

Evaluating the long-term fate of carbon in a restored intertidal habitat

Corresponding Author: Ms Eleanore Burrell

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

This manuscript details soil and associated organic carbon deposition following managed realignment of a coastal impoundment 19 years post management action (e.g. reconnecting the wetland to the ocean). Through extensive sediment sampling (thousands of 5 cm sediment increments covering accretion throughout the 80 ha site) and change in elevation (based on lidar), a total volume of soil and associated carbon was determined. The authors claim that using a constant rate of accretion would not result in accurate C accounting when considered as a natural climate solution due to heterogeneity across the site.

Sediment accretion that is highly dependent on elevation within the tidal frame is well known and this paper would benefit from better integrating that literature in the Introduction and Discussion. Evaluating sediment accretion through lidar is somewhat novel in a coastal wetland, but largely because rates of accumulation at this site were large because it is a disturbance ecosystem. The accuracy of the lidar flights and how they changed in time is an omission in this paper, as without it no conclusions about when deposition happened relative to the management action can be made. The authors reference lidar data throughout the 19 years, but do not use any but the two extreme time points.

Taking thousands of sediment samples to determine how C density is changing across the site is a huge undertaking. The authors do not demonstrate that this approach was a significant improvement over using Tier 1 (e.g. constant C density) values. Numerous studies have demonstrated that C density in coastal wetlands varies little due to sediment packing between organic and lithogenic fractions (see <https://doi.org/10.1002/2015EF000334>, [10.1088/1748-9326/aae157](https://doi.org/10.1088/1748-9326/aae157), and <https://doi.org/10.1029/2024JG008254>) and thus rate of accretion is the biggest driver of C stocks, as this manuscript demonstrates. The authors do not assess what the Tier 1 stock value would be. Also, monitoring costs post restoration are a significant barrier to blue carbon implementation on a market-basis, so would be good to include in this manuscript whether such intense field efforts are needed. An important finding would be that remote sensing approaches, such as lidar, are sufficient for soil organic C accounting in these types of restorations.

Soil C source is important, as in the NCS literature there is still debate over whether the ecosystem should credit carbon that is buried or removed from atmosphere (e.g. the autochthonous versus allochthonous issue, see <https://doi.org/10.1111/gcb.70022>). This needs to be discussed in this manuscript.

Please see the attached pdf file for the full comments, which were made in line.

Reviewer #2

(Remarks to the Author)

The manuscript presents the first high-resolution, full-depth assessment of organic carbon (OC) accumulation across a restored intertidal habitat in the UK, Paull Holme Strays, located on the north bank of the Humber Estuary. The site, breached in 2003 as part of a managed realignment scheme designed for both coastal flood protection and habitat restoration, provides a valuable long-term case study of post-restoration sediment and carbon dynamics.

Drawing on an extensive dataset comprising 234 sediment cores and 3,987 sediment samples collected across vegetated saltmarsh and intertidal mudflat habitats, the authors aim to: (1) quantify site-level OC stocks and habitat-specific accumulation rates since site creation; (2) characterise vertical OC profiles by partitioning labile and recalcitrant fractions in

order to assess the extent and rate of labile OC loss with depth; (3) define an empirically derived surface layer to enable consistent spatial comparisons across heterogeneous elevations; and (4) evaluate how environmental variables (e.g., elevation) and sedimentological characteristics (e.g., grain size) correlate with spatial variability in OC storage.

The study integrates repeated Digital Terrain Models derived from airborne LiDAR (from 2003 to 2022) to estimate net sediment accretion and erosion, which inform core depth selection and carbon stock calculations. Sampling was stratified across three elevation bands, with additional reference cores collected from adjacent natural salt marshes. Sediment cores were sectioned at 5 cm intervals and analysed for dry bulk density, grain size, total, inorganic and organic carbon (via elemental analysis and loss-on-ignition procedures), and thermogravimetric partitioning of labile and recalcitrant OC fractions. Sediment properties were subsequently modelled as a function of elevation zone and depth within cores. Overall, the study is ambitious and methodologically robust. The sampling intensity is exceptional, and the integration of long-term topographic data with detailed geochemical analyses represents a substantial empirical contribution to the understanding of carbon accumulation in managed realignment systems. However, while the dataset is impressive and the analytical framework appears sound, the analysis and discussion of the results could be further strengthened to fully exploit the richness of the data and maximise the broader relevance of the findings.

