before and after drying, samples were weighed to calculate dry bulk density values following standard methodologies (Appleby and Oldfield, 1978).

The freeze-dried samples were homogenised to a fine powder prior to analysis. To determine the bulk elemental (OC and nitrogen (N)) and stable isotope ($\delta^{13}$Corg and $\delta^{15}$N) composition, ~12 mg of milled soil was placed into tin capsules and sealed. A further 12 mg of soil was placed into silver capsules. To remove carbonate (from $CaCO_3$), the samples encapsulated in silver underwent acid fumigation (Harris et al., 2001; Bao et al., 2019). The stable isotope analyses were undertaken using an elemental analyser coupled to an isotope ratio mass spectrometer (*Thermo Scientific Delta V* EA-IRMS). The acidified samples were analysed for OC and $\delta^{13}C_{org}$, while N and $\delta^{15}$N values were produced from the samples encapsulated in tin. By analysing the N and $\delta^{15}$N separately, the risk of altering the isotopic values through the acid fumigation step is negated (Kennedy et al., 2005). Triplicate measurements of samples ($n = 160$) produced standard deviations (1σ) of 0.02 % for N and 0.06 ‰ for $\delta^{15}$N, 0.03 % for OC and 0.07 ‰ for $\delta^{13}C_{org}$. Further quality control was assured by repeat analysis of high OC sediment standard (B2151, E*lemental Microanalysis*) with reference values of $C = 7.45 \pm 0.14$ %. $N = 0.52 \pm 0.02$, $\delta^{13}C = -28.5 \pm 0.1$ % and $\delta^{15}N = 4.32 \pm 0.2$ %. The reference standards (*n = 310, 2 standards for every 10 samples*) deviated from the known values by: OC = 0.08 %, $\delta^{13}C = 0.10$ ‰, $N = 0.03$ % and $\delta^{15}N = 0.13$ ‰. The isotope values are reported in standard delta notation relative to Vienna Peedee belemnite (VPDB) and air. The C/N ratios are reported as molar ratios: C/N = (OC/12)/(N/14).

The $\delta^{13}C_{org}$, $\delta^{15}$N and C/N values were used with the open-source Bayesian isotope mixing model FRUITS (Fernandes et al., 2014) to estimate the fraction of terrestrial/in situ and marine OC input to the

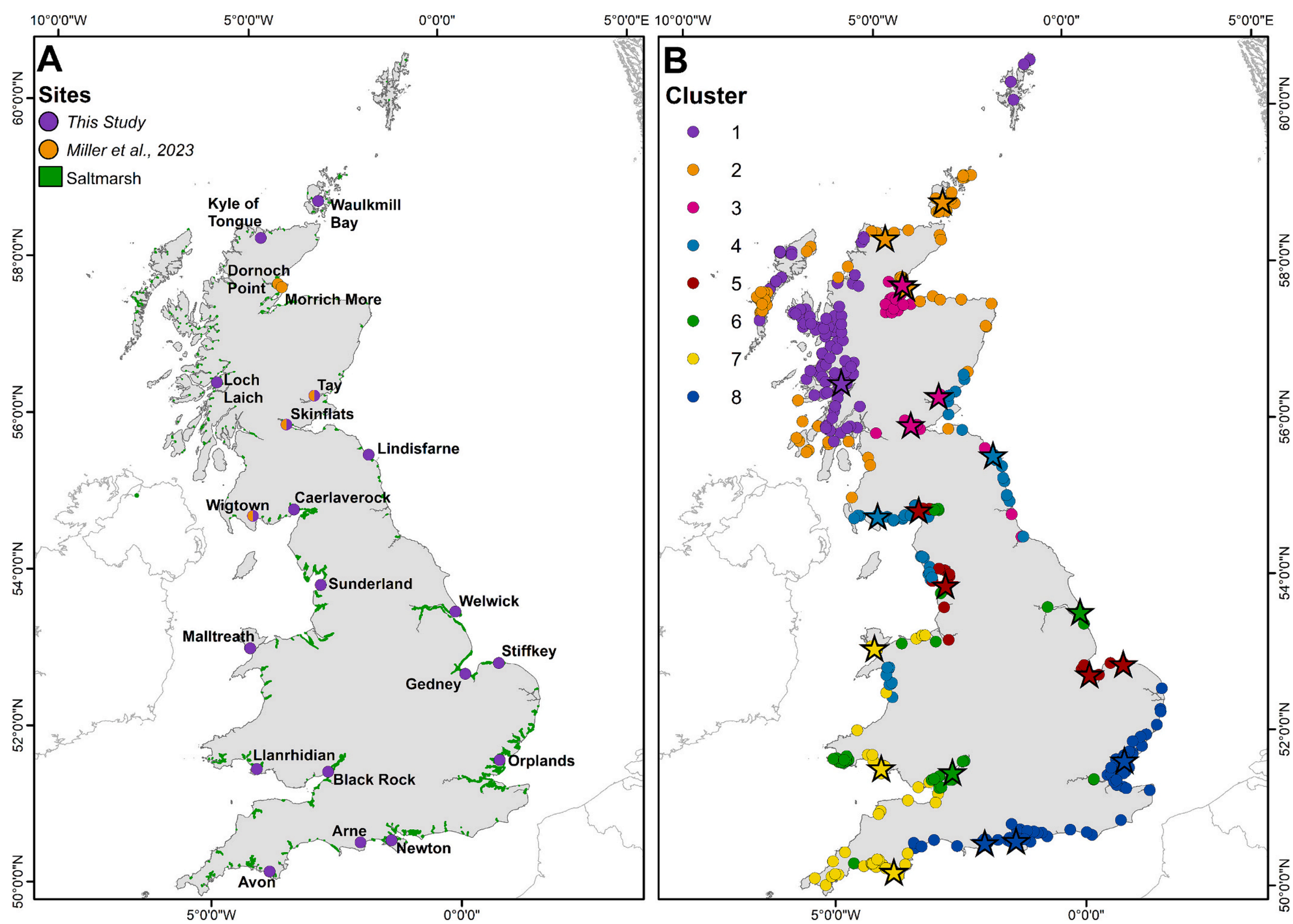


**Fig. 1.** Saltmarshes of Great Britain (**A**) Sampling locations alongside the mapped extent of saltmarsh habitat (*exaggerated by 1.5 times for visibility*). (**B**) Great British saltmarshes grouped into eight clusters identified by partitioning around medoids cluster analysis (Smeaton et al., 2023). Stars represent the 21 saltmarshes in this study and the colour represents their associated cluster. Descriptions of each of the eight groups can be found in Supplementary Table 1.

saltmarsh soils (Smeaton and Austin, 2017; Miller et al., 2023). Published bulk elemental and isotopic values representing the terrestrial (*n = 148*) and marine (*n = 104*) environments local to the marshes, alongside saltmarsh above (*n = 228*) and belowground biomass (*n = 33*) from around GB (Smeaton et al., 2022b) were compiled for use as OC source values in the mixing model. Due to the diversity of the underlying bedrock geology in GB (Waters et al., 2016), it is likely that fossil/petrogenic C is incorporated into the saltmarsh soils in unknown and varying quantities, potentially altering the $\delta^{13}C_{org}$ values. Except for the west coast of Scotland, where petrogenic OC input to the coastal zone is estimated to be below <0.1 % (Smeaton et al., 2021), it has not been possible to quantify the fossil/petrogenic C input or its influence on the $\delta^{13}C_{org}$ values in the saltmarsh soils of this study.

