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Organic matter composition and origin differ between restored and natural UK saltmarshes up to 100 years after the breach

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Abstract. Restoring saltmarshes to enhance atmospheric carbon dioxide uptake is thought to represent a means of climate change mitigation. While carbon stocks in restored marshes were found to reach equivalence with natural sites, the shares of autochthonous and allochthonous carbon sources entering these marshes are less well known. This issue is important because allochthonous carbon is usually excluded from stock calculations. To determine if differences do exist, the conventional tools for determining organic matter source – elemental, stable isotope and thermogravimetric analyses – were applied to sediments from four restored saltmarshes of different ages. Comparisons were then made with existing data from nearby natural marshes. Breach depth horizons in individual cores were successfully identified using foraminifera, unicellular marine protists. The OC/N-ratio was persistently lower in restored saltmarshes compared with natural counterparts even 100 years after the creation of a breach. Additionally, $\delta^{13}C$ signals indicated a mixture of organic matter sources to the restored sites and there was often a higher proportion, based upon thermal sensitivity, of recalcitrant material in the organic matter of the restored marshes. Together, these results indicated that a higher proportion of allochthonous organic matter was entering these restored marshes. Understanding the composition of the organic matter in restored marsh sediment will allow the development of robust and constructive climate change mitigation methods.

1 Introduction

Saltmarshes represent the interface between terrestrial and marine ecosystems. Breaching the seawalls surrounding areas previously claimed for agriculture (i.e. de-embankment) is a method of saltmarsh restoration (French, 2006; Garbutt and Wolters, 2008). Originally, the main aim of de-embankment in the UK was compensatory habitat creation with locations selected based upon coastal protection needs, while also emphasising the nature conservation benefits (Pethick, 2002; Wolters et al., 2005). More recently, attention is being placed upon the increased atmospheric carbon dioxide (CO_2) removal that results from this land use change (Connor et al., 2001; Jones et al., 2024). Currently, a "Saltmarsh Code" is in development in the UK that will allow this increase to be quantified and converted to carbon credits that can be sold as a means of funding restoration and of offsetting the emissions of the buyer, emphasising the importance of this issue (Burden et al., 2023). It is the capacity of saltmarshes to continuously accrete sediment and build elevation, combined with waterlogged conditions caused by tidal inundation and a high organic matter (OM) input from productive saltmarsh plants, that create an effective organic carbon (OC) sink. Part of the OM in saltmarsh sediment is preserved, thus ensuring the sequestration of the OC it contains. Rapid rates of OC accumulation have been recorded in the

years immediately following the creation of a breach (Wollenberg et al., 2018; Mossman et al., 2022) and OC stock levels have recovered in as little as 4 to 20 years after restoration in some instances (Santini et al., 2019; Poppe and Rybczyk, 2021). High levels of variability within and between restored sites, however, mean there is much uncertainty about when and if restored saltmarshes come to replicate the conditions of natural long-standing habitats of the same type.

The differences already shown to exist between restored saltmarshes and natural reference sites are numerous. Agricultural soil layers remain in restored saltmarshes after the creation of the breach, and these relatively compacted layers persist as saltmarsh sediment accumulates on top (Tempest et al., 2015). Ultimately, water is unable to penetrate these layers, and drainage is impacted (Spencer et al., 2017). In turn, the development of topographic variation is prevented and characteristics like elevation and creek density continue to resemble those of agricultural fields and lack the diversity present in natural marshes (Shafer and Streever, 2000; Brooks et al., 2015; Lawrence et al., 2018). Waterlogging and a lack of elevation gradients mean that plant community diversity is often lower in restored saltmarshes because the small-scale variation required for a mosaic of plant species with different inundation frequency requirements is missing (Mossman et al., 2012a, b; Lawrence et al., 2022). Given these differences, the potential for differing OC dynamics in restored saltmarsh is strong.

One key factor in saltmarsh carbon dynamics is the origin of the OM. As well as sediment, OM from outside the marsh, be it from marine, coastal or riverine sources, is delivered by tides, and this is termed allochthonous (Zhou et al., 2007). Whether or not this OM should be included in carbon crediting schemes is debated because its storage cannot be directly linked to the restoration action undertaken (Needelman et al., 2018; Houston et al., 2024; Williamson et al., 2025). On the other hand, OM produced in situ (i.e., autochthonous) by the growth of saltmarsh plants provides an OC input that can only be attributed to the restoration. The contributions of allochthonous OM to saltmarsh stocks is highly variable (Williamson et al., 2025). However, in many cases it represents a significant portion, especially in minerogenic marshes (e.g., Gebrehiwet et al., 2008; Wang et al., 2011; Martins et al., 2022; Krause et al., 2022; Fu et al., 2024; Amann et al., 2024). This is important for the reasons already outlined but also because the autochthonous input can be remineralised over a decadal timescale while the allochthonous input is more effectively preserved (Bartholdy et al., 2014; Van de Broek et al., 2018; Mueller et al., 2019a; Komada et al., 2022). Therefore, OM provenance is a central question to address when comparing restored marshes with natural counterparts.

Common tools to determine the possible mixture of allochthonous and autochthonous components present in saltmarshes are the ratio of OC to nitrogen (N) and the ^{13}C content of OC in the sediment (e.g., Jiménez-Arias et al., 2020; Xia et al., 2021; de los Santos et al., 2023). The former is useful because the high level of protein in marine algae produces a large N content that lowers the OC/N-ratio compared with terrestrial plants that contain C rich cellulose (Meyers, 1994; Zhou et al., 2007; Hulisz et al., 2013). Specifically, OC/N-ratios below 10 are indicative of recently deposited marine OM (Hulisz et al., 2013). Depending on the origin of the OM (i.e., higher plants or algae) and the photosynthetic pathway being used (i.e., C_3 or C_4), different amounts of the heavier carbon isotope are incorporated into tissues during growth, producing distinctive signatures that can be identified with the latter method (Boutton et al., 1998; Mueller et al., 2019b). Three signals with relevance in saltmarsh ecosystems are marine particulate OM (POM)/algae, terrestrial plants (C_3; be they from a saltmarsh or agricultural field) and *Spartina* spp. (C_4). The $\delta^{13}C$ values of these sources tend to increase in the order listed. Untangling the results of this analysis is rarely a simple task, and consideration must be given to whether the signals at different depths along a sediment core are indicative of a change in OM source or if variation is simply due to OM decomposition (Luk et al., 2021).

Another important method for characterising the OM present in saltmarshes is via thermogravimetric analysis (TGA), whereby the fractions of labile or recalcitrant OM in a sediment sample can be differentiated and quantified (Smeaton and Austin, 2022). In the context of TGA, labile OM refers to thermally sensitive molecules that burn at lower temperatures and are thus potentially more easily degradable in the environment (Schmidt et al., 2011). On the other hand, recalcitrant OM is largely lost at higher temperatures and so represents potentially more complex and stable molecules. In a saltmarsh ecosystem, OC is stabilized in marsh soils under reducing, oxygen-deficient conditions because the absence of O_2 as a highly efficient terminal electron acceptor constrains microbial decomposition (Megonigal et al., 2003). In minerogenic marshes, additional stabilization mechanisms known from upland soils may also contribute, particularly the formation of mineral–organic associations. Although these associations may be weaker or less abundant than in well-aerated upland soils, recent studies suggest that they nevertheless contribute to OC stabilization in marsh sediments (Neiske et al., 2025). When undergoing thermogravimetric analysis, the mineral associated OM is burnt off at higher temperatures and thus classed as recalcitrant while organic macroaggregates are unprotected when removed from their anoxic environment and burn in the labile temperature range (Pallasser et al., 2013; Li et al., 2023; Ortner et al., 2025). These three methods are combined to achieve a more insightful picture of saltmarsh carbon dynamics and can be used to make comparisons between restored and natural marshes.

A crucial first step when measuring the properties of restored saltmarshes is to differentiate between the pre- and post-breach sediment layers. In addition to making accurate comparisons with natural marshes, this is particularly important when calculating OC stocks and accumulation rates be-

cause of the need to determine the land use of the site at the time of OM deposition (Smeaton et al., 2023). Radiometric dating is often applied to saltmarshes but in the case of restored sites this is often not feasible due to the young age of a site and/or disruption of sediment layers during site construction. Previous efforts have successfully used diatoms and moisture content to determine the breach depth (Spencer et al., 2008). Problems with using diatoms, however, include poor preservation making it necessary to identify remains, instead of full valves, and the impossibility of any identification in samples containing coarse silt and sand (Spencer et al., 2008). The foraminifera – unicellular marine protists (Sen Gupta, 2003) – present in saltmarshes have long been used to reconstruct past sea-level changes (e.g., Edwards and Horton, 2006) and were employed in one study to find the transition in sediment cores from tidal flat to saltmarsh ecosystems (Mueller et al., 2019a). Furthermore, foraminifera have previously been used as proxies to identify human disturbance in saltmarsh sediment (e.g., García-Artola et al., 2016; Müller-Navarra et al., 2019) and the importance of salinity for most species makes clear the potential for using foraminifera to differentiate between the horizons in restored marsh cores. In this study, application of this technique presented an opportunity for its refinement and an assessment of its performance in saltmarshes restored via seawall breaching.

In this study, the variables quantified were OC, N and $\delta^{13}C$ signatures – the former two allowing OC/N ratios to be calculated – and the fractions of labile and recalcitrant OM, based upon TGA. The aim was to make comparisons across four different restored sites of different ages by applying this wide array of analyses that are not often brought together to produce a comprehensive discussion of saltmarsh restoration as a natural climate solution. We combined the new restored marsh data collected with an existing database of natural marsh reference sites. To achieve our overarching goal, the first objective was to determine the depth of the breach in our sediment cores using foraminifera, making it possible to identify which core sections were representative of pre- and post-breach settings. As a result, the biogeochemical variables examined could be compared across sites and the possible reasons for any differences or similarities attributed to the stages of marsh development. Finally, we used the breach depth estimates to calculate OC stocks for the post restoration sections of the cores.

2 Study sites

The focus of the study is the east of England (Fig. 1a and b), where saltmarshes are a common feature along the coastline that provide biodiversity and coastal protection benefits and where several restoration projects have already been implemented (Boorman, 2003).

As examples of older restored sites, previous studies have looked at marshes restored "accidentally" when storms created breaches in the surrounding sea walls, often as long as a century ago. These sites are often called unmanaged realignments. Differences in the sediment characteristics between restored and natural sites – such as microporosity and pore connectivity – resulting from the presence of the agricultural soil layer were not identified in sites breached accidentally during storm surges (Spencer et al., 2017); however, plant community differences, such as an absence of perennials and the predominance of the shrub *Atriplex portulacoides* have been identified (Mossman et al., 2012b). Furthermore, recently created unmanaged sites were found to lack topographical diversity (Williams and Dale, 2023). Overall, this suggests that other persistent differences could exist in unmanaged sites that represent the future development of more recently restored marshes.

2.1 Restored saltmarshes

2.1.1 Aldboro Point

Aldboro Point (Fig. S1a in the Supplement) lies within the Colne estuary, approximately 12 km southeast of Colchester (51.832375, 0.986063). This marsh represents the oldest site included in the study and thus represents an unmanaged realignment, with tidal inundation reintroduced in 1921 by a storm-created breach in the seawall (Burd, 1992; Burd et al., 1994; Wolters et al., 2005). The reported history of the area prior to the final breach suggested very inconsistent conditions. Enclosure with field boundaries occurred after 1840, by 1874 no seawall was present and the 1896 Ordnance Survey (OS) mapping indicated the area was again enclosed (Burd et al., 1992). It is not definitively known when the final breach occurred, but the 1921 OS map showed a saltmarsh. For simplicity in this study, the breach was assumed to have occurred at the latest possible date, in 1921, as in other studies (e.g., Atkinson et al., 2001; van Oevelen et al., 2000; Wolters et al., 2005). Therefore, at the time of sampling, the marsh was assumed to be 102 years old. The plant species recorded in 2023 at the selected sampling locations (Fig. 1c; Table S1 in the Supplement) included *Puccinellia maritima*, *A. portulacoides*, *Limonium vulgare* and small patches of *Spartina anglica* (Table S2). The tidal range is 4.5 m (Wolters et al., 2005).