General comments

Study site

While the site description is generally clear, the manuscript would benefit from additional contextual information on the local tidal regime. In particular, providing details on tidal range and general hydrodynamic setting within the Humber Estuary would help readers better interpret the elevation-stratified sampling design. Because much of the manuscript's argument hinges on the interaction between elevation, inundation frequency, sediment supply, and OC preservation, a clearer description of the tidal framework would strengthen the conceptual grounding of the study and make the elevation bands more ecologically meaningful to readers who are less familiar with the site.

Methods

The methodological framework is extensive and appears rigorous; however, in some sections the explanation could be made clearer, particularly for a multidisciplinary audience.

Specifically, the procedures used to calculate OC accumulation rates and carbon sequestration are not fully transparent in the current text.

Although the statistical approach appears appropriate and sophisticated, the data analysis section may be challenging for readers without a strong statistical background. In particular, the paragraph describing the use of Generalised Additive Models could benefit from a brief introductory sentence explaining, in general terms, what the method is designed to achieve (e.g. modelling non-linear relationships and depth-dependent patterns while accounting for spatial structure). This does not require substantial expansion, but a concise framing sentence would make the modelling strategy more accessible and facilitate interpretation of the results section.

Results and discussion

The manuscript presents a rich and carefully generated dataset and offers several interesting interpretations regarding the controls on OC accumulation and preservation across elevation gradients. However, some aspects of the discussion could be further developed to strengthen the mechanistic interpretation and broaden the relevance of the findings.

- While the discussion appropriately highlights spatial variability in sedimentation and links it to hydrodynamic forcing and proximity to the breach, the hydrodynamic framework remains somewhat implicit. A more explicit characterisation of internal site dynamics would improve interpretation. For example: Where within the managed realignment area is sediment transport and tidal energy expected to be highest? Is the system approaching a ecogeomorphological equilibrium, and if so, what trajectory is anticipated? A clearer conceptual model linking elevation, hydrodynamics, sediment supply, and vegetation development would help contextualise the spatial patterns described.

- The manuscript recognises the importance of vegetation in shaping OC dynamics, but its role could be explored more explicitly. It remains unclear whether vegetation composition is homogeneous within elevation bands or whether species turnover may contribute to differences in OC inputs and preservation. Are there differences in dominant plant communities across elevation bands? Do rooting depths vary among vegetation types? If so, could variation in the depth distribution of live roots influence the observed vertical patterns of labile OC? In addition, were potential pre-breaching differences in soil properties considered? Such legacy effects could partly explain present-day OC patterns. If available, LiDAR data or historical aerial imagery could provide useful information on vegetation structure, development, and temporal evolution across the study area. The sharp decline in labile OC below ~40 cm is interpreted primarily in terms of remineralisation. However, it would be valuable to consider whether this depth also corresponds to the typical rooting zone of the dominant vegetation. Distinguishing between loss of labile OC due to post-depositional remineralisation and reduced fresh root inputs with depth would strengthen the interpretation of the vertical profiles.

- The inclusion of a natural saltmarsh reference site is commendable. However, given that both saltmarsh and mudflat habitats are analysed within the managed realignment area, it would be useful to clarify whether natural mudflat reference sites were considered. Such comparisons could help disentangle restoration-stage effects from habitat-specific carbon dynamics.

- The discussion rightly notes the importance of allochthonous sediment inputs in rapidly accreting zones. However, the potential influence of OC source characteristics on fraction stability deserves more explicit consideration. For example, could imported (allochthonous) OC already be partially stabilised and therefore relatively more recalcitrant? To what extent might differences in OC source explain variation in labile vs. recalcitrant fractions across elevations?

- Relatedly, it would be appropriate to acknowledge that allochthonous OC inputs may not necessarily represent net carbon sequestration at the system scale, but rather redistribution of carbon within the broader estuarine environment. Even a brief

discussion of this accounting issue would improve conceptual clarity, particularly in the context of blue carbon assessment and its implication for carbon crediting.