### 2.4. Radionuclide dating

Age-depth models for each core were produced based on the radionuclides $^{210}$Pb and $^{137}$Cs, measured using gamma spectroscopy using Ortec gamma spectrometers at the Consolidated Radio-Isotope Facility (CoRIF) at the University of Plymouth, United Kingdom. We measured activities of $^{210}$Pb and its parent isotope $^{226}$Ra in 1–cm slices from each core. The number of samples per core varied between 20 and 44 according to core length and stratigraphy. A Bayesian framework within the *rplum* package (Blaauw et al., 2022) in R (R Core Team, 2023) was used to develop age-depth models. Rather than using $^{137}$Cs data to corroborate $^{210}$Pb-based age-depth models, we achieved smaller temporal uncertainties by combining the ~1963 CE and/or Sellafield discharge $^{137}$Cs peak with the $^{210}$Pb data in a single model for each core (Aquino-López et al., 2018, 2020). The *rplum* approach alleviates the need for using the lowermost samples to estimate the equilibrium depth where total and excess $^{210}$Pb activities become indistinguishable (Appleby, 2001) and is applicable to $^{210}$Pb profiles where the equilibrium depth has not been reached. From each age-depth model, we obtained age estimates and 2σ uncertainties in calibrated years CE, along with 1-cm resolution sedimentation rates (cm yr$^{-1}$), the average sedimentation rate for each core was calculated using all depth intervals.

In addition to $^{210}$Pb and $^{137}$Cs analyses, we selected six pairs of samples from six cores at five sites for radiocarbon ($^{14}$C) dating. Each pair consisted of a plant macrofossil sample and a bulk (humin) sample recovered from the same core depth. The humin fraction was chosen for dating over humic compounds as it is insoluble in water at all pH values and immobile within the soil (Balesdent, 1987). The humin fraction was extracted following the acid–alkali–acid method (Pessenda et al., 1996). The extracted humin fraction was combusted to carbon dioxide ($CO_2$), cryogenically purified, and converted to graphite using zinc/iron reduction (Slota et al., 1987). Sample graphites were analysed using an accelerator mass spectrometer at the Natural Environment Isotope Facility (East Kilbride, UK). A lack of sufficient identifiable above-ground terrestrial plant macrofossils and substantial and inconsistent offsets between macrofossil and humin samples meant that we did not sample further cores for $^{14}$C dating and we do not incorporate $^{14}$C data in any of the age-depth models. The $^{14}$C dates are reported in Supplementary Table 3.

### 2.5. Organic carbon accumulation rates

To determine the OCAR (g C m$^{-2}$ yr$^{-1}$), the soil OC density (g C cm$^{-3}$) was calculated by combining the dry bulk density values and OC content for each of the 1-cm slices. The soil OC density was then multiplied by the corresponding sedimentation rate derived from the age-depth models. The mean OCAR for each core was calculated by averaging the centimetre-resolution OCARs for the saltmarsh soil unit.

### 2.6. Statistical analysis

To test if OC density, sedimentation rate and OCAR differ between marsh zones across individual GB saltmarshes, ANOVA and Tukey-Kramer (TK) statistical tests (Driscoll, 1996) were utilized. Prior to undertaken the statistical analysis the data was tested for normality using Shapiro-Wilk Test (González-Estrada and Cosmes, 2019). If the dataset was not normal it was first checked for outliers and if none were found the data was transformed using the Box-Cox transformation approach (Sakia, 1992).

### 2.7. Upscaling

Saltmarsh soil OC accumulation was estimated for the 21 saltmarshes following the approach of Miller et al. (2023). For each saltmarsh, the mean (and standard deviation) OCAR for the high and mid-low marsh zones were multiplied with the areal extent of those respective zones (Haynes, 2016; Natural Resources Wales, 2016; Environment Agency, 2023) to calculate the annual OC accumulation at each marsh.

This study estimates OCAR from the high and mid-low marsh zones but lacks data in the pioneer and *Spartina* zones, which occupy ~4 % and ~ 7 % of the total areal extent of GB saltmarsh, respectively (Haynes, 2016; Natural Resources Wales, 2016; Environment Agency, 2023). To facilitate the estimation of total OC accumulation across the marshes, the mid-low OCAR is used as a surrogate value for the pioneer and *Spartina* zones. Additionally, at sites where we do not have a high marsh OCAR value we utilise the mid-low OCAR value from that marsh. Because a large proportion of saltmarsh mapping took place over a decade ago (Haynes., 2016; Natural Resources Wales, 2016), an error of ±5 % was applied to the areal data to account for expansion and/or contraction of the saltmarshes (Smeaton et al., 2022a).

The calculations were undertaken in a Markov Chain Monte Carlo (MCMC) framework. MCMC analysis was applied within the OpenBUGS software package (Lunn et al., 2009) by taking 1,000,000 out of 10,000,000 random samples from a normal distribution of each variable (area, OCAR) from each marsh zone and multiplying the area by the OCAR to generate a pool of results. Applying standard descriptive statistical techniques to the pool of generated solutions allows calculation of the mean, median, standard deviation, and the 5th and 95th percentiles.

To upscale the OC accumulation measurements from the 21 saltmarshes in this study to all saltmarsh habitat in GB, the classification approach developed by Smeaton et al. (2023) was utilized. The clustering approach developed by Smeaton et al. (2023) as advantages over other classification and upscaling methods such as using the saltmarsh type or vegetation communities (Adam, 1978; Burd, 1989; Haynes, 2016; Smeaton et al., 2022a). These alternative approaches negate to take local conditions into consideration when classifying saltmarsh, for example an estuarine marsh in the North of Scotland and the South of England would be determined to be similar when in reality this is unlikely. By using variables, that take in to consideration local variation the clustering approach (Smeaton et al., 2023) allows marshes with similar climatic, oceanographic, geomorphic, and ecological characteristics to be grouped, which provides foundation for upscaling. Even with this approach the 21 saltmarshes only represent 18 % of the total GB saltmarsh area. Therefore, it is probable that the variation in OC accumulation across all GB marshes will not be fully captured.

To estimate the OC accumulation of all GB saltmarshes, the areal extent of each marsh zone within each of the eight clusters was multiplied with the corresponding mean OCAR for each marsh zone calculated from the sampled saltmarshes that fall into each cluster (Fig. 1B). Again, a ± 5 % error was applied to the areal extent of all marsh zones to account for changes since the surveys were undertaken. All calculations were carried out within the MCMC framework.