Monitoring of the vegetation at Aldboro Point in 1993 (72 years after the breach; Burd et al., 1994) showed that species diversity was low, with only 18 % of the "target" species present (Wolters et al., 2005). The most abundant species (41 %–60 % cover) were *Suaeda maritima* and *P. maritima*. Another study using data collected in 2004 (83 years after the breach) found that species richness in Aldboro Point did not differ significantly from a nearby natural reference marsh but that the plant community in the former was dominated by *A. portulacoides* and in the latter by *P. maritima* (Garbutt and Wolters, 2008). Data from the monitoring project of Burd and colleagues (1994) was used to calculate an initial

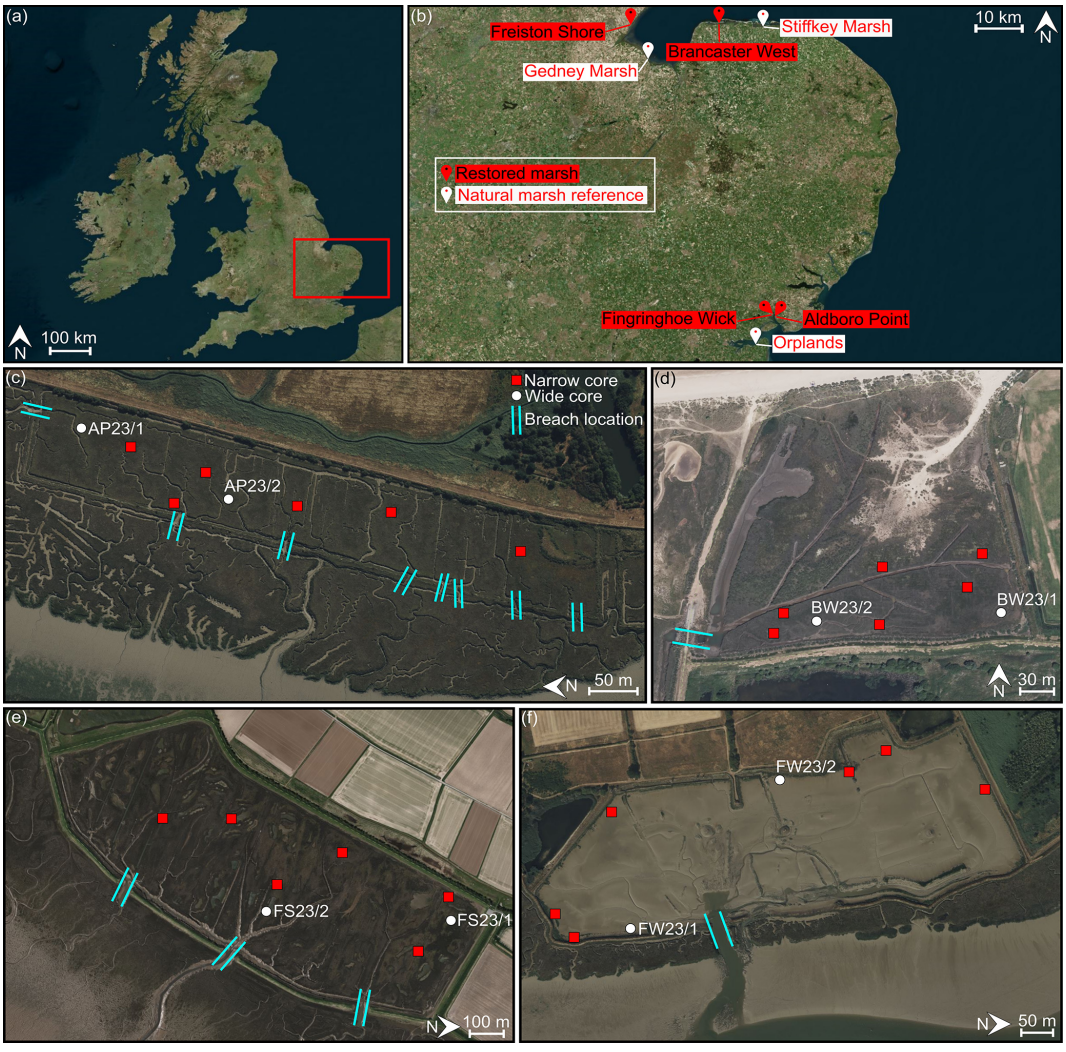


Figure 1. Locations of the sampling sites within **(a)** the UK and **(b)** the east of England and of the narrow (red squares) and wide (white circles) cores taken from **(c)** Aldboro Point, **(d)** Brancaster West, **(e)** Freiston Shore and **(f)** Fingringhoe Wick. The red markers in panel **(b)** represent the marshes that were sampled as a part of this study while the white markers are the natural marsh reference sites sampled by Smeaton and colleagues (2023, 2024). Breach locations in panels **(c)**–**(f)** are marked with turquoise lines. Map imagery © Microsoft Bing Maps; satellite imagery © DigitalGlobe (Maxar), 2020.

sediment accretion rate of 3.00 mm yr^{-1} and an average of 7.22 mm yr^{-1} by another project (van Oevelen et al., 2000).

2.1.2 Freiston Shore

Freiston Shore (Fig. S2b) is located within The Wash, ~ 8 km east of Boston in Lincolnshire (52.965328, 0.092937). The most recent artificial embankment in Freiston Shore was constructed in 1980 and the three breaches in the seawall were deliberately created in 2002, making the site 21 years old during sampling (Symonds and Collins, 2007). At the selected sampling locations (Fig. 1e; Table S1), the plant species present predominantly included *A. portulacoides*, *P. maritima*, and *Salicornia* spp., with smaller quantities of *S. anglica*, *L. vulgare* and *Aster tripolium* present (Table S2). The tidal range experienced by the site is 6.5 m (Wolters et al., 2005).

Unlike the other study sites, Freiston Shore has been the subject of many investigations looking at a variety of factors. For example, it was reported that 88 % of the restoration site was vegetated only 4 years after breach creation (Friess et al., 2012), that substantial channel erosion had occurred at certain locations (Friess et al., 2014) and that the restored marsh had a wave amplification, as opposed to attenuation, effect (Kiesel et al., 2019). Especially relevant to this study was a previous investigation of sediment accretion rates between 2002 and 2006 (Spencer et al., 2012). The study by Wolters and colleagues (2005) referred to in Sect. 2.1.1 also included Freiston Shore and they reported that this site contained the same proportion (18 %) of target species as Ald-

boro Point, but only 1 year after the breach. Ten years after the initial breach was created in Freiston, topographic manipulation was carried out to increase habitat diversity and this led to an increase in plant species beta-diversity (Lawrence et al., 2022).

2.1.3 Brancaster West

The third site, Brancaster West (Fig. S1c), is situated on the North Norfolk coast, around 15 km west of Wells-next-the-Sea (52.972107, 0.631014). Brancaster West was selected for restoration in 1996, work began in 2001 and was completed in 2002 (Doody, 2002; Myatt-Bell et al., 2002; Wolters et al., 2005). Like Freiston Shore, this site was 21 years old at the time of sampling. Prior to restoration, the area was used as a freshwater grazing meadow and differs from the other sites included in this study as the tide flows in via piped culverts, as opposed to a simple breach dug in a seawall (Doody, 2002). This difference does not impede comparisons, however, as the site still experiences regular tidal inundation that drives sediment and OM delivery, sediment redox conditions and plant species zonation. Development of the plant communities in the 5 years following the breach has been recorded and showed that *Salicornia europaea* and *S. maritima* were generally most dominant (Mossman et al., 2012a). In addition, it was shown that the vegetation still differed significantly from the communities in natural reference marshes 5 years after restoration was implemented, which was put down to strongly reducing conditions in the Brancaster West sediment (Mossman et al., 2012a). Most of our sampling locations (Fig. 1d; Table S1) were overwhelmingly dominated by *S. anglica* and *A. portulacoides* but there were more diverse patches in which *L. vulgare, Salicornia* spp., *A. tripolium*, *P. maritima* and *Triglochin maritima* were present (Table S2). The tidal range in the area is 6.5 m (Wolters et al., 2005).

2.1.4 Fingringhoe Wick

The youngest restored marsh (Fig. S1d) selected in this study sits within the Fingringhoe Wick Nature Discovery Park in Essex and, like Aldboro Point, lies within the Colne estuary (51.842106, 0.974856). The site is an area of former agricultural land to which tidal inundation was reintroduced by the creation of two breaches in the seawall in 2015, making it 8 years old during sampling (Vaughan, 2019). Prior to breaching the sea wall, the southern section of the area was used as an arable field while the northern part was a pasture (Cai et al., 2022). This marsh largely resembles an unvegetated mudflat, but saltmarsh plant communities have begun to colonise the fringes of the site. Only three plant species were found across all the sampling stations (Fig. 1f; Table S1): *S. anglica*, *Salicornia* spp. and *A. portulacoides* (Table S2). The tidal range is 4.5 m (Wolters et al., 2005).

2.2 Natural marsh reference sites

Three natural saltmarshes, investigated in the studies conducted by Smeaton et al. (2023, 2024), were selected for their proximity to the restored saltmarshes (Fig. 1b) and were used as baselines to compare the biogeochemical variables of interest. Aldboro Point and Fingringhoe Wick, two sites almost opposite to one another in the Colne estuary, were compared with Orplands, approximately 16 km away. Freiston Shore was paired with Gedney Marsh, also $\sim$16 km away, and Brancaster West with Stiffkey Marsh, $\sim$20 km away. Detailed information about these natural saltmarshes is available elsewhere (Smeaton et al., 2023, 2024; https://catalogue.ceh.ac.uk/documents/5cc9ee72-ed88-4e71-bd8d-e3511bb9ed12, last access: 4 November 2026). To make comparisons possible, results from cores sampled at a 1 cm resolution were binned into the same depth intervals we sampled (see Sect. 3.1).

3 Methodology

3.1 Sample collection

Fieldwork was conducted during June and August of 2023. From each of the four restored saltmarshes, eight sediment cores were collected – two wide diameter (5 cm) cores extracted with a Russian peat corer and six narrow diameter (2.7 cm) cores extracted with a gouge auger. The distances of each coring location from the nearest seawall breach are recorded in Table S1. The wide cores were transported whole to the laboratory while the narrow were subsampled in the field at the following resolution: every 2 cm in the top 10 cm and every 5 cm over the remainder of the cores. Within each of the two wide core sampling locations at every site, three replicate wide-diameter cores were always taken from within the same $\sim 30\,cm^2$ area to ensure enough material was available for all the required analyses. Within each of the six narrow core sampling locations at every site, only one core was taken because fewer analyses were planned for these samples so less material was required. 100 cm deep cores were collected from Aldboro Point, and 50 cm deep cores were extracted from the other study sites, as it was anticipated that sediment accretion following the breach in the more recently restored sites (i.e., those less than 21 years old) would be less than 50 cm. Although sedimentation rates of $7.5\,cm\,yr^{-1}$ have been reported for restored sites in the Severn estuary, far lower ranges ($< 2\,cm\,yr^{-1}$) have been recorded within east of England restored marshes (Mossman et al., 2022). Furthermore, very high sedimentation rates usually only occur for the first few years following a breach, until the elevation of a site within the tidal frame has increased (Mossman et al., 2022). Therefore, the assumption that no more than 50 cm of sediment had accreted in the younger restored sites was deemed legitimate. Usually, it was not possible to

reach the maximum corer depth. In all cases, the plant species present within the 1 m^2 area surrounding each coring location were recorded. Cores were stored at −20 °C after being returned to the laboratory and until further analyses were conducted. Hence forth, cores from Aldboro Point are referred to as AP23/1-8, Freiston Shore FS23/1-8, Brancaster West BW23/1-8 and Fingringhoe Wick FW23/1-8. Wide cores are always numbered 1 and 2 (Fig. 1c–1f).

3.2 Foraminiferal analysis

Foraminiferal analysis was used to identify the breach horizons. One replicate core from each of the two wide core sampling location were cut into 1 cm slices in the laboratory. Between 3.0 and 3.5 g of sediment was taken from each slice, and the precise wet mass of each recorded. These samples were then sieved and the fraction between 63 and 500 µm retained for analysis. Samples were refrigerated in 5 % isopropyl (HEXEAL) before analysis to ensure a high level of preservation. Rose Bengal staining was not used to differentiate between living and dead foraminifera, meaning that all counts represented the total foraminiferal population (Scott and Medioli, 1980). This was deemed acceptable because the main purpose of analysing the foraminiferal populations was to determine the breach depth and it has been shown that living foraminifera are overwhelming concentrated at the surface (Saffert and Thomas, 1998; Hayward et al., 2014). Samples were split into eight equal aliquots and when foraminifera were present, the aim was to count a minimum of 50 individuals for each sample, following Kemp et al. (2020). If foraminifera were absent from the first aliquot, the entire sample was processed to confirm this was the case throughout. Foraminiferal species assemblage composition was only assessed in samples containing over fifty tests (Kemp et al., 2020). The breach was deemed to have occurred at the lowest depth at which any number of foraminiferal tests (i.e., ≥ 1) were first encountered. This criterion was applied to Fingringhoe Wick, Brancaster West and Freiston Shore while the age-depth model results (see Sect. 3.3.) were relied upon for Aldboro Point. Murray (1979) was followed for taxonomic assignments to species level. In the cases of *Quinqueloculina* spp., *Elphidium* spp., *Ammonia* spp., *Rosalina* spp. and *Haplophragmoides* spp. only genus level identification was performed. Numbers of tests are given relative to the wet mass of the sample prior to sieving.