## 3. Results

### 3.1. Ages and sedimentation rates

Of the 21 marshes studied, six are estimated to have formed prior to 1900, eleven between 1900 and 1950, and a further four after 1950 (Fig. 2A). Fig. 2 summarises age-depth models for 34 cores from 21 sites, including 6 cores from 5 sites originally sampled by Miller et al. (2023). Individual age models with 2σ temporal uncertainties are provided alongside radionuclide results in Supplementary Fig. 22–26. Average sedimentation rates in saltmarsh soils vary between 0.12 cm $yr^{-1}$ at Morrich More (northeast Scotland) to 1.28 cm $yr^{-1}$ at Dornoch Point (northeast Scotland). Across all sites, the mean sedimentation rate is 0.41 ± 0.16 cm $yr^{-1}$ (Fig. 2B). Sedimentation rates for all cores are provided in Supplementary Fig. 27.

### 3.2. Carbon accumulation rates

Across GB saltmarshes, there is high variability in both the dry bulk density and OC content of the soils. We observe the common trend that dry bulk density decreases as OC content increases (Fig. 3A). The saltmarsh soil's dry bulk density and OC content differ significantly across the sites. The mean dry bulk density across all sites is 0.52 ± 0.27 g $cm^{-3}$ with values ranging from 0.05 g $cm^{-3}$ in the surficial fibrous peat layers found in the northern Scottish saltmarshes (e.g., Waulkmill Bay) to 1.66 g $cm^{-3}$ in the silts and sands found deeper in the profile at marshes such as Lindisfarne and Sunderland. The mean OC content of the saltmarsh soils is 8.54 ± 7.09 %, with values ranging between 0.11 % in the sandy soils at Dornoch Point to 37.66 % in the fibrous peat layers at Skinflats (Fig. 1). The variation in dry bulk density and OC content across the sites results in mean core OC density values ranging between 0.011 g C $cm^{-3}$ in the mid-low marsh at Wigtown Bay to 0.078 g C $cm^{-3}$ in the mid-low marsh at the Kyle of Tongue. Across all cores, the average OC density of the saltmarsh soils is 0.034 ± 0.010 g C $cm^{-3}$ (Fig. 3B). At sites with cores from both high and mid-low marsh zones, the OC density in the high zone is always higher than those measured in the mid-low marsh (Fig. 3B). When statistically tested using an ANOVA the difference between OC densities in the high and mid-low marsh are generally deemed to be statistically significant, yet in several cases (Black Rock, Sunderland, and Dornoch Point) the difference between the groups is not statistically significant (Supplementary Table 15).

Organic carbon accumulation rates for saltmarsh soils average 110.88 ± 43.12 g C $m^{-2}$ $yr^{-1}$ across all sites and range between 27.57 g C $m^{-2}$ $yr^{-1}$ at Loch Laich to 343.68 g C $m^{-2}$ $yr^{-1}$ at Wigtown Bay (Fig. 4). Across all sites, on average, the high marsh zone cores accumulate OC at a greater rate (115.52 ± 64.07 g C $m^{-2}$ $yr^{-1}$) in comparison to the cores from the mid-low marsh zone (108.90 ± 76.33 g C $m^{-2}$ $yr^{-1}$).

### 3.3. Sources of organic carbon

GB saltmarsh soils are characterised by $\delta^{13}C_{org}$ values of −26.2 ± 2.1 ‰, $\delta^{15}N$ values of 5.2 ± 2.0 ‰, and C/N ratios of 16.6 ± 4.3. As with the OC content, these values vary between cores with $\delta^{13}C_{org}$ values ranging between −17.5 ‰ to −31.4 ‰, $\delta^{15}N$ values 0.29 ‰ to 9.8 ‰ (Fig. 5), and C/N ratios ranging from 7.5 to 35.5. When compared, the high and mid-low marsh zones vary little with mean values mirroring those of the whole dataset; however, the most depleted $\delta^{13}C_{org}$ values are observed in the high marsh (Fig. 5). In comparison, the $\delta^{13}C_{org}$ and $\delta^{15}N$ values of the basal soils (the sediments related to the pre-saltmarsh intertidal flat) are enriched and the C/N ratios are lower than those observed in the saltmarsh (Fig. 5).

The variation in the isotopic and elemental ratios of these bulk soil samples are indicative of OC originating from multiple sources (terrestrial, in situ and/or marine). As observed in other studies (Saintilan et al., 2013; Geraldi et al., 2019; Miller et al., 2023), there is an overlap in the $\delta^{13}C_{org}$, $\delta^{15}N$ and C/N values of saltmarsh biomass and terrestrially derived soil and vegetation (Supplementary Table 4), which prevents the differentiation of in situ OC production from other terrestrial OC inputs to the saltmarshes. The outputs from the Bayesian isotope mixing model estimates that, across all cores and sedimentary units, 66.1 ± 15.0 % of the OC originates from terrestrial and/or in situ sources, with values ranging between 10.1 % in the Arne marsh and 98.7 % in the fjord-head systems at the Kyle of Tongue and Loch Laich. If averaging the 1-cm resolution data across the saltmarsh soils, the model estimates that 72.0 ± 14.4 % of the OC is derived from terrestrial/in situ

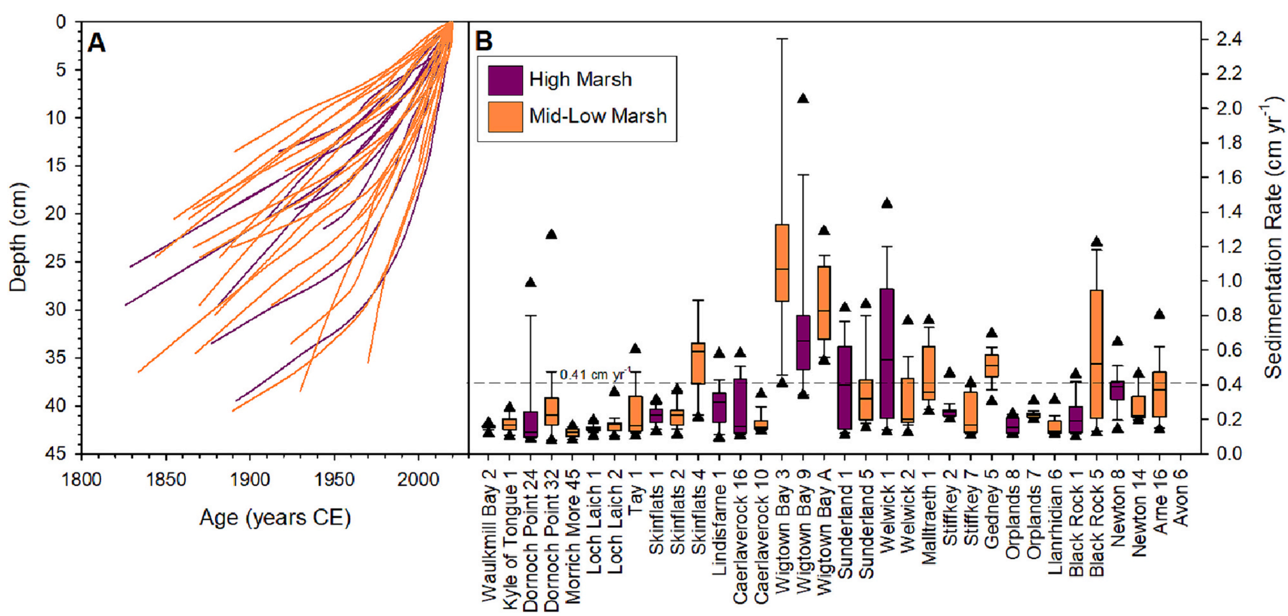


**Fig. 2.** (**A**) Mean age-depth models for 34 cores developed from $^{210}$Pb and $^{137}$Cs data using *rplum* (Blaauw et al., 2022). (**B**) Centimetre-resolution sedimentation rates derived from the age-depth models, arranged by latitude (furthest north on the left-hand side). The solid line within the boxes represents the median values, and the triangles illustrate the 5th and 95th percentiles. The dashed line represents the mean sedimentation rate calculated from all cores in this study. Supplementary Figs. 22–26 display age models and sedimentation rates from all 34 cores.