3.3 Radiometric dating

Radiometric dating was only conducted with one wide diameter core from Aldboro Point, the oldest site, because of the need for sediment old enough to achieve interpretable ^{210}Pb and ^{137}Cs profiles. When wet subsampling core AP23/1 in the laboratory, material from each centimetre wide slice from the two replicate cores, AP23/1A and AP23/1B, were combined to provide enough material for radiometric analysis. Total (i.e., unsupported and supported) ^{210}Pb was determined indirectly via alpha spectrometry (ORTEC Alpha Ensemble) by measuring its decay product, ^{210}Po, and assuming secular equilibrium (Ebaid and Khater, 2006). In more detail, approximately 0.3 g of each 1 cm core slice between 0 and 40 cm was spiked with a known amount of ^{209}Po radiotracer (National Physical Laboratory) and digested using 12 mL of a mixture of 69 % nitric acid (ARISTAR) and 47 % hydrogen fluoride (NORMATOM; 3/1 mixture) in a microwave assisted digestion system (CEM Mars 6). After neutralising any remaining free fluoride ions, each digest solution was transferred to a glass beaker, evaporated to dryness, and taken up to 25 mL using a 0.5 mol HCl solution to allow for the spontaneous deposition of ^{209}Po and ^{210}Po on a silver disc for 5 h at 90 °C. Each silver disc was finally counted via alpha spectrometry for up to 5 d. Selected adjacent slices (0–3, 8–10, 13–15, 16–18, 19–23, 24–26, 27–29, 30–32 and 38–40 cm) were combined to prepare a suitable geometry for gamma spectrometric analysis (ORTEC HPGe detector) and determine levels of ^{226}Ra (i.e., supported ^{210}Pb via ^{214}Pb) and ^{137}Cs at 352 and 662 keV, respectively (Woodward-Rowe et al., 2025).

In R (version 4.4.1), the package *rplum*, version 1.0.0 (Blaauw et al., 2023), was used to develop a Bayesian age-depth model generated from ^{210}Pb and ^{137}Cs data. This negated the need to select an equilibrium depth and allowed for the easy integration of the ^{137}Cs chronohorizon (Aquino-López et al., 2018). Sediment accretion rates (SAR; mm yr^{-1}) were also obtained from the *rplum* model.

3.4 Bulk elemental and isotopic analyses

OC and N content, as well as dry bulk density, were measured in every sample from all cores, narrow and wide. Similarly to the replicate core used for the foraminiferal analysis, another replicate was sliced into 1 cm slices in the laboratory before being freeze dried along with the narrow core subsamples that were sliced in the field, as detailed in Sect. 3.1. After freeze drying, samples were weighed and this dry mass was divided by the volume of the sample prior to drying to calculate dry bulk density (Dadey et al., 1992). Moisture content was calculated for only the wide cores because it was possible to record the wet mass when subsampling in the laboratory; the dry masses were then subtracted from the wet masses and the products divided by the wet masses.

To approximately 1 g of every dried sample, we added 15 mL – split between three 5 mL aliquots – of 6 % sulphurous acid (Fisher Scientific) to remove carbonates by producing calcium sulphate dihydrate, water and carbon dioxide (Gibbs, 1977; Caughey et al., 1995). Acidified samples were allowed to stand for 72 h before being dried again in the freeze dryer. Finally, samples were homogenised for 30 s in a ball mill. From these homogenised samples, 5 mg were weighed into tin capsules and their OC and N content determined by elemental analysis with an CE440 elemental anal-

yser (Exeter Analytical). It was sometimes necessary to repeat measurements for samples with conspicuously low N results by weighing 20 mg into a capsule, instead. A capsule containing approximately 1.6 mg acetanilide (Sigma-Aldrich) was run as a standard between every group of six sediment samples for quality control purposes. OC/N ratio was calculated by dividing the OC content of a sample by its N content.

Only the wide diameter cores were subject to bulk sediment $\delta^{13}C$ analysis and only every other centimetre was processed, except where the OC content showed high variability, in which case every centimetre was analysed in that section. To ensure that an appropriate amount of carbon dioxide gas was obtained after combusting the sediment sample for the Finnigan Delta plus XP Isotope Ratio Mass Spectrometer (Thermo Fisher Scientific), the amount of sediment weighed into the tin capsule prior to this analysis was based upon the OC content and varied between 0.03 and 1.60 mg. Capsules containing approximately 0.5 mg of an internal laboratory standard (USGS89 collagen) were run in pairs before and after every 12 sediment samples to act as a quality control and to assess measurement drift throughout the measurement batches. The analytical precision of ^{13}C analysis was ± 0.10 ‰ representing one standard deviation of all collagen analyses ($n = 16$). Values are given in δ notation versus VPDB.

3.5 Thermogravimetric analysis

Approximately 20 mg of the same dried and acidified sediment samples reported in Sect. 3.4 were used to determine total OM, labile OM and recalcitrant OM content with a TRIOS SDT 650 (TA Instruments). The samples were heated from 40 up to 1000 °C under a constant stream of N_2. The rate of increase was 10 °C min^{-1}. To classify the OM, the methodology presented in Smeaton and Austin (2022) was followed where labile OM is lost in the temperature range between 200 and 400 °C, the recalcitrant fraction between 400 and 650 °C, and total OM was represented by the entirety of this range.

3.6 Organic carbon stock calculations

To calculate OC stocks, we used the narrow and wide core data separately because they were subsampled at different resolutions and followed Howard et al. (2014). First, OC density was calculated by multiplying the OC content of a sample by its dry bulk density (Figs. S2 and S3). Second, the carbon density of a core segment was multiplied by its length. Next, these values were summed across the length of a core that was deemed representative of a saltmarsh ecosystem. The sections of the cores taken to represent the post-breach marsh was determined upon a case-by-case basis: for Aldboro Point the radiometric dating results were used and for the other sites the foraminiferal analysis was the basis of this determination. In every case, it was considered, after applying the foraminifera-based breach depth range to the narrow core results, whether the additional evidence provided by the biogeochemical analysis suggested that the breach depth range should be adjusted. This was deemed necessary for two sites: Brancaster West and Fingringhoe Wick, and in both instances involved extending the breach depth range. With the narrow core results, averages of the OC density totals – above the breach range depth in question – of each core within a site were taken.

3.7 Statistical analysis

To determine whether statistical differences existed between the biogeochemical variables (% OC, % N, OC/N ratio, proportion of recalcitrant OM) measured in our restored sites and those also recorded in the natural marshes, we used linear mixed effects models with sampling site and core identification being used as random variables. The lmer function from the *lme4* package in R was used (Bates et al., 2015). OC and N data were log transformed prior to analyses to obtain normal distributions of residuals, which was determined by the visual inspection of diagnostic plots. Transformation was not necessary for OC/N ratios or proportion of recalcitrant OM. All statistical analyses were performed in R version 4.4.1 (R Core Team, 2024). Given the presence of random effects, denominator degrees of freedom were estimated with the Satterthwaite method (Kuznetsova et al., 2017).

4 Results

4.1 Age-depth model

The core AP23/1 from Aldboro Point was the only one subject to ^{210}Pb and ^{137}Cs dating. These data were used to create a Bayesian age-depth model (Fig. 2a) in *rplum* (Blaauw et al., 2023). The peak in ^{137}Cs levels clearly visible between 21 and 22 cm depth was attributed to legacy discharge from the Bradwell Power Station, approximately 12 km from the site, which peaked in 1975 (European Commission, 1990; modelled as 1975 ± 5 years; Fig. 2b). Activity concentrations of ^{210}Pb decreased from the surface of the core down to 27–28 cm depth at which point concentrations stabilised (Fig. 2c). The level of supported ^{210}Pb activity concentration (i.e.,^{226}Ra determined via its decay product ^{214}Pb at 352 keV by gamma spectrometry) averaged at 24.5 ± 1.9 Bq kg^{-1}, a value derived from the measurement of seven combined slices evenly spaced along the length of the core (Fig. 2c). The 2σ uncertainties produced by the model were less than 20 years up to a depth of 25–26 cm, below which point uncertainties increased down the core and reached 70 years in the lowermost sample (Fig. 2a).

Using the estimated ages of deposition assigned to each section of the sediment core, it was possible to determine the depth that represented the year 1921, the year of the

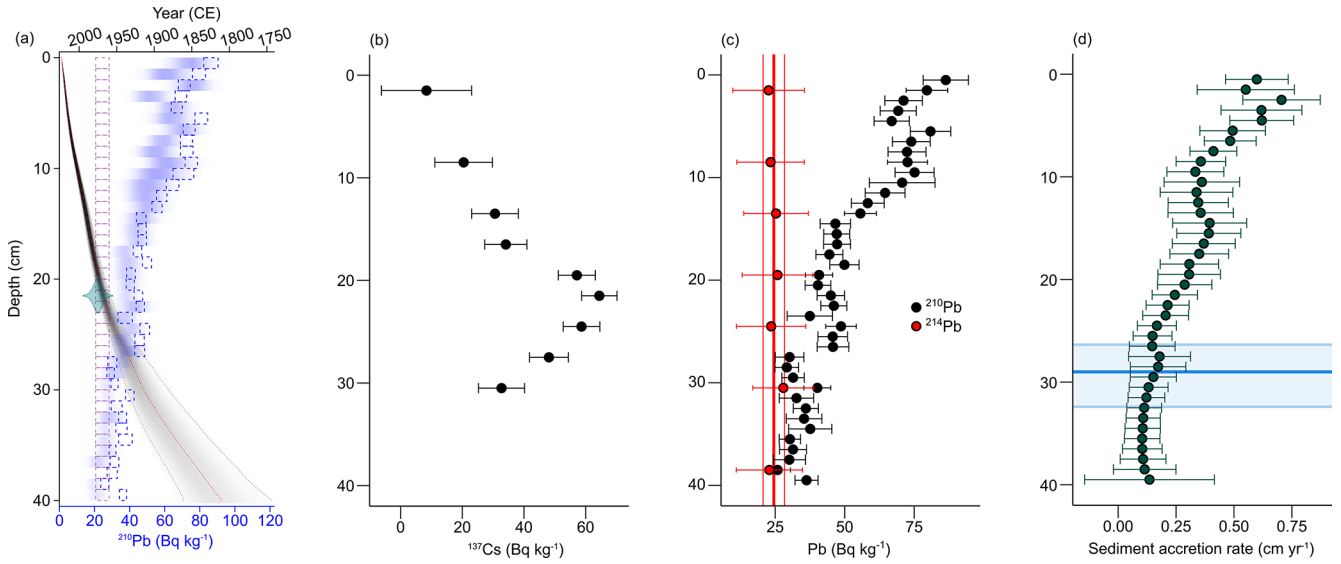


Figure 2. (a) The Bayesian age depth model for AP23/1, with the model represented by the black shaded area and the blue shaded area showing total ^{210}Pb levels. The green shaded area between 21–22 cm depth represents the ^{137}Cs peak at the calendar date 1975 ± 5 years. The model was developed with the *rplum* package (Blaauw et al., 2023) using **(b)** ^{137}Cs and **(c)** ^{210}Pb data. A mean ^{214}Pb value was used for the model, and this is represented by the thick red line with the 2σ standard deviations represented by the thin lines. **(d)** Sediment accretion rates for each core slice were obtained from the model. The blue shaded area represents the estimated depth of the breach, based upon the ages assigned by the model to each centimetre of sediment. The thick blue line shows the depth estimated from the mean ages while the two thin lines show the depths calculated using the minimum and maximum ages (i.e., 2σ uncertainties). Error bars are ± 2σ.

breach. From the mean ages, 29.0 cm was assigned as the breach depth, and using the 2σ uncertainty values, the maximum and minimum breach depths were assigned to 32.4 and 26.4 cm depth, respectively (Fig. 2d). These are the depths represented by the blue lines and shaded areas on all subsequent Aldboro Point figures.

Sediment accretion rate (SAR) values for each centimetre of sediment in the top 40 cm of the core were also derived from the age-depth model developed using *rplum* (Blaauw et al., 2023; Fig. 2d). The average SAR between the bottom slice of the core (39–40 cm) up to 26–27 cm was 0.14 ± 0.28 cm yr^{-1}. Above 26–27 cm, the SAR increased gradually up to the top of the core (Fig. 2d). The beginning of this increase in SAR roughly coincided with the breach depth range estimated using the age-depth model. SAR increased gradually between 27 and 14 cm depth before remining relatively constant until 7 cm. Values then continued to increase up to the top of the core, with a maximum SAR of 0.60 ± 0.14 cm yr^{-1} recorded between 2 and 3 cm.