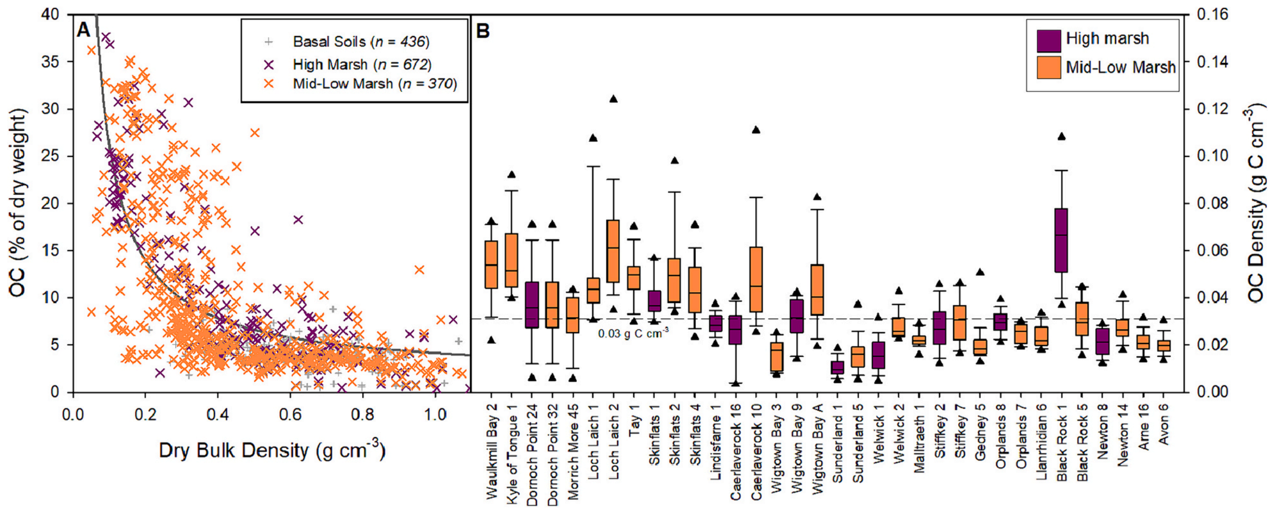


**Fig. 3.** Organic carbon density of Great British saltmarsh sediments. **(A)** Dry bulk density vs organic carbon (OC) content. Black line reflects the correlation ($y = 2.3874\times^{-1.053}$) between the dry bulk density and OC (%). (**B**) Centimetre-resolution OC density (g C cm$^{-3}$) of the saltmarsh cores (*core identification along the x-axis*) arranged by latitude (furthest north on the left-hand side). The solid line within the boxes represents the median value, and the triangles illustrate the 5th and 95th percentiles. The black dashed line represents the mean OC density calculated from all cores in this study. Supplementary Fig. 28 displays downcore OC content records for all 34 cores.

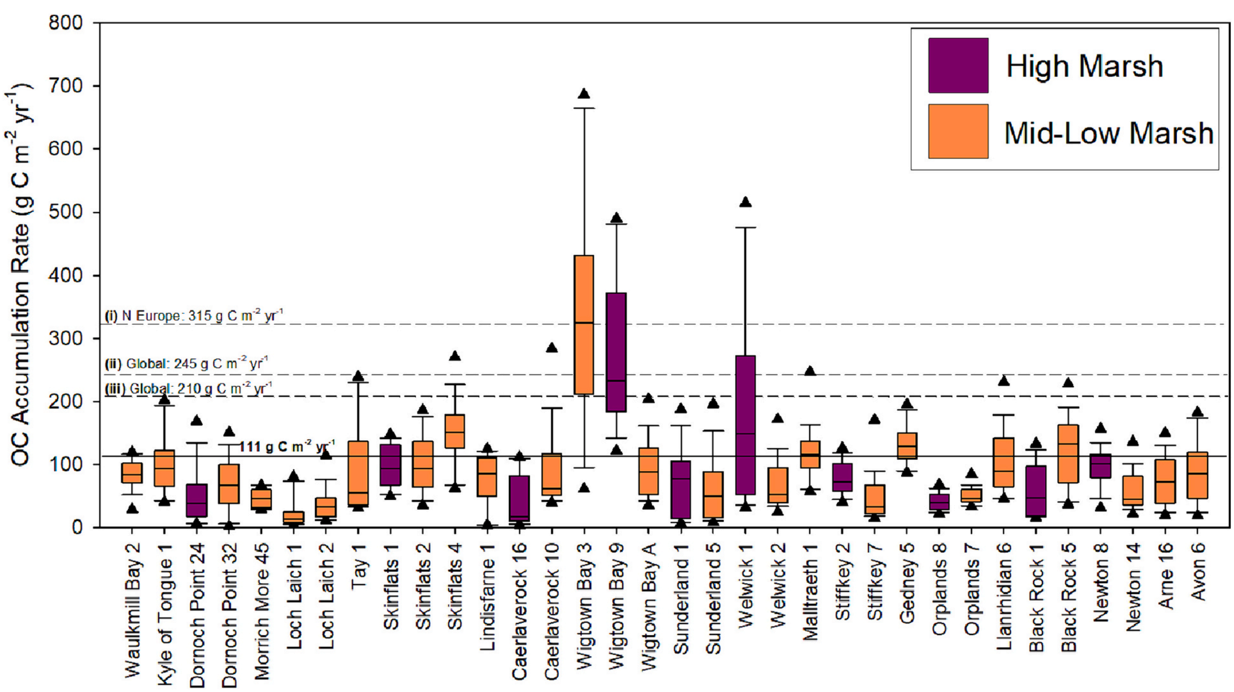


**Fig. 4.** Centimetre-resolution organic carbon (OC) accumulation rates (g C m$^{-2}$ yr$^{-1}$) for the 34 cores (Fig. 1) derived from the age-depth models and sedimentation rates (Fig. 2), arranged by latitude (furthest north on the left-hand side).The solid line within the boxes represents the median value, and the triangles illustrate the 5th and 95th percentiles. The black solid line represents the mean OC accumulation rate (110.88 g C m$^{-2}$ yr$^{-1}$) calculated from all cores in this study. Grey dashed lines highlight previously published regional and global average OC accumulation rates **(i)** Ouyang and Lee (2014), **(ii)** Ouyang and Lee (2014) and **(iii)** Chmura et al. (2003). Supplementary Fig. 29 displays downcore OCAR records for all 34 cores.

sources. Up to 92.8 ± 18.7 % of OC in the Skinflats saltmarsh soils comes from terrestrial/in situ sources, while the OC within the Arne saltmarsh largely originates from the marine environment with only 28.9 ± 17.1 % sourced from terrestrial/in situ sources. On average, 77.7 ± 14.9 % of the OC in the high marsh cores is derived from terrestrial/in situ sources compared to 69.7 ± 14.2 % in the mid-low marsh cores. Down core estimates of terrestrial/in situ OC accumulation are detailed in Supplementary Fig. 30.

### *3.4. Saltmarsh OC accumulation across sites and nations*

The 21 saltmarshes in this study accumulate 8873 ± 2840 t of OC annually, of which we estimate that 5961 ± 1908 t of OC originate from terrestrial and/or in situ sources. Significantly different OC accumulation rates are observed between the individual marshes. Gedney, for example, gains 2771 ± 991 t of OC annually, whereas Loch Laich only accumulates 4 ± 1 t annually (Fig. 6A). However, this disparity in OC accumulation is largely driven by areal extent of the marshes, as

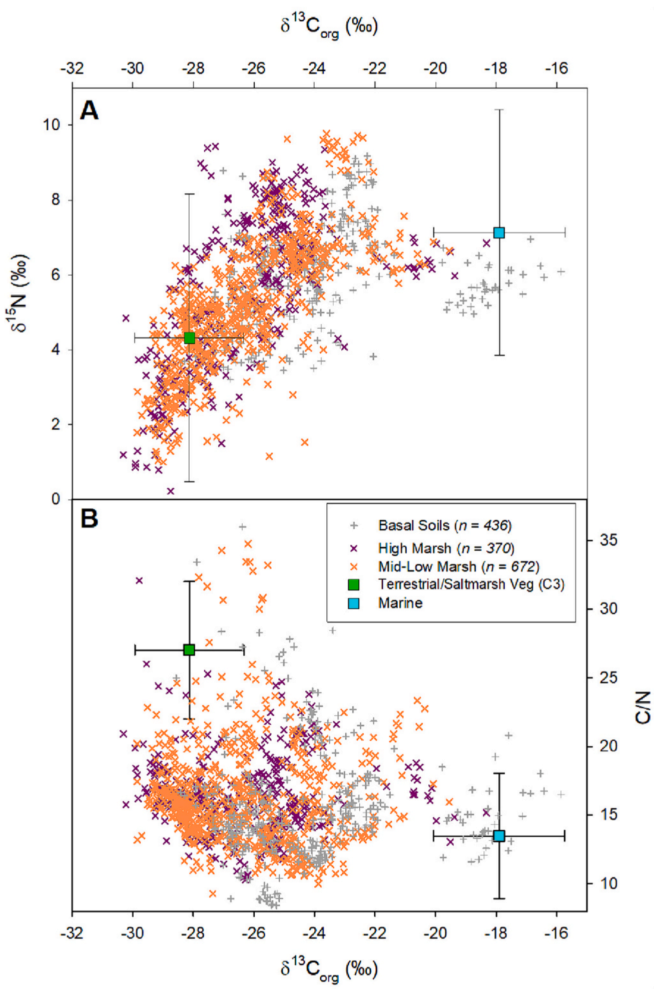


**Fig. 5.** Cross plots of (**A**) $\delta^{13}C_{org}$ versus $\delta^{15}N$ and (**B**) $\delta^{13}C_{org}$ versus C/N for soil samples from the 21 saltmarshes. Terrestrial, marine and saltmarsh source values derived from samples collected from across Great Britain (Smeaton et al., 2022b). Full details of the source values can be found in Supplementary Table 3.

illustrated by Gedney and Waulkmill Bay occupying areas of 20.49 $km^2$ and 0.11 $km^2$, respectively.

The 451.65 $km^2$ of saltmarsh habitat in GB is estimated to accumulate 46,563 ± 4352 t of OC annually, with 5th and 95th percentile estimates of 39,338 and 53,754 t OC $yr^{-1}$ (Fig. 6B). Of this total, 68 % (31,809 ± 3418 t OC) of OC originates from terrestrial and/or in situ sources, with the marine environment providing the remaining 32 % of OC (Fig. 6B). English saltmarshes, which represent ~74 % of the total area of GB saltmarsh, accumulate 32,276 ± 2992 t of OC $yr^{-1}$, the largest quantity of the three nations. Welsh and Scottish marshes accumulate 7726 ± 977 t OC $yr^{-1}$ and 6561 ± 1050 t OC $yr^{-1}$ respectively (Fig. 6B). Per saltmarsh area, English marshes accumulate the lowest quantity of OC (98.59 ± 8.62 g C $m^{-2}$ $yr^{-1}$ on average), followed by Scottish (113.32 ± 17.86 g C $m^{-2}$ $yr^{-1}$) and Welsh (129.07 ± 15.84 g C $m^{-2}$ $yr^{-1}$) marshes. Supplementary Tables 5–11 provide a full breakdown of the data.

Terrestrial/in situ OC constitutes 66 % and 69 % of the OC accumulating in English and Welsh saltmarshes respectively, while in Scotland 77 % of the OC originates from terrestrial/in situ sources. Northern Ireland saltmarshes occupy an area of 2.38 $km^2$ (Joint Nature Conservation Committee, 2013), approximately 0.5 % of the GB total. It is therefore reasonable to assume that the quantity of OC accumulating in total United Kingdom (i.e., Great Britain and Northern Ireland) saltmarshes would only be marginally greater than the GB estimate.

## 4. Discussion

### *4.1. Organic carbon accumulation in GB saltmarshes*

By upscaling high-resolution OC accumulation records from 34 cores across 21 sites, we estimate that 46,563 ± 4352 t of OC are accumulating annually, supplementing the estimated 5.20 ± 0.65 Mt. of OC currently stored in GB saltmarshes (Smeaton et al., 2023). Previous attempts to estimate OC accumulation in GB saltmarshes used either a limited number of cores from only one region (Miller et al., 2023) or a single OCAR value across the areal extent of all marshes (Luisetti et al., 2019; Pearson, 2020).