4.2 Foraminifera

4.2.1 Aldboro Point

Based upon the radiometric dating results, the breach depth was identified at 32.4 and 26.4 cm depth, and, to a degree, this was corroborated by the results from the foraminiferal analysis of core AP23/1. High numbers (> 70) of foraminiferal tests were found in almost every centimetre analysed from core AP23/1 (Fig. 3a). In samples from 31 to 33 cm depth, however, less than 40 tests were found, and these immediately proceeded and overlapped the lower limit of the breach depth range. Furthermore, there was a notable decrease in the numbers of tests per gram wet mass between 40–41, 35–36, 33–34 and 30–31 cm. Similar dips in numbers of tests per gram were detected in other parts of the core (i.e., between 90–91, 80–81, 70–71 and 55–56 cm) but these reductions in density were less sustained (Fig. 3a). The other core taken from Aldboro Point (AP23/2) followed a different pattern with several samples analysed that contained less than fifty tests (Fig. 3b). Additionally, there was generally a lower number of tests per gram in this core, with values no higher than 57 in all samples except for at the surface (398 tests) and between 81 and 75 cm depth (157–196). Within the estimated breach depth range, was one sample that contained 42 tests (i.e., 11 tests per gram; from 30–31 cm). Almost every sample examined from the Aldboro Point cores had assemblages overwhelmingly dominated by the agglutinated species *Entzia macrescens* (Fig. S4a and b).

4.2.2 Freiston Shore

The cores from Freiston Shore contained high numbers (> 80) of tests in all selected samples, including those from the lowest core depths achieved (19–20 and 45.0 cm in FS23/1 and FS23/2, respectively; Fig. 3c and d). Numbers of tests per g were lower in FS23/1, except for in the up-

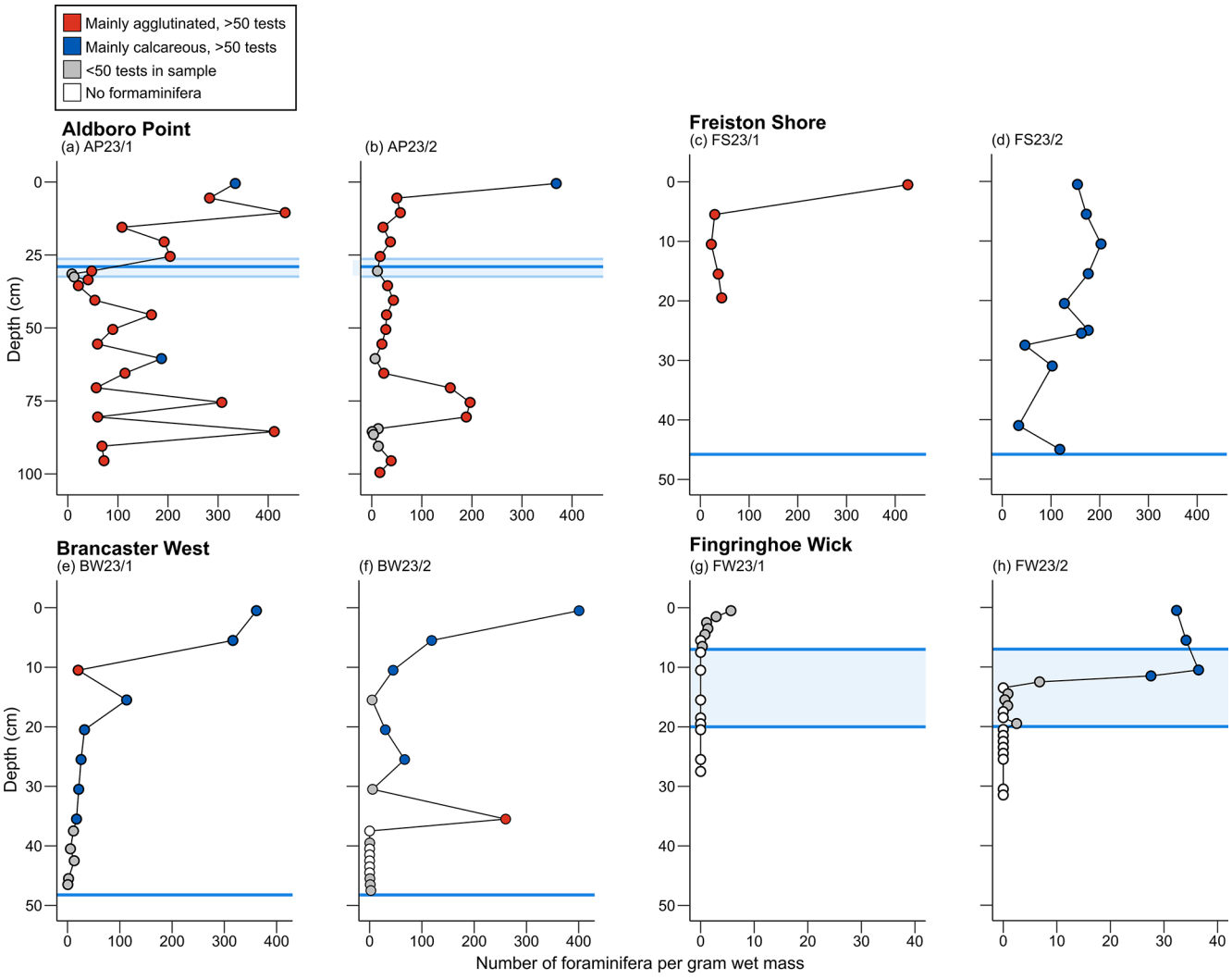


Figure 3. The numbers of foraminifera per gram of sediment in each centimetre section of sediment processed from the two wide-diameter cores taken from **(a–b)** Aldboro Point, **(c–d)** Freiston Shore, **(e–f)** Brancaster West and **(g–h)** Fingringhoe Wick. The blue shaded areas represent the depth range in which the breaches could have occurred and were based upon the age depth model (Fig. 2) for Aldboro Point and upon the foraminifera results for the other sites (details are discussed in Sect. 4.2.1, 4.4.2, 4.2.3 and 4.2.4). In the Aldboro Point panels, the thick line shows the depth estimated from the mean ages of the age depth model, while the two thin lines show the depths calculated using the minimum and maximum ages (i.e., 2σ uncertainties).

permost sample which contained the highest density value across both cores. The main difference between FS23/1 and FS23/2 was the overwhelming predominance of agglutinated species in the former and calcareous species in the latter. It was concluded that the breach depth was not reached and that the cores were representative of saltmarsh sediment only. As a result, the blue shaded area was placed just below the depth of the lowermost sample analysed (Fig. 3c and d)

4.2.3 Brancaster West

Brancaster West cores contained no or only very low numbers (< 60) of foraminiferal tests below 35 cm depth (Fig. 3e and f). In BW23/1, low numbers of test were present in all five samples analysed between 47 and 38 cm depth (Fig. 3e). After this point, densities gradually increased up the core and samples were dominated by calcareous species. The one exception to this trend was a sample from 10–11 cm depth that contained a lower density of predominately agglutinated tests. BW23/2 contained less consistent patterns of test densities and assemblage compositions than BW23/1. The lowermost sample analysed (47–48 cm) contained a low number of tests and the next ~ 8 cm of sediment samples either contained similar amounts or were entirely empty of foraminifera (Fig. 3f). The core layer between 37 and 38 cm contained no foraminifera, but the layer above (36–37 cm) had 260 tests per gram, and these were predomi-

nately agglutinated species (Fig. 3f). The sample between 30 and 31 cm contained only 19 tests and all remaining samples from higher up the core contained predominantly calcareous species at far lower densities, except for in the uppermost sample (Fig. 3f). Similarly to Freiston Shore, the foraminifera data suggested that the breach depth was not reach in Brancaster West, meaning that the blue shaded area was placed below the depth of the lowermost sample analysed (Fig. 3e and f). Unlike Freiston Shore, the breach depth range of this site was later altered after examining the results of the biogeochemical analyses.

4.2.4 Fingringhoe Wick

There was a clear difference between the two cores from the youngest site, Fingringhoe Wick. FW23/1 contained no foraminifera until a depth of 6–7 cm, and above this point only very low numbers of teststests – 13 at most (0–1 cm) – were found (Fig. 3g). On the other hand, FW23/2 contained empty samples until a depth of 19–20 cm, low numbers (1–21 tests) in most samples between this point and 12–13 cm and then high numbers (> 100) in all subsequent samples, bar one (Fig. 3h). Therefore, the possible breach depth for this site was between the first emergences of foraminifera in both cores, meaning a range between 7 and 20 cm.

4.3 Organic carbon and nitrogen content

In the Aldboro Point narrow core segments, OC and N content followed a pattern of gradually increasing values up the cores, similarly to the pattern in the corresponding natural marsh reference site, Orplands (Fig. 4a and b). In Aldboro Point values remained relatively stable between the bottom sample to 25–30 cm depth (i.e., near the estimated breach depth of 31 cm). Above this point, values increased up the core, reaching an OC peak of $6.55\,\% \pm 1.40\,\%$ at 4–6 cm and a N peak of $0.59\,\% \pm 0.08\,\%$ at 2–4 cm. In the Orplands cores, a similar, steady increase in OC and N content was seen, ending in $5.02\,\% \pm 0.71\,\%$ OC and $0.48\,\% \pm 0.14\,\%$ N in the surface sediment.

Freiston Shore and Gedney Marsh cores also shared a similar pattern of OC and N content (Fig. 4c and d). In the Freiston Shore narrow cores, values remain constant from the bottom to a depth of around 9 cm and from this point an increase was seen, with the uppermost samples containing $3.41\,\% \pm 0.75\,\%$ OC and $0.33\,\% \pm 0.07\,\%$ N. Gedney Marsh values increased with depth and reached peaks of $4.81\,\% \pm 0.69\,\%$ OC and $0.33\,\% \pm 0.08\,\%$ N in the uppermost samples. In the cases of Freiston Shore and Aldboro Point, the close adherence of the restored marsh OC and N depth profiles with those of their natural marsh counterparts meant that the foraminifera-derived breach depth range was deemed acceptable and did not require adjustment.

In Brancaster West, OC and N content followed a distinctly different pattern (Fig. 4e and f). Again, and as was expected, the natural marsh reference site, Stiffkey Marsh, displayed a pattern of steady increase up the core, reaching $8.37\,\% \pm 1.3\,\%$ OC and $0.51\,\% \pm 0.02\,\%$ N in the surface samples. The lowermost samples (42–43 cm) from Brancaster contained $3.45\,\% \pm 0.38\,\%$ OC and $0.34\,\% \pm 0.09\,\%$ N. However, from 30–35 cm depth and in the three successive samples, there was a jump to a maximum of $6.46\,\% \pm 3.51\,\%$ OC and $0.58\,\% \pm 0.30\,\%$ N. From 10–15 cm, values dropped down to $2.48\,\% \pm 0.37\,\%$ OC and $0.22\,\% \pm 0.04\,\%$ N and small, successive increases were sustained to the surface (Fig. 4e and f). Based upon these results, the breach depth range was extended from 48 to 17 cm so that the stock calculated from the former depth included the OC and N peaks while those from the latter excluded these values.

Like Aldboro Point, Fingringhoe Wick was paired with Orplands for a natural reference site and thus was also compared against the same pattern of steady increase in OC and N up the cores (Fig. 4g and h). At the bottom of the Fingringhoe Wick cores (40–45 cm), OC content was $1.34\,\% \pm 0.21\,\%$ and N content $0.14\,\% \pm 0.01\,\%$. There followed an increase in both variables, with a clear jump in values from 20–25 cm depth and over the two subsequent depth categories (15–20 and 12–15 cm). Values peaked at $7.34\,\% \pm 3.20\,\%$ for OC and $0.58\,\% \pm 0.21\,\%$ for N. In this case, the jump in OC and N content began below our foraminifera estimated breach depth. At 8–10 cm – still within the estimated breach depth – values fell to $2.85\,\% \pm 0.56\,\%$ OC and $0.30\,\% \pm 0.04\,\%$ N and similar levels were sustained to the surface (Fig. 4g and h). We extended the lower limit of the breach depth range from 20 to 25 cm based upon these results.

Overall, there was not a significant difference between the OC and N content of the restored marshes compared with their natural counterparts ($p = 0.17$ and 0.20, respectively; Table S3). The interaction between marsh type and depth, however, was significant ($p =< 0.001$, in both cases), meaning that differences between marsh types did exist at certain depth intervals (Table S3). Namely, and as already described, differences in OC and N content between restored and natural marshes were often strongest in the top ~ 10 cm of the cores.