On average, saltmarshes in Great Britain accumulate OC at a rate of 110.88 ± 43.12 g C $m^{-2}$ $yr^{-1}$, with values ranging between 27.57 and 343.68 g C $m^{-2}$ $yr^{-1}$ (Fig. 3).The young and shallow nature of saltmarsh deposits in GB (Miller et al., 2023; Smeaton et al., 2023) means that the OC does not reach a state of inert long-term storage as it is still degrading, albeit at a decreasing rate with depth (Supplementary

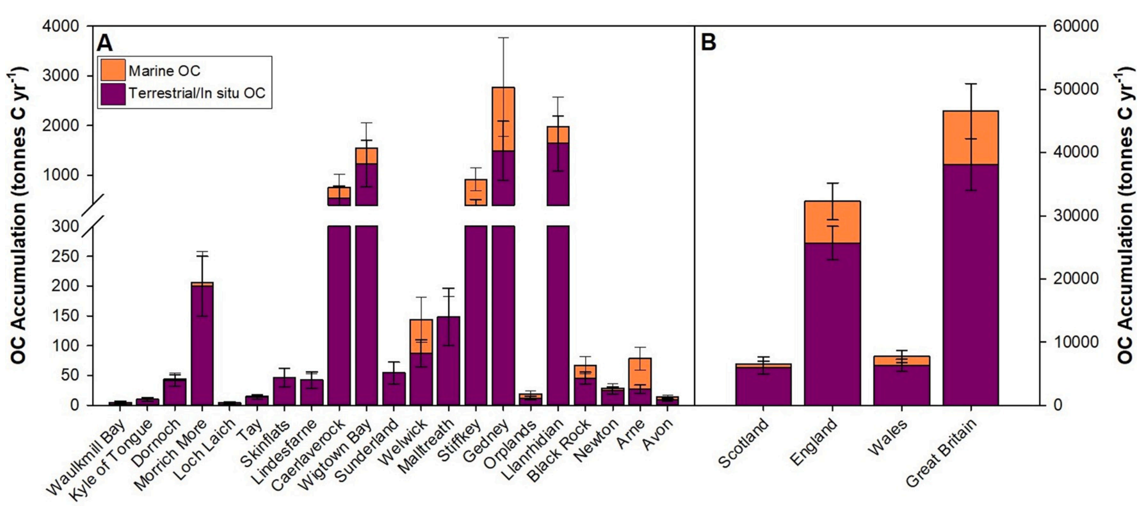


**Fig. 6.** Saltmarsh organic carbon (OC) accumulation in Great Britain. (**A**) Annual OC accumulation (tonnes C $yr^{-1}$) across the 21 saltmarshes with the contribution of marine and terrestrial and/or in situ OC sources highlighted. (**B**) Total annual OC accumulation in the saltmarsh habitat of Great Britain and its constituent nations. A full breakdown of the OC accumulation can be found in Supplementary Tables 6–11.

Figs. 28). Therefore, OC burial in these saltmarsh soils, as with any natural burial system (e.g., Middelburg, 2018), are not in long-term equilibrium, but instead reflect a balance of gains and loss terms, which are spatially and temporally complex resulting in the large range of OCARs calculated within and across saltmarshes in this study.

The range of OCAR values observed in GB marshes are comparable with recent studies of northern European natural saltmarshes in Denmark (Graversen et al., 2022; Leiva-Dueñas et al., 2024), Germany (Mueller et al., 2019) and realigned marshes that have reached maturity (~100 years from creation) in southern England (Burden et al., 2019). However, newly created marshes, such as Steart Marsh in Somerset, report mean sedimentation rates of 4.7 cm $yr^{-1}$ and OCAR of up to 1960 g C $m^{-2}$ $yr^{-1}$ (Mossman et al., 2022) which are an order of magnitude higher than the sedimentation rates (0.07–1.18 cm $yr^{-1}$) and OCARs (27.57–343.68 g C $m^{-2}$ $yr^{-1}$) reported in this study and across the wider literature (Cundy and Croudace, 1995; Callaway et al., 1996; Andrews et al., 2008; Teasdale et al., 2011; Adams et al., 2012; Burden et al., 2019; Miller et al., 2023). The disparity between these published rates and the unusually high rates of Mossman et al. (2022) are almost certainly due to the rapid and early infill of newly created accommodation space following managed realignment of the site in 2014. This early infill process is significantly faster than the rate at which natural saltmarshes can accumulate material and the OCAR in these locations must therefore be treated with caution and are not comparable to naturally functioning saltmarsh ecosystems. This highlights the importance of defining when a realigned area can be considered a saltmarsh (Intergovernmental Panel on Climate Change, 2013; McMahon et al., 2023).

While it might seem logical to conclude that high saltmarsh OCAR would equate to high OC storage values (kg C $m^{-2}$) and OC stocks (t C), this is not the case (Fig. 7). The main driver for the magnitude of the OC stock is the areal extent of the saltmarshes, with large marshes such as Llanrhidian, Morrich More and Stiffkey possessing the largest stocks. Variation in OCAR is governed by sedimentation rates and OC density, which are themselves driven by factors such as sediment supply, geomorphology, and vegetation composition. In contrast, OC storage (i.e. the amount of OC per unit area) in GB saltmarshes is potentially driven by an underlying regional history of relative sea-level change and sediment availability (Allen, 2000; Smeaton et al., 2023; Gore et al., 2024). The saltmarshes in the north of Scotland are the oldest of the marshes in this study and have experienced an extended period of comparatively stable relative sea level (Barlow et al., 2014; Shennan et al., 2018), resulting a longer duration of organic saltmarsh sediment accumulation and elevated OC storage when compared to the younger sites (Fig. 7). The south of England, by contrast, has experienced more rapid relative sea-level rise during the early and mid-Holocene, enhanced by continued isostatic subsidence (Shennan et al., 2018). This has favoured the drowning of estuaries and river valleys, increased accommodation space, and resulted in the deposition of predominantly minerogenic sediments (Allen, 2000; Waller and Long, 2003). Reduced rates of sea-level rise in the late Holocene, combined with enhanced sedimentation from terrestrial sources linked to anthropogenic activities including forest clearance and mineral exploitation, allowed estuaries to "catch up" (Pye and Blott, 2014; Vis et al., 2015). Sediments infilled the available accommodation space and provided conditions suitable for the accumulation of organic saltmarsh deposits, although the onset occurred substantially later than in northern GB (Long et al., 2000).

Estimates of saltmarsh OC accumulation from this study differ significantly from global estimations (Table 1), raising questions on the applicability of such global datasets in calculating OC accumulation for individual nations or regions where such data are absent. Global estimates of the rate at which OC accumulates in saltmarshes range between 210 and 250 g C $m^{-2}$ $yr^{-1}$, resulting in total accumulation in the range of 10.2–59.0 Mt. OC $yr^{-1}$ (Table 1). These rates significantly exceed the 110.88 ± 43.12 g C $m^{-2}$ $yr^{-1}$ observed in the GB marshes (Table 1). The disparity in the OCAR is driven by spatial biasing of sampling location towards high OCAR areas, methodological approaches, and data quality of records within these global datasets (Chmura et al., 2003; Ouyang and Lee, 2014). Both Chmura et al. (2003) and Ouyang and Lee (2014) use the same dataset compiled from 143 saltmarsh OCAR records, yet while Chmura et al. (2003) estimate global OCAR to be 210.0 ± 24.0 g C $m^{-2}$ $yr^{-1}$, Ouyang and Lee (2014) estimate 244.7 ± 26.1 g C $m^{-2}$ $yr^{-1}$. The difference in these is driven by the exclusion of a number of datasets by Ouyang and Lee (2014) due to perceived quality control issues. The disparity between these studies is further highlighted by the fact that Chmura et al. (2003) and Ouyang and Lee (2014) estimate that 44.6 and 10.2 Mt. of OC $yr^{-1}$ accumulates in global marshes, respectively. These significant differences are due to upscaling methodologies; Chmura et al. (2003) apply a mean OCAR to the global marsh extent while Ouyang and Lee (2014) calculate regional OCAR, which are then applied to region-specific areal extents.

Of particular note is the estimate by Ouyang and Lee (2014) that

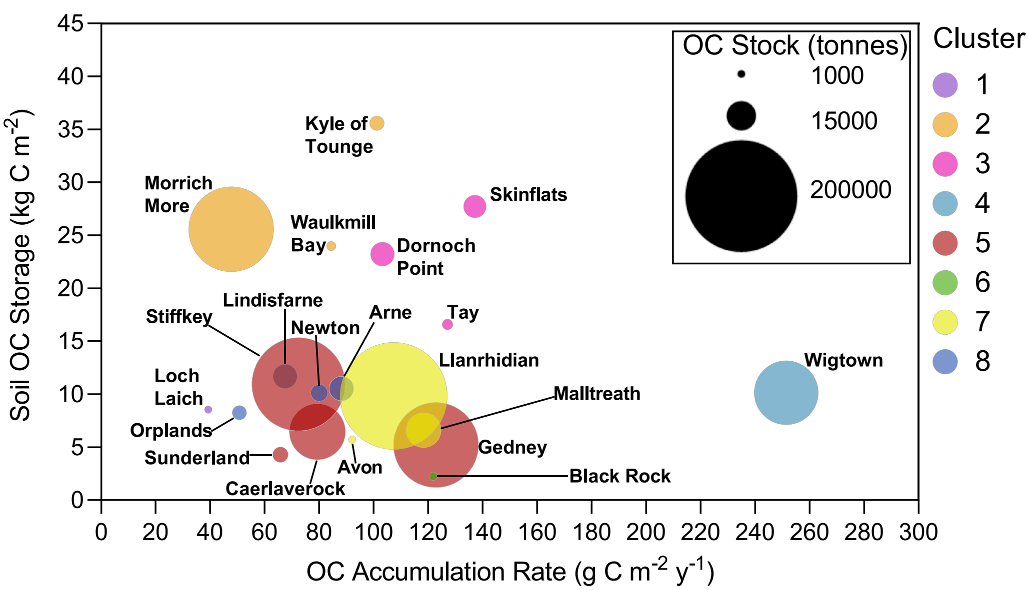


**Fig. 7.** Organic carbon (OC) accumulation rates (g C $m^{-2}$ $yr^{-1}$) compared to soil OC storage (kg C $m^{-2}$) and OC stock (tonnes) estimates – the latter from Smeaton et al. (2023). Colours represent the cluster in which each saltmarsh is grouped (Fig. 1B; Smeaton et al., 2023).

**Table 1**
National saltmarsh organic carbon accumulation rates (OCAR) and total organic carbon (OC) accumulation estimates from this study in comparison to national, regional, and global datasets and sequestration (†) and accumulation rates for other ecosystems. *Error presented as standard error opposed to standard deviation.

| Nation | OCAR (g C $m^{-2}$ $yr^{-1}$) | | | Total OC Accumulation (Tonnes $yr^{-1}$) | | | References |
|---|---|---|---|---|---|---|---|
| | Mean (± σ) | 5th | 95th | Mean (± σ) | 5th | 95th | |
| Scotland | 113.3 ± 17.9 | 83.7 | 142.6 | 6561 ± 1050 | 4843 | 8299 | This Study |
| England | 98.6 ± 8.6 | 84.4 | 112.5 | 32,276 ± 2922 | 27,470 | 37,088 | |
| Wales | 129.1 ± 15.8 | 103.4 | 155.0 | 7726 ± 977 | 6157 | 9347 | |
| Great Britain | 110.9 ± 43.1 | 88.9 | 120.4 | 46,563 ± 4352 | 39,338 | 53,754 | |
| Scotland | 83.4 ± 15.6 | – | – | 4385 ± 481 | 3473 | 5621 | Miller et al., 2023 |
| Wales | 84.0 | – | – | 6379 | – | – | Pearson, 2020 |
| Essex, Realigned | 65.0–104.0 | – | – | – | – | – | Burden et al., 2019 |
| United Kingdom | – | – | – | 37,000 | – | – | Luisetti et al., 2019 |
| Denmark | 4.6–141.6 | – | – | – | – | – | Graversen et al., 2022; Leiva-Dueñas et al., 2024 |
| Germany | 112.0–149.0 | | | | | | Mueller et al., 2019 |
| Portugal | 18.0–94.0 | – | – | – | – | – | Martins et al., *2022*; Mazarrasa et al., 2023 |
| Spain | 16.5–121.0 | – | – | – | – | – | Mazarrasa et al., 2023 |
| | | | | | | | |
| Regional and Global Estimates | | | | | | | |
| Northern Europe* | 315.2 ± 62.9 | – | – | – | – | – | Ouyang and Lee, 2014 |
| Europe & Scandinavia* | 312.4 ± 50.6 | – | – | 720,000 ± 120,000 | – | – | |
| North West Europe* | 62.5–220.0 | – | – | 75,000 –385,220 | – | – | Legge et al., 2020 |
| Global* | 210.0 ± 24.0 | – | – | 44,600,000 | – | – | Chmura et al., 2003 |
| Global* | 244.7 ± 26.1 | – | – | 10,200,000 | – | – | Ouyang and Lee, 2014 |
| Global | 167.7 ± 136.5 | – | – | 48,520,000 - 59,010,000 | – | – | Wang et al., 2021 |
| Global* | 250.0 | – | – | – | – | – | Temmink et al., 2022 |
| | | | | | | | |
| Other ecosystems | | | | | | | |
| Forests, Great Britain | 103.5† | – | – | 926,431† | – | – | Zellweger et al., 2022 |
| Forests, global | 110–360 | – | – | – | – | – | Requena Suarez et al., 2019; Cook-Patton et al., 2020 |
| Monoculture forest plantations, global | 90–820 | – | – | – | – | – | Bukoski et al., 2022 |

northern European saltmarshes accumulate 315.2 ± 62.9 g C $m^{-2}$ $yr^{-1}$. This estimate exceeds the global average and is substantially higher than the average OCAR estimate both in GB (*this study*) and Denmark (Graversen et al., 2022) (Table 1). The Ouyang and Lee (2014) northern European estimate is derived from 20 cores collected from 5 marshes in the UK (11 cores), the Netherlands (2 sites, 4 cores), Denmark (1 core) and Poland (2 sites, 4 cores). Across these records, four different methodologies are used to calculate the sedimentation rate (surface elevation tables, marker horizons, radionuclide dating using $^{210}$Pb and also using $^{137}$Cs as a single chronological marker) and only two of the cores have direct OC measurements. In comparison to the OCAR calculated in this study and others within the region (Graversen et al., 2022; Miller et al., 2023), we conclude that the Ouyang and Lee (2014) results are likely to represent a significant overestimation of OCAR in Northern European saltmarshes.