4.4 Recalcitrant organic matter

The proportion of OM classed as recalcitrant was high across all sites, restored and natural, with most values being greater than 0.5 (i.e., 50 % recalcitrant; Fig. 5). In Aldboro Point and Freiston Shore, there was a small decrease in recalcitrant OM content up the cores, and, in both cases, this closely matched the patterns of the natural reference sites (Fig. 5a and b). Brancaster West samples below 15 cm depth also had values that overlapped with the natural reference site Stiffkey Marsh, but above this point, there was a divergence (Fig. 5c). A share of between 0.64 ± 0.03 and 0.67 ± 0.02 of OM was classed as recalcitrant in Brancaster West from 15 cm

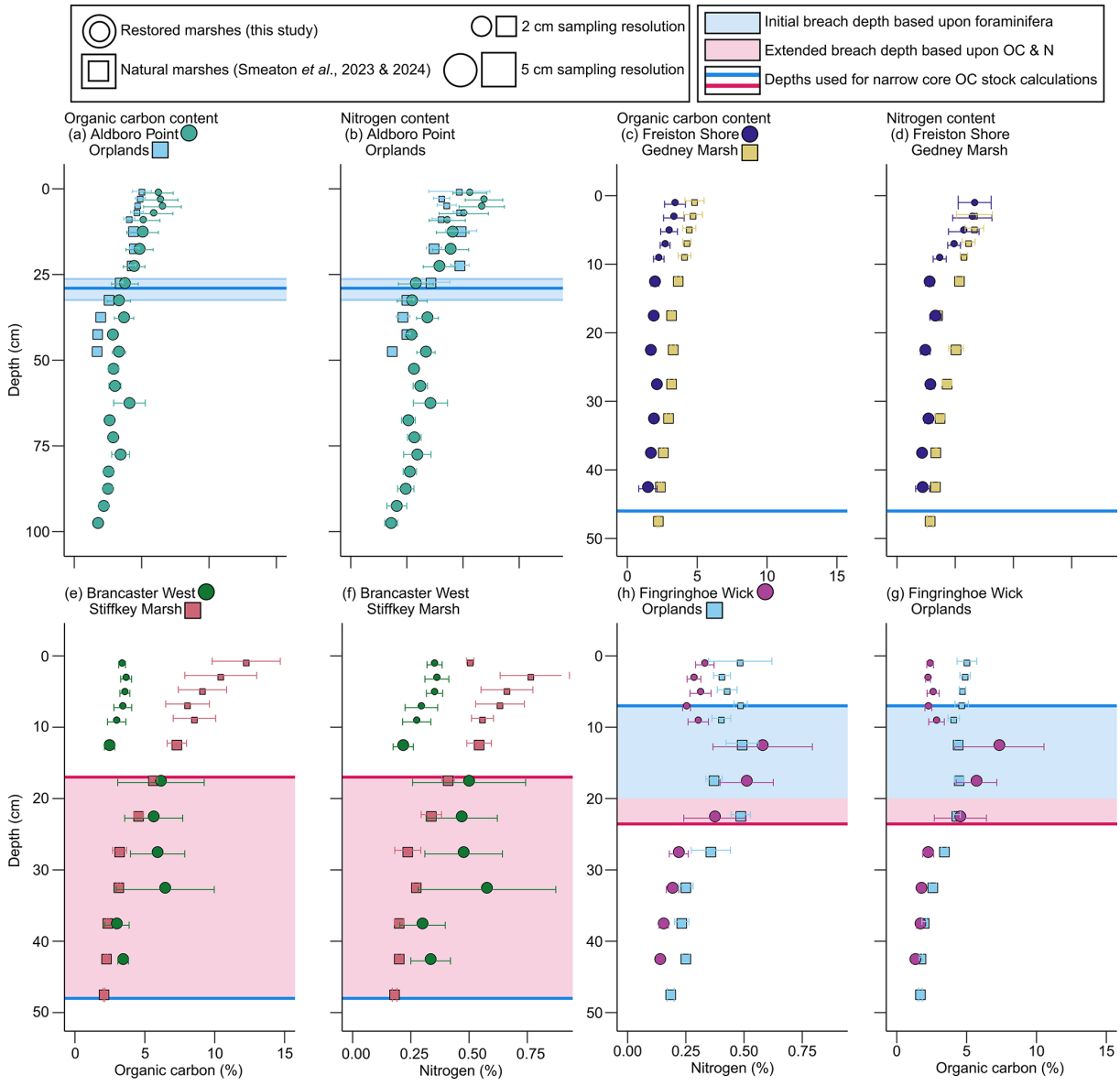


Figure 4. Organic carbon and nitrogen content of the narrow diameter cores and the corresponding natural marsh reference sites: **(a–b)** Aldboro Point and Orplands, **(c–d)** Freiston Shore and Gedney Marsh, **(e–f)** Brancaster West and Stiffkey Marsh and **(g–h)** Fingringhoe Wick and Orplands. Restored marsh datapoints are always represented by circles while natural marsh data, collected by Smeaton et al. (2023, 2024), are represented by squares. Smaller symbols represent 2 cm samples while larger ones represent 5 cm samples. The shaded blue areas denote the depth range at which the breaches may have occurred and is based upon radiometric dating for Aldboro Point and foraminiferal analysis for the other three sites. Additionally, the breach depth ranges of Fingringhoe Wick and Brancaster West were expanded based upon the biogeochemical variables presented in this and subsequent sections; these extensions are indicated by the red shaded areas. This was not deemed necessary for the other sites because the biogeochemical results did not suggest a different breach depth to that estimated from the foraminifera and radiometric dating results.

to the tops of the cores while in Stiffkey, the share was between 0.45 ± 0.04 and 0.56 ± 0.02. Recalcitrant OM content was higher in the Fingringhoe Wick samples compared with those from Orplands throughout the length of the cores, but this difference became starker from 9 cm upwards (Fig. 5d). The share of recalcitrant OM in this top section was between 0.67 ± 0.02 and 0.68 ± 0.01 in Fingringhoe Wick and between 0.54 ± 0.02 and 0.55 ± 0.01 in Orplands. Proportion of recalcitrant OM did differ significantly between marsh type ($p = 0.047$) while depth ($p =< 0.001$) and the interaction between depth and marsh type ($p =< 0.001$) had far stronger effects (Table S3). This lends support to the observation that recalcitrant OM content differed most strongly between samples from the top ~ 10 cm of the marshes (Fig. 5).

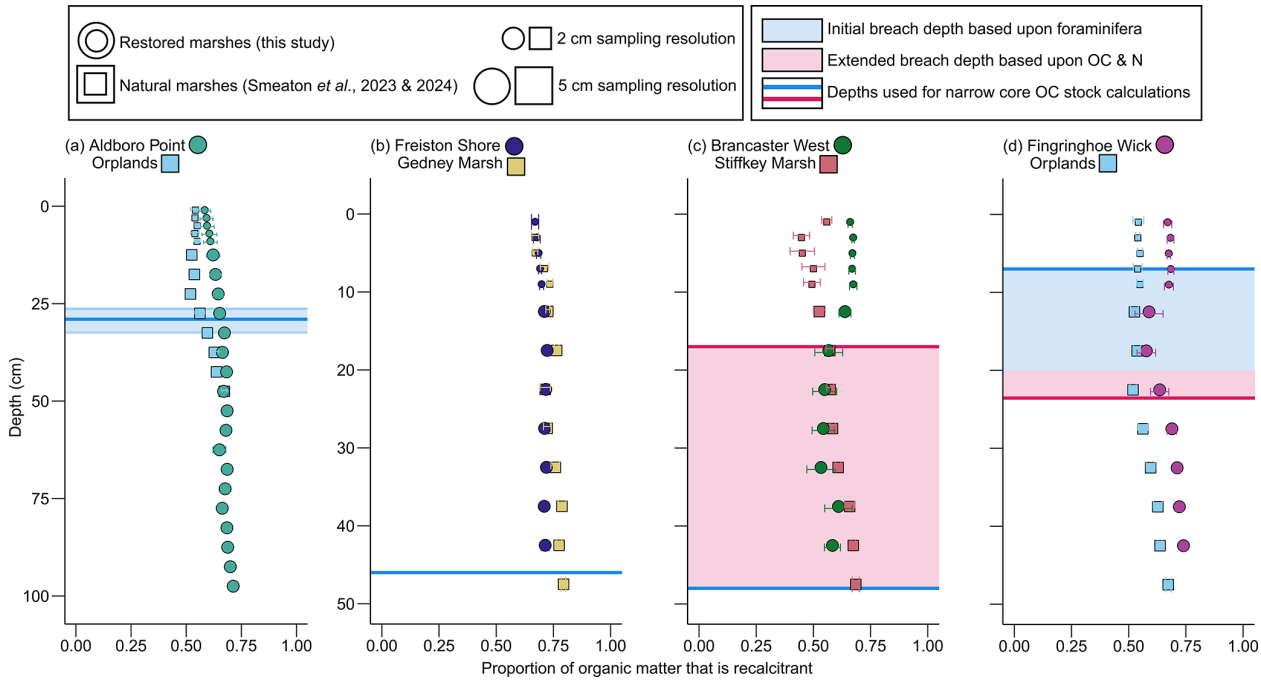


Figure 5. Proportion of total OM classified as recalcitrant by thermogravimetric analysis in the narrow diameter cores and the corresponding natural marsh reference sites: **(a)** Aldboro Point and Orplands, **(b)** Freiston Shore and Gedney Marsh, **(c)** Brancaster West and Stiffkey Marsh and **(d)** Fingringhoe Wick and Orplands. Restored marsh datapoints are always represented by circles while natural marsh data, collected by Smeaton et al. (2023, 2024), are represented by squares. Smaller symbols represent 2 cm samples while larger ones represent 5 cm samples. The shaded blue areas denote the depth range at which the breaches may have occurred and is based upon radiometric dating for Aldboro Point and foraminiferal analysis for the other three sites. Additionally, the breach depth ranges of Fingringhoe Wick and Brancaster West were expanded based upon the biogeochemical variables presented in Figs. 4, 6 and 7; these extensions are indicated by the red shaded areas.

4.5 Organic carbon to nitrogen ratios and δ^{13}C signatures

Figure 6 showed that the OC/N values in restored saltmarshes were consistently lower than those observed in natural sites. Indeed, across all samples displayed in Fig. 6, the mean OC/N for the restored samples was 9.95 ± 2.31 (1σ) and for the natural samples 14.30 ± 1.83 (1σ). Statistical analysis showed the difference between marsh type to be significant ($p = 0.01$; Table S3). While it is true that treating sediment samples with sulphurous acid can lead to losses of total N (Fernandes and Krull, 2008), if losses did occur and the N content of our samples were higher than recorded, this would only result in lower OC/N ratio values and thus further exacerbate the difference between natural and restored marshes.

The OC/N ratios in the narrow cores (Fig. 7a–d) varied with depth. In Aldboro Point, there was a peak of 13.98 ± 1.42 at 25–30 cm that coincided with the breach depth range. Above this, ratios decreased to 11.44 ± 0.87 at the surface (Fig. 7a). Orplands, the corresponding natural marsh reference, also had increasing values up to a depth of 15–20 cm, at which point a peak of 13.60 ± 0.29 was reached before decreasing to 12.95 ± 1.15 at the surface (Fig. 7a). The OC/N ratios in Freiston Shore and Gedney Marsh decreased from the lowermost sample to the surface, although variability was greater in the former (Fig. 7b). In Brancaster West, the lowermost sample had a value of 10.70 ± 1.58 and ratios remained around this level, except for occasional peaks during the breach depth range. The Stiffkey Marsh OC/N ratios increased until 25–30 cm depth; above this point, values remained relatively constant to the surface (Fig. 7c). Between 45 and 20 cm in Fingringhoe Wick, values increased from 9.48 ± 0.79 to 11.50 ± 0.45, with the peak occurring below the estimated breach depth range (Fig. 7d). Following this, values fell to 7.44 ± 0.48 at the surface.