Our results therefore indicate that northern European saltmarshes in fact play a smaller role in global OC accumulation. The results highlight the need for high quality national/regional OC accumulation studies, as the use of current mean global/regional OCAR (Chmura et al., 2003; Ouyang and Lee, 2014) are generating unreliable estimates across some regions; and in the case of GB and northern Europe this appears to have generated a very significant overestimation of the quantity of OC accumulating in these saltmarshes. Such overestimation could potentially result in suboptimal management decisions, undermine the evidence to support GHG emissions accounting, exaggerate natural capital accounts and ultimately weaken the confidence of investors in credible voluntary C markets linked to saltmarsh restoration projects.

The average OCAR of GB saltmarshes is similar to a recent estimate of carbon sequestration by GB forests (103.5 g C $m^{-2}$ $yr^{-1}$; Zellweger et al., 2022) and at the lower end of estimates of sequestration by global forests (110–3605 g C $m^{-2}$ $yr^{-1}$; Requena Suarez et al., 2019) and monoculture forestry plantations (90–820 5 g C $m^{-2}$ $yr^{-1}$; Bukoski et al., 2022). Estimates of carbon accumulation in forests soils over thousands to tens of thousands of years are lower (Morison et al., 2012; Vanguelova and Pitman, 2010); however, the duration of accumulated OC in GB saltmarshes (typically hundreds of years) makes the comparison with sequestration in living forest biomass more appropriate.

### 4.2. GB saltmarsh climate mitigation potential

Annually, the saltmarsh habitat of GB accumulates 170,885 ± 15,974 t $CO_2$eq. It is currently unclear what quantity of the OC accumulating in these marshes is sequestered from the atmosphere (through in situ production) and therefore providing a direct climate mitigation service. In this study, it is estimated that ~32 % of the OC held within the marsh soils originates from the marine environment (Fig. 5). The other 68 % of the OC that accumulates each year is derived from either the terrestrial environment or in situ production. As we cannot differentiate between these sources of OC, it is not possible to quantify the amount of OC directly sequestered from the atmosphere by the saltmarshes. Rather, we can only highlight that it is an as-yet unknown fraction of the 31,809 ± 3418 t of OC accumulating each year that is derived from terrestrial/in situ sources (Fig. 6B). While the accumulation of allochthonous OC in the saltmarsh soils does not directly equate to $CO_2$ being sequestered from the atmosphere, its storage and preservation in the soils does provide a climate regulation service that should not be overlooked.

Increasing the quantity of organic carbon accumulating can enhance the role of saltmarsh habitats in climate mitigation. The most direct way to increase saltmarsh OC accumulation is to increase marsh areal extent (Hudson et al., 2021). In the UK, 220 $km^2$ of coastline has been identified as suitable for realignment to create new saltmarsh habitat to improve flood defence, biodiversity, and climate mitigation services provided by these ecosystems (Marine Management Organisation, 2019; Austin et al., 2022). If this goal was achieved and the saltmarshes reached maturity, we estimate an additional 89,525 t $CO_2$eq $yr^{-1}$ would accumulate. The small quantities of OC accumulating in GB saltmarshes do not prohibit the inclusion of these environments in national emission reporting (Burden and Clilverd, 2021) and natural capital accounting (Hooper et al., 2019), but when integrating GB saltmarshes into C markets (Friess et al., 2022; Mason et al., 2022), caution must be applied to assure that these markets are viable, considering the low OCARs.

While GB saltmarshes only accumulate a small quantity of OC annually (Table 1), this does highlight the importance of the OC already stored in these ecosystems. The OC within the soils of GB saltmarshes equates to 19.1 ± 2.4 Mt. $CO_2$eq (Smeaton et al., 2023). Though not directly comparable, as the OC stores have built up over decades to centuries, it must be recognised that if the OC within these saltmarshes were to be remineralised and released as $CO_2$ to the atmosphere, there would be an appreciable increase in atmospheric $CO_2$ concentrations. While implausible that all GB saltmarshes would be lost simultaneously, these systems are under growing pressure. It has been estimated that there has been an 85 % loss in saltmarsh areal extent in England since the 1800s (Environment Agency, Chief Scientist's Group, 2023) with loss rates of up to 0.4 $km^2$ $yr^{-1}$ observed in the south of England (Hughes and Paramor, 2004; Ladd et al., 2019). These trends are predicted to continue into the 21st century as a result of rising sea level (Horton et al., 2018). The loss of saltmarsh will result in the release of OC currently stored and, due to the reduction in areal extent and the low OCARs observed in GB systems, any OC lost will not be recoverable (Goldstein et al., 2020). Consequently, it is essential that the OC currently held in the soils of GB saltmarshes is protected; the avoided emissions from the prevention of OC loss is several orders of magnitude more important to global climate than the annual accumulation of OC in these marshes.

## 5. Conclusion

The saltmarshes of Great Britain on average accumulate organic carbon at a rate of 110.88 ± 43.12 g C $m^{-2}$ $yr^{-1}$, resulting in these marshes annually accumulating 46,563 ± 4353 t of organic carbon.. However, the rate at which these saltmarshes accumulate organic carbon is considerably lower than the global estimates. The organic carbon accumulation rates quantified in this study suggest the role that GB and potentially northern European saltmarshes more generally play in global climate mitigation is less than previously thought and has been overestimated in global and regional compilations and are comparable to sequestration rates in temperate forests. Enhanced understanding of GB saltmarsh OC accumulation rates must be considered if these ecosystems are to be included in emissions reporting, natural capital accounting and carbon markets. Although the small quantity of organic carbon accumulating each year in these systems does not prevent their inclusion into such areas, caution will need to be applied especially when monetising the annual accumulation of organic carbon. The findings of this study further highlight the importance of the significant quantities of organic carbon already stored in these saltmarshes. Preventing the loss (i.e. avoided emissions) of this vulnerable store of organic carbon could be up to several orders of magnitude more important to global climate than the annual accumulation of organic carbon in Great British saltmarshes.

## CRediT authorship contribution statement

**Craig Smeaton:** Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ed Garrett:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Martha B. Koot:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Cai J.T. Ladd:** Writing – review & editing, Investigation, Funding acquisition, Conceptualization. **Lucy C. Miller:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Lucy McMahon:** Writing – review & editing, Investigation. **Bradley Foster:** Investigation. **Natasha L.M. Barlow:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **William Blake:** Writing – review & editing, Methodology, Investigation, Formal analysis. **W. Roland Gehrels:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition. **Martin W. Skov:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Conceptualization. **William E.N. Austin:** Writing – review & editing, Methodology, Funding acquisition.

## Declaration of competing interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Data availability

The datasets generated for this study can be found in the Environmental Information Data Centre (www.eidc.ac.uk) and Marine Scotland Data (https://data.marine.gov.scot/). The data includes Miller et al., 2022, Smeaton et al., 2022c and Koot et al., 2023.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.172104.

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