The δ^{13}C values in Aldboro Point and Freiston Shore were largely within the same ranges reported for their respective natural marsh reference sites (Fig. 6a and b). The former having values intermediate between the values recorded for C_3 saltmarsh plants and marine OM while the latter had values clustered more closely with the marine OM sources alone. In Brancaster West and Fingringhoe Wick, a wide range of δ^{13}C values were observed compared with the close clustering of the natural marsh sites (Fig. 6c and d). Brancaster West δ^{13}C values ranged between -29.50 ‰ and -19.70 ‰, while at Fingringhoe Wick the range was between -28.90 ‰ and -20.80 ‰. To contrast, the range in Stiffkey Marsh

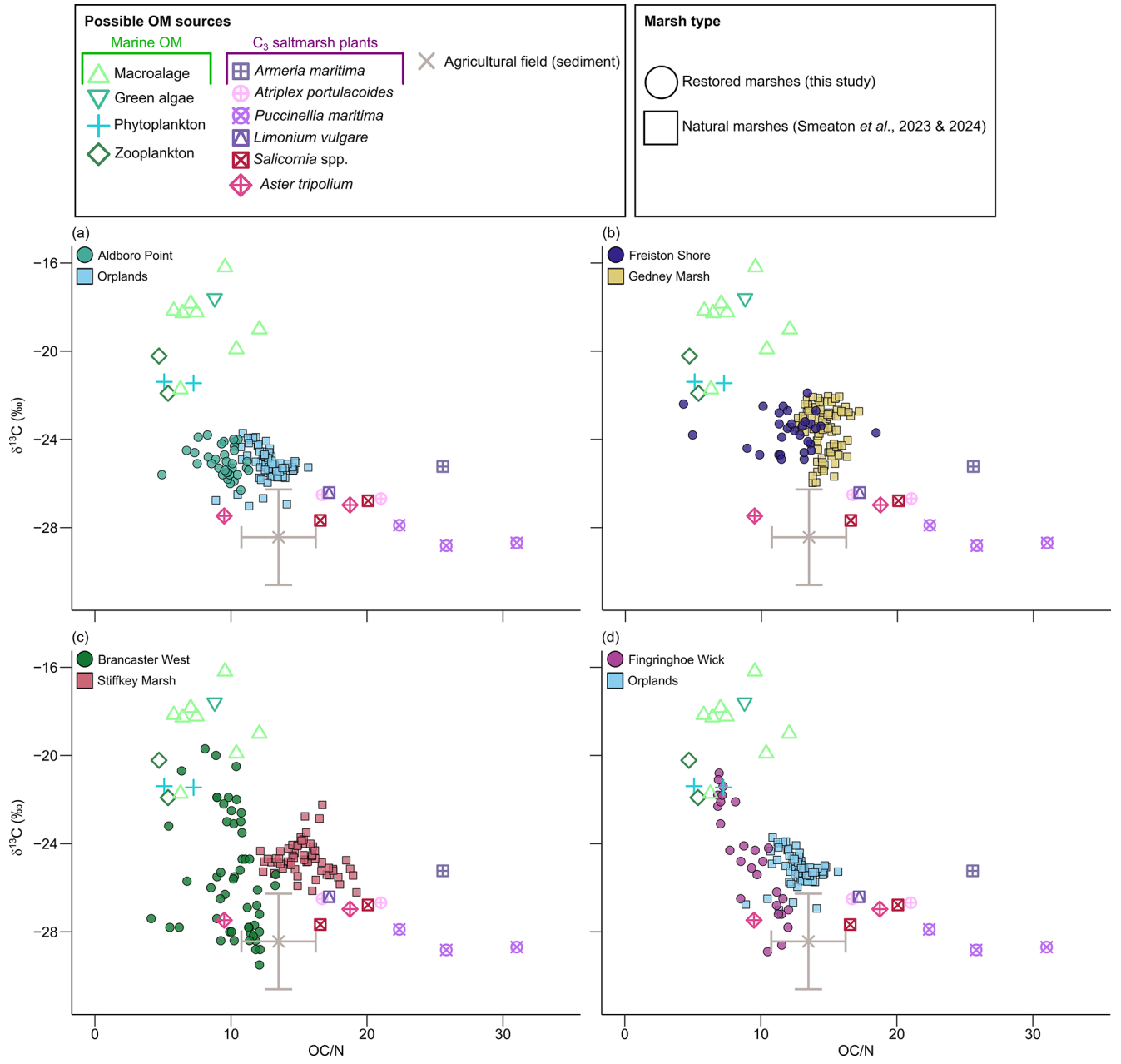


Figure 6. δ^{13}C and OC/N values of the post breach sections of the wide diameter cores taken from restored marshes as a part of this study and from natural marshes by Smeaton et al. (2024) from **(a)** Aldboro Point and Orplands, **(b)** Freiston Shore and Gedney Marsh, **(c)** Brancaster West and Stiffkey Marsh and **(d)** Fingringhoe Wick and Orplands. Restored marsh datapoints are always represented by circles while natural marsh data are represented by squares. Values of possible OM sources are adapted from Khan et al. (2015) and Smeaton et al. (2022).

was −26.21 ‰ to −22.24 ‰ and in Orplands −27.02 ‰ to −23.72 ‰. Values in the former two sites, therefore, were closer to the distinctive range of *S. anglica* (−14.97 ‰ to −11.94 ‰; Khan et al., 2015). Aldboro Point and Freiston Shore δ^{13}C values were consistent along the entire length of the cores while Brancaster West and Fingringhoe Wick values generally increased from the bottoms of the cores to the tops (Figs. 6; S5).

4.6 Estimating organic carbon stocks

By incorporating the different sources of evidence gathered during the study, it was possible to calculate several different OC stock values for each site (Table 1). Because foraminifera analyses were conducted for wide cores alone, the foraminifera-derived breach depth specific to each of these cores was used as the basis for the wide core stock calculations. Wide core stock estimates used the OC con-

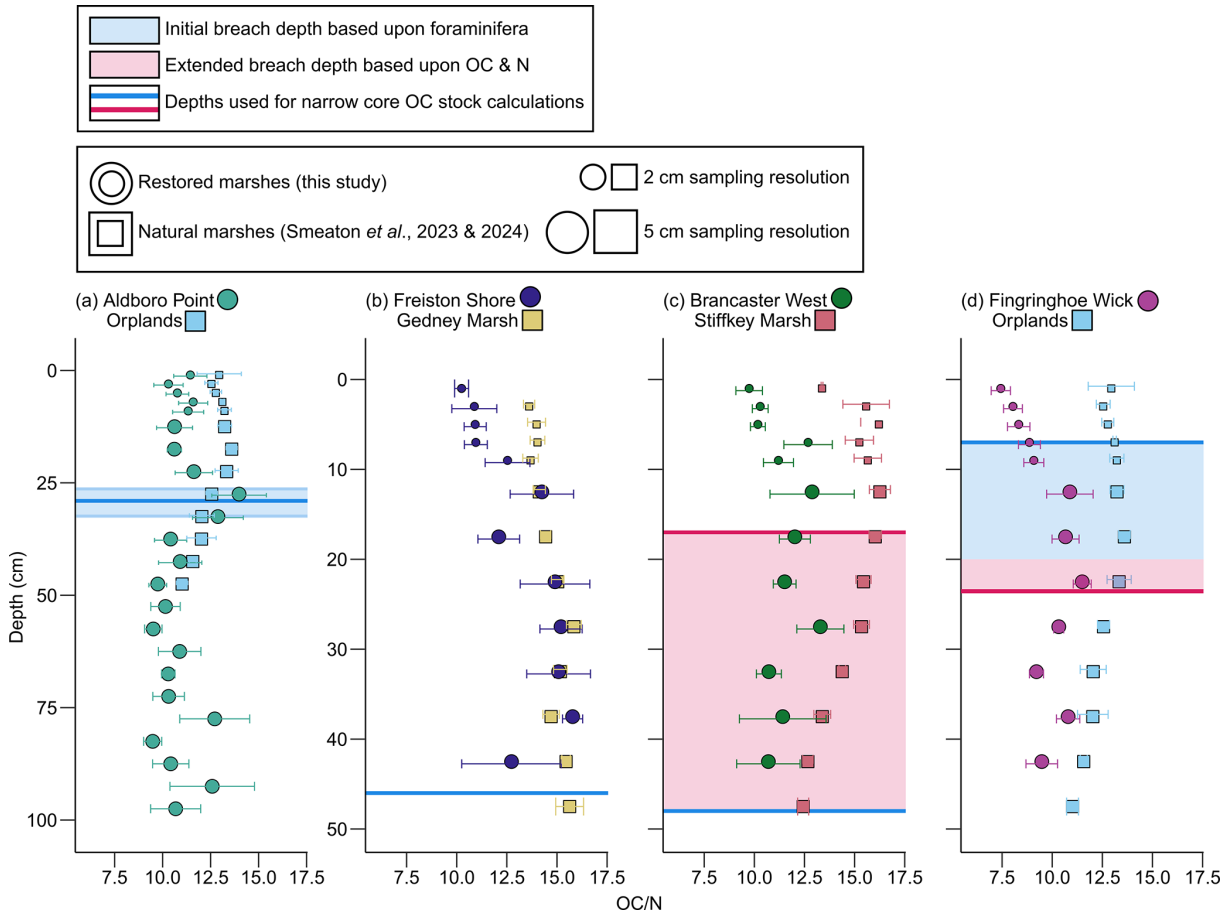


Figure 7. Ratio of OC to N in the narrow diameter cores taken as a part of this study and the corresponding natural marsh reference sites: **(a)** Aldboro Point and Orplands, **(b)** Freiston Shore and Gedney Marsh, **(c)** Brancaster West and Stiffkey Marsh and **(d)** Fingringhoe Wick and Orplands. Restored marsh datapoints are always represented by circles while natural marsh data, collected by Smeaton et al. (2023, 2024), are represented by squares. Smaller symbols represent 2 cm samples while larger ones represent 5 cm samples. The shaded blue areas denote the depth range at which the breaches may have occurred and is based upon radiometric dating for Aldboro Point and foraminiferal analysis for the other three sites. Additionally, the breach depth ranges of Fingringhoe Wick and Brancaster West were expanded based upon the biogeochemical variables presented here and in Figs. 4 and 6; these extensions are indicated by the red shaded areas.

tent values obtained for each centimetre of sediment in these cores (Fig. S5). With the narrow cores, the top and bottom of the extended breach depth ranges, based upon the OC and N values, were both used for Fingringhoe Wick and Brancaster West. In the case of Fingringhoe Wick, two stock estimates were calculated using the narrow cores: one using the segments from depths above the lowest, OC and N breach depth and another using only the segments above the highest possible breach depth, based upon the foraminifera results. Two OC stock values were also calculated for Brancaster West and in this case the uppermost breach depth was based upon the additional evidence gleaned from the biogeochemical variables examined. It was assumed that the breach depth was not reached for Freiston Shore so only one narrow core stock estimate, using all core segments gathered, was calculated. For Aldboro Point, only the breach depth based upon the mean ages from the age-depth model was used and so only one narrow core estimate was calculated. It was possible to calculate mean and standard deviation values for the narrow core estimates because six of these cores were taken in each location.

5 Discussion

A total of 32 cores were taken from four restored saltmarshes in the east of England, ranging in age from eight to 102 years. Comparisons were made with the extensive natural marsh dataset developed by Smeaton and colleagues (2023, 2024). The most consistent difference between our restored sites compared with their natural counterparts was lower OC/N ratios in the former (Fig. 6; Tables S3 and S4). Furthermore, the proportions of recalcitrant OM tended to be higher in the top $\sim$10 cm of restored site sediment than

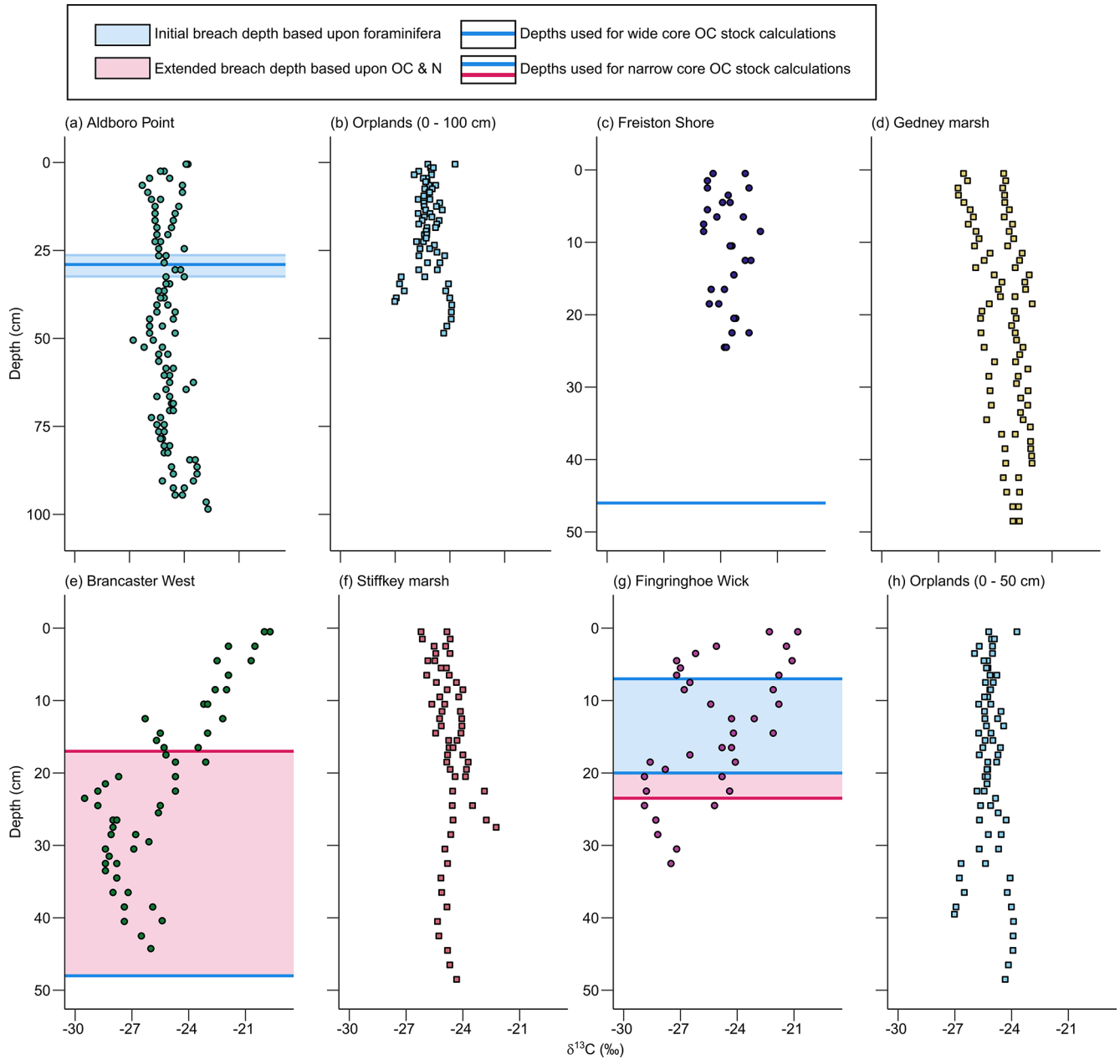


Figure 8. ^{13}C profiles of the wide cores taken from **(a)** Aldboro Point, **(b)** Orplands (shown over 0–100 cm depth), **(c)** Freiston Shore, **(d)** Gedney Marsh, **(e)** Brancaster West, **(f)** Stiffkey Marsh, **(g)** Fingringhoe Wick and **(h)** Orplands (shown over 0–50 cm depth). Restored marsh datapoints **(a, c, e, g)** are always represented by circles while natural marsh data **(b, d, f, h)**, collected by Smeaton et al. (2023, 2024), are represented by squares. The shaded blue areas denote the depth range at which the breaches may have occurred and is based upon radiometric dating for Aldboro Point and foraminiferal analysis for the other three sites. Additionally, the breach depth ranges of Fingringhoe Wick and Brancaster West were expanded based upon the biogeochemical variables presented in Figs. 4, 6 and 7; these extensions are indicated by the red shaded areas.

in the natural reference sites (Fig. 5; Table S3). These differences were interpreted as representing a greater input of marine, allochthonous and potentially partially decomposed OM to restored saltmarshes. Up to 100 years after restoration, OC/N values had not recovered, which implies that the origin of OM remained different. Accordingly, determination of whether restored saltmarsh OC stocks represent CO_2 removal additional to that produced without the restoration is a crucial step in the carbon crediting process. Additionally, the consistent differences identified between natural and restored sites can be used as indicators in restoration (Table S4).

Table 1. Organic carbon stocks calculated using the foraminiferal, biogeochemical and radiometric dating results gathered during the study. Autochthonous and allochthonous OM were not distinguished and so these estimates include OC from both sources. Maximum breach depth (in "Core(s) used for estimate" column) refers to the lowermost breach depth estimate while minimum refers to the shallowest breach depth estimate. It was impossible to obtain wide cores in Freiston Shore of a similar length to the narrow cores, and so the estimates for the former are necessarily lower. Wide core estimates are calculated solely from the foraminifera-based breach depth estimates specific to each individual core. Narrow core estimates for Fingringhoe Wick and Brancaster West were calculated from breach depth estimates that were extended based upon OC and N results. Extending the breach depth estimates of Freiston Shore and Aldboro Point based upon OC and N data was not deemed necessary and so these narrow core stocks were based upon the foraminifera and radiometric dating derived breach depths, respectively. Stock estimates without standard deviation are based upon individual wide cores.

Site	Age of site (years)	Core(s) used for estimate	Maximum length of core(s) used in calculation (cm)	OC stock ± SD ($kg\,m^{-2}$)
Fingringhoe Wick	8	Narrow cores from maximum breach depth	25	5.84 ± 2.09
		Narrow cores from minimum breach depth	8	0.90 ± 0.19
		Wide core FW23/1	7	1.95
		Wide core FW23/2	20	3.28
Brancaster West	21	Narrow cores from maximum breach depth	45	11.70 ± 2.55
		Narrow cores from minimum breach depth	15	2.80 ± 0.32
		Wide core BW23/1	44.5	14.01
		Wide core BW23/2	40.8	22.86
Freiston Shore	21	Narrow cores from maximum breach depth	45	7.52 ± 1.20
		Wide core FS23/1	26	3.37
		Wide core FS23/2	26	4.96
Aldboro Point	102	Narrow cores from mean breach depth	30	5.98 ± 1.28
		Wide core AP23/1	29	4.03
		Wide core AP23/2	29	5.26

5.1 Breach identification

If the foraminifera method tested in this study is to be applied elsewhere it is vital to consider and account for within site variability by analysing several cores taken from locations widely dispersed across the site. Furthermore, deep cores are often necessary to reach the breach horizon because, despite a time lag between breach and colonisation, small numbers of tests can be washed onto a marsh immediately after tidal reintroduction. Additionally, defining zones, such as high marsh, low marsh and tidal flat, based upon foraminiferal assemblage data from restored marshes is not necessarily an accurate means of tracking the development of a site over time because difference may not extend beyond the highly sensitive foraminifera. Furthermore, in this study, the radiometric dating tools were very useful for identifying breach depth and may be more suitable if the goal is calculating accurate OC stocks. However, to deal with variability within a site, a combination of methods, including the foraminifera analysis, is likely to be the best approach.

The expected result from the foraminifera analysis was exemplified in core FW23/2 (Fig. 3g and h), in which foraminifera were entirely absent in all samples from the bottom of the core to a depth of 20–21 cm, representing an agricultural field with no tidal inundation. From 20 up to 12 cm, samples contained low numbers of tests (< 21), and this was taken to represent the period during which the breach was created, and some foraminifera and/or propagules could have washed in by the tides (Weinmann et al., 2019), supporting the existence of a time lag between breach creation and colonisation (Masselink et al., 2017; Milker et al., 2022). From 12 cm to the surface of the core, more than 100 tests were found in every sample examined, suggesting that foraminifera had successfully colonised this part of the site from this depth upwards. All the other cores analysed were harder to interpret and required greater nuance. Therefore, our results indicated that foraminifera could contribute to the identification of the breach depth in restored saltmarshes if a few key limitations and methodological refinements are borne in mind by future studies.

First, and most simply, to identify the breach depth range successfully, deep cores are required. For example, foraminifera were found along the entire length of the cores taken from Freiston Shore and Brancaster West, and this was interpreted as an indication that the breach depth was not reached. In the case of the former site, using the mean sediment accretion rate of $1.06 \pm 0.20\,\mathrm{cm\,yr^{-1}}$ calculated by Spencer et al. (2012) between 2002 and 2006 for the interior of the restoration area suggested that approximately 20 cm of sediment could have accreted in the 21 years since the breach in Freiston Shore. This suggests that the breach depth in the high marsh core FS23/1 was closely missed, given that this core was 20 cm long. The higher rates of accretion recorded closer to the breach (e.g., a rate of $2.54\,\mathrm{cm\,yr^{-1}}$ in the 4 years following restoration) would explain the consistent presence of foraminifera in FS23/2, a 46 cm core, taken 150 m from the closest breach, while FS23/1 was 376 m away from its nearest breach (Fig. 1d; Table S1). Conversely, the site had not been claimed from the sea for long before the creation of the breach, suggesting the possibility that these assemblages were representative of the pre-1980s saltmarsh. All the samples analysed from Freiston Shore contained high numbers of foraminifera, but the Brancaster West cores presented a more complex case. These did contain samples entirely absent of foraminifera, but they were interspersed with other samples that contained low numbers of tests. It is possible that the breach depth was just missed and that analysing samples from a greater depth would have meant reaching the agricultural layer from which foraminifera are normally entirely absent – similarly to the pattern seen in core FW23/2 from Fingringhoe Wick. Therefore, the data from Brancaster West and Freiston Shore demonstrated the importance of taking deep cores (> 50 cm) – even if a relatively short time (~ 20 years) has elapsed since the breach – to ensure that the breach depth can be confidently identified. However, the challenge of taking deep cores from some sites, as was the case in the high marsh zone in Freiston Shore (i.e., where we only achieved a 20 cm coring depth), could present a barrier.

A second factor that requires careful consideration is the high background variability across a site. In marked contrast to core FW23/2, foraminifera were absent from most of FW23/1, the other Fingringhoe Wick core. This implied that sediment accretion rates differed substantially between the two locations. Using the bottom of the breach depth range, the sediment accretion rate over the 8 years since the breach in the vicinity of FW23/1 was $0.88\,\mathrm{cm\,yr^{-1}}$ while in that of FW23/2 it was $2.50\,\mathrm{cm\,yr^{-1}}$. This result contradicts the sediment accretion rates recorded by another study in the first 15 months following the breach: these were higher in the formerly arable section of the marsh (where FW23/1 was taken) compared with the former pasture (where FW23/2 was taken; Cai et al., 2022). In the years immediately following restoration, Pethick (2002) stated that accretion rates could be zero due to a lack of vegetation to hold the sediment in place, especially in the winter months and/or during storms. A possible explanation for the slower rate of accretion in FW23/1, therefore, is the removal of any sediment settling there by the tide due to the closer proximity of this coring location to the breach (i.e., Fig. 1d; Table S1). The breach depth range applied to the Fingringhoe Wick narrow cores was necessarily wide because of a need to reflect the results from both these cores. Variability in moisture content changes in the two cores tended to support this wide range (Fig. S6). Another example of within site variability comes from Brancaster West. As discussed, examining the foraminifera data in isolation suggested that the breach depth was below 50 cm depth. However, interpreting the OC and N peaks as representative of the pre-breach vegetation and/or root mat layer (see Sect. 5.2.1) meant adjusting the upper limit of the breach depth range to 17 cm depth. Given that the OC and N was examined primarily by looking at the mean values across all the narrow cores at different depths and that only two wide cores were used for foraminiferal analysis, it is possible that giving greater attention to individual locations within a marsh would yield more closely constrained breach depth results.

Adjusting the foraminifera-determined breach depth ranges of Fingringhoe Wick and Brancaster West based upon the OC and N data, points to another important conclusion drawn by this study – the desirability of employing multiple different methods to characterise sediment cores, where possible. The results from Aldboro Point also lend support to this point. The many and relatively short-term changes in use undergone by this site may have meant that there was insufficient time for the area to undergo the processes that lead to agricultural land directly behind seawalls being situated at elevations far below mean high tide (Pethick, 2002). As a result, the site could have quickly recovered after the final breach in 1921, and this explains the lack of empty samples around the time of the breach. In this case, however, it was possible to supplement the foraminifera results with radiometric dating to identify the breach depth. Doing so allowed the breach depth to be identified with confidence. Furthermore, it showed that the fall in test densities in AP23/1 matched the breach depth estimated from the age-depth model, but this was not true of AP23/2, again pointing to within site variability.

Another conclusion drawn from this study was that defining zones, such as high marsh, low marsh and tidal flat, based upon foraminiferal assemblage data from restored marsh cores is not necessarily an accurate means of tracking the development of a site over time because difference may not extend beyond the highly sensitive foraminifera. Looking at the foraminiferal species assemblages alone strongly suggested that FS23/1 was representative of a high marsh environment while FS23/2 represented a tidal flat, owing to the dominance of agglutinated tests in the former and calcareous ones in the latter (Fig. 3e and f). However, the plant communities in both coring locations were overwhelmingly dominated by *A. portulacoides* (90 % cover; Table S2), meaning that defining the ecosystem type based upon foraminiferal species would bear

no semblance to the reality. It is possible that the lack of topographical variation in restored marshes means the zonation of plants and foraminifera were uncoupled and/or that *A. portulacoides*, the plant species often seen to dominate in restored sites, was tolerant of a wider range of inundation frequencies than the foraminiferal community.

Other factors that could limit the usefulness of the foraminifera method are bioturbation and sediment mixing. These could mean that the foraminiferal assemblages found within a centimetre of sediment represent a mixture of populations formerly present upon the marsh surface during very different periods of its development, as opposed to representing just one period. Furthermore, bioturbation can enable the passage of electron acceptors (e.g. sulphate) into deeper sediment layers and thus allow for organic matter mineralisation, acid production and calcium carbonate dissolution (i.e., the destruction of foraminiferal tests; Berkeley et al., 2007). Another possible limitation is that foraminifera can live down to 50 cm or deeper in the sediment/soil (e.g., Patterson et al., 2004; Tobin et al., 2005; Duchemin et al., 2005; Milker et al., 2015). This could influence the fossil assemblages if recent infaunal species lived deeper in the sediment. Most species are found at shallower depths and hence the impact of infaunal species should not be large, but this is nevertheless an important factor to acknowledge.

The OC stocks calculated using the restored saltmarsh sections of the cores from Freiston Shore, Brancaster West and Fingringhoe Wick varied widely depending on which cores (wide or narrow) and breach depth estimates were used (Table 1). This points to the limited usefulness of using foraminifera analysis alone to identify a breach depth that is then used as the basis for calculating a stock. A large reason for this variability, however, is elevation and accretion rate differences within a site and while radiometric dating might represent a more accurate means of identifying breach depth, its application could not overcome the issue of within-site variation without dating several cores from different location. The costliness of this analysis means this approach is unlikely to be feasible and, therefore, a combination of different approaches that includes the foraminifera analysis applied in this study, could prove most effective.

5.2 Difference in OM composition between restored and natural saltmarshes

The clearest and most consistent difference between restored and natural marshes was the lower OC/N ratio values in the former (Table S3; Fig. 6), suggesting a difference in the sources of OM. Other studies have also found that restored saltmarshes had lower OC/N ratios than their natural counterparts and the differences were put down to a predominately allochthonous/marine input to the restored sites (Drexler et al., 2020; Mueller et al., 2020).

5.2.1 Age

There were, however, exceptions to the tendency for lower OC/N ratios in restored sites. Clear peaks in OC, N and OC/N ratios were seen above and during the foraminifera-based breach depth ranges of two younger sites: Brancaster West and Fingringhoe Wick. In Brancaster West it is likely that these peaks represent the terrestrial vegetation present prior to the breach. This vegetation was quickly killed by the reintroduction of the tide but was left in place to decompose and become buried in the accumulating sediment (Davy et al., 2011). The large breach depth range applied to the Brancaster West cores meant that stocks were calculated that both excluded and included these non-halophyte OC peaks (Table 1). It can be argued that, had the area not been converted to saltmarsh, this OC would never have been buried in anoxic sediments and thus should be included in the stock calculation. The TGA analysis did not indicate that this terrestrial vegetation layer differed substantially, in terms of thermal stability, from natural marsh OM at a similar depth, meaning that its longer-term fate could be similar. The clearest conclusion to be drawn is that whether this layer is included in the calculation has a large impact on the magnitude of the stock, with a difference of almost 9 kg OC m^{-2} between the two narrow core estimates (Table 1).

Peaks in OC content at breach depth were also identified in the sites investigated by Adams et al. (2012) and were assumed to represent the root mat of the agricultural fields present prior to restoration. The peaks we identified in the Fingringhoe Wick cores could represent a similar layer or, like in Brancaster West, these peaks could be a layer of pre-restoration vegetation. Extending the breach depth range of Fingringhoe Wick so that the lower limit encompassed the OC and N peaks allowed us to calculate a stock for this site that represent a situation in which the OM in these layers derived from the non-halophyte plants present prior to restoration. Conversely, using the upper breach depth to calculate the stock represents two different possibilities. First, a situation in which the OM was identified as the root matt layer and excluded. Alternatively, a circumstance in which it was accepted that the OM represented the pre-restoration surface vegetation, but it was nevertheless not deemed acceptable to include this OM in the saltmarsh OC stock.

An alternative explanation for the OC and N peaks could be the large influx of OM shown to enter a marsh in the first ~ 5 years following the creation of a breach, which necessarily comes from allochthonous sources because of the lack of saltmarsh plants in this early phase (Wollenberg et al., 2018; Poppe and Rybczyk, 2021; Mossman et al., 2022). However, the higher OC/N ratios of the peaks compared with the samples in the top 10 cm of the selected cores suggest this early OM was of a less strongly marine source than the material entering the marsh later. In Aldboro Point, there were no peaks in OC and N during or near the breach but there was a clear peak in OC/N ratio (Fig. 7a), suggesting that the

OM had decomposed in the long time since the breach but that its origin was similar. The lack of OC peak is reflected in the relatively low stock estimates calculated for Aldboro Point, compared with those of the younger sites (Table 1). The higher OC/N ratios of restored marshes surface sediments could support the loss of the root layer by providing more nitrate to drive decomposition (Bulseco et al., 2019).

5.2.2 Organic matter composition

The proportion of OM classed as recalcitrant was significantly higher in the top 10 cm of sediment from Brancaster West and Fingringhoe Wick compared with their natural equivalents (Table S3; Fig. 5). Often, labile OM content is higher in the surface sediments but decreases at lower depths due to the preferential decomposition of this material by microorganisms (Gore et al., 2024). However, in these sites, the OM present in the surface sediments was thermally insensitive and so potentially more stable and complex. One possible explanation for this could be that a higher proportion of allochthonous OM entered the restored marshes. The labile component of this material could have been lost during decomposition in an external location before being washed into the restored sites. Alternatively, the OM entering the restored sites could simply have been inherently more recalcitrant. Another plausible explanation is that both restored and natural marshes received broadly similar allochthonous inputs, particularly given their geographic proximity, with observed differences instead driven by site-specific factors such as elevation, hydrology, or sediment dynamics that influence OC retention. Elevation especially is a plausible driver because restored sites are often situated at lower elevations than their natural counterparts. Indeed, the plant communities present in Brancaster West and Fingringhoe Wick point to low marsh settings that receives regular tidal inundation (Table S2).

5.2.3 Vegetation

In Fingringhoe Wick and Brancaster West, *Spartina anglica* (70 %–90 %) was the only plant species present in the wide core sampling locations (Table S2) and the ^{13}C enriched signal of this C_4 plant explains the steadily increasing $\delta^{13}C$ values towards the surface of the cores (Figs. 6; S5). Despite this, values were lower than the signal expected from this plant alone, which suggests a contribution from allochthonous material combined with the autochthonous *S. anglica* to produce a mixed signal (Middelburg et al., 1997). Furthermore, most of the OC/N ratio values recorded for Fingringhoe Wick were below 10 (Figs. 6 and 7), the threshold reported for recently deposited marine OM (Hulisz et al., 2013). This could indicate that allochthonous OM made a particularly large contribution to the stock of the youngest site, a possibility compatible with the fact that the area still largely resembles a mudflat (Fig. S1d).

Terrestrial plants potentially present before the breach have relatively low $\delta^{13}C$ values that are reported to range between −25.0 ‰ and −27.0 ‰ (Goñi and Hedges, 1995) and sediment from agricultural fields has a mean value of −28.4 ‰ ± −2.17 ‰ (Smeaton et al., 2022). A similar range was observed within and above the breach depths of Brancaster West (−29.5 ‰ to −24.7 ‰ between the bottom and 20 cm depth; Figs. 6c; S5) and Fingringhoe Wick (−28.9 ‰ to −27.2 ‰ between 33 and 18 cm in FW23/2; Figs. 6d; S5). This, in combination with the higher OC/N values, corroborates that the peaks represented the vegetation and/or root mat of the agricultural fields and not allochthonous OM entering the sites after restoration. In the case of Fingringhoe Wick, if the peak is assumed to represent the agricultural root mat, it is expected to occur prior to the initial appearance of foraminifera in the cores. The fact that the peaks occur during the foraminifera identified breach depth range points to variability in sediment accretion rates and marsh development within the site. If the OC and N peaks in the Brancaster West cores are indeed representative of the pre-breach vegetation, their appearance at depths above the samples containing low numbers of foraminifera are to be expected, because sediment entering the site would initially settle around this vegetation and only gradually come to cover it completely.

Enrichment in ^{13}C with increasing depth was not seen in Aldboro Point and Freiston Shore (Figs. 6; S5). Values from the bottom of the breach depth ranges to the tops of the cores were relatively stable, ranging between −26.3 ‰ and −23.8 ‰ in the former and −24.9 ‰ and −21.9 ‰ in the latter. This implies that the expected changes to the OM components over time due to decomposition (Ehleringer et al., 2000) had not occurred. This could mean the OM was relatively stable and had not broken down significantly. Alternatively, microbial processes could be occurring at certain depths that produce OC with a $\delta^{13}C$ signature that maintained the overall sediment $\delta^{13}C$ value despite changes to the OM from the surface (Goñi and Thomas, 2000). Most of the samples from Aldboro Point and Freiston Shore fell in-between the values reported for C_3 saltmarsh plant species and various marine OM sources, and this again points to a mixed signal. Therefore, Freiston Shore, a 21-year-old site, and Aldboro Point, a 102-year-old site, must also have received an input of allochthonous OM, despite plant communities that suggest a higher elevation setting compared with Brancaster West and Fingringhoe Wick (Table S2). The coring locations of the natural marshes were dominated by *A. portulacoides* and *P. maritima*, with *S. anglica* representing a minor contribution (< 15 % cover) to the populations of one coring location within Gedney Marsh and another within Stiffkey Marsh (Ladd et al., 2022). The presence of these C_3 plants explained the close similarity between the $\delta^{13}C$ profiles of the reference sites and those of Aldboro Point and Freiston Shore (Fig. 6a and b).

5.2.4 Organic matter decomposition and stabilisation

OC, N and OC/N values were more clearly different between restored and natural sites in the top ~ 10 cm of the investigated cores. This is opposite to previously reported results (Havens et al., 1995) and counterintuitive as newly accreting layers of marsh sediment often show signs of becoming increasingly "natural" because of vegetation modifying the surface sediment (Craft et al., 1988, 2002; Hulisz et al., 2013). Lower OC/N ratios in saltmarshes can be put down to additional N being delivered by the tide and produced in-situ and/or a higher amount of algal biomass being incorporated into the OM (Adams et al., 2012). Except for Gedney Marsh, all natural references marshes had OC/N ratios that decreased with depth (Fig. 6), indicating OM decomposition (Gebrehiwet et al., 2008) and/or the incorporation of N from fungi and bacteria into the OM (Goñi and Thomas, 2000). The lower values of the surface sediments in the restored saltmarshes suggest that part of this signal was produced by OM entering the marshes that had already undergone this process of combination with fungal, bacterial or algal biomass. Another element that points to differences in the composition of the OM in restored site was the proportion of OC to OM (Fig. S7). Freiston Shore samples had lower values than those of the natural reference site throughout the cores while the other three sites had lower values primarily in the upper ~ 10 cm of sediment. Organic matter that is less OC rich could also be an indicator that the material in the restored sites had already undergone the initial stages of decomposition while the material in the natural sites was newer.

6 Conclusions

The vegetation and the root mat layers indicative of the agricultural field present prior to restoration were identified in two of our four sites from the OC and N content, the OC/N ratio and the δ^{13}C signature. Based upon the breach depth determined with the foraminifera method, the OC peaks produced by the terrestrial vegetation and root mats were included in some stock calculations and led to far higher values than when they were excluded. Where deemed appropriate, caution should be taken to identify and discount this OC when stocks are being calculated for carbon crediting schemes. Conversely, pre-breach vegetation could represent a legitimate contribution to the OC stock because it would not have become buried in an anoxic sediment layer without the creation of the breach. Likewise, the higher proportion of marine OM entering restored sites has important implications for carbon crediting schemes. If allochthonous OC is to be excluded from stock calculations, this finding suggests that the climate change mitigation benefit derived from saltmarsh restoration will be smaller than from conserving and protecting natural, existing sites. Future work to determine the precise mechanisms by which restored sites, particularly older or well-established ones like Aldboro Point and Freiston Shore, continue to accumulate larger amounts of allochthonous OM than their natural counterparts, could aid with the development of management strategies to avoid this outcome – if it is deemed desirable and useful to do so.

As a result of combining multiple sources of evidence collected from a range of restored saltmarshes of different ages, this study highlights the large variability that exists within and between restored sites. By combining the foraminifera, biogeochemical and radiometric dating results, we calculated several OC stock estimates for each site that reflect a range of different possible interpretations. The foraminifera derived breach depths used to calculate individual wide-core based stocks represent a situation in which only a limited amount of evidence and resources are available. The narrow core estimates, on the other hand, were usually based upon multiple sources of evidence and represent a wide coverage of overall marsh area. To increase confidence in these stock estimates, different steps would need to be undertaken for each individual site. Across all of them, determining the breach depth – be that with foraminifera and biogeochemical analyses or with radiometric dating – in additional cores from different locations would be beneficial. In Freiston Shore and Brancaster West, deeper cores would need to be taken. This is particularly true of the former, because the current stock estimate certainly represents an underestimate. Finally, for Brancaster West and Fingringhoe Wick, decisions would need to be made about the identify of the OM peaks and, based upon this, about whether they can be legitimately included in the stock calculation.

Data availability. The datasets used in this study are publicly available in the online repository figshare: https://doi.org/10.6084/m9.figshare.31812925 (Gore et al., 2026).

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