- The manuscript states that the combination of high-resolution sampling, elevation stratification, and fraction-specific depth analysis “disentangles short-term turnover from longer-term carbon preservation” and clarifies a pattern “previously unexplained” in managed realignment systems. While the dataset is indeed exceptional in resolution and scope, the degree of conceptual novelty could be more carefully framed.
- The empirical identification of a “dynamic surface layer” is potentially useful, however, the concept of an “Evidence-Based Surface Depth for OC Analysis” would benefit from clearer definition and justification. For example, is this depth expected to be transferable to other restored sites? Does it depend on sedimentation rate, vegetation type, or site age? A more explicit conceptual explanation of how this threshold should be interpreted and applied would enhance its practical and theoretical value.

Specific comments

- Figure 1: Please clarify whether the vertical datum is correctly reported as Ordnance Datum Newlyn (ODN). The abbreviation appears inconsistent (ODN vs ODM).
- Line 107: There appears to be a typographical error (semicolon after “for”).
- Line 140: A full stop appears to be missing at the end of the sentence.
- Line 182: “using the graphical method of Folk and Ward [37] graphical method...”
There is a repetition (“graphical method”). Additionally, the authors state that grain-size analysis was conducted using a Malvern Mastersizer 2000, but statistical parameters were calculated using Gradistat. As the Mastersizer software provides grain-size statistics directly, could the authors clarify why Gradistat was used?
- Lines 222–225: The methodological description would benefit from an additional reference to support or contextualise the robustness of the approach.
- Lines 323–324: “Models confirmed elevation (as of 2022) and depth (change in elevation since restoration) were the primary controls on OC content”. The definition of “depth” is unclear here. In this sentence, depth appears to refer to change in elevation since restoration (i.e., accumulated sediment thickness), whereas elsewhere in the manuscript it seems to refer to depth below the present sediment surface. Please clarify terminology and ensure consistent usage throughout the manuscript to avoid confusion.
- Figure 3: For improved comparability, it may be helpful to use the same OC% scale for both restored habitats and the reference station. A consistent axis range would facilitate direct visual comparison.
- Line 390 and associated paragraph (dynamic surface layer ~40 cm): The section describing the identification of a ~40 cm “dynamic surface layer” is presented as central to the manuscript, yet the concept of an “Evidence-Based Surface Depth for OC Analysis” remains somewhat unclear. Although the segmented regression analysis appears to support the breakpoint statistically, the conceptual framing and practical implications of this threshold would benefit from clearer explanation.
- Lines 409–428 (comparisons with other sites): The comparative discussion with other managed realignment sites is interesting and potentially valuable. However, for consistency and interpretability key contextual parameters (e.g., tidal range, suspended sediment concentration) should also be explicitly reported for the present study site. In addition, where possible, comparisons across sites should be standardised (e.g., consistent units for sediment concentration, consistent reporting of tidal range for all sites mentioned).
- Line 453: “While the long-term fate of this initial influx has previously been uncertain”. The sentence appears incomplete if standing alone. It should be linked to a main clause. Please verify sentence structure.

Reviewer #3

(Remarks to the Author)

Burrell et al. “Buried Potential? Evaluating Long-Term Sequestration in a Restored Intertidal Habitat” reports on research focused on a realigned saltmarsh in the Humber estuary. The sampling resolution is extremely high and allows the site to be investigated at an unprecedented resolution.

The data set is highly impressive but their issues that require resolving prior to publication.

My main concerns are methodological.

1 – TGA analysis is a mass loss measurement so does not measure carbon rather it is a proxy for Organic Matter. The authors combine the TGA data with the bulk OC data this is not possible. Text is required to clearly state. For this section I strongly suggest you discuss the TGA data as OM (Labile, recalcitrant and total). Additionally, when discussing lability make clear it is thermal.

2- For the accretion data the readers need to understand the errors involved in the approach. What is the vertical accuracy of the Lidar, has this changed through the years and overall how does the error propagate through the stock calculations.

Other points

Should carbon be in the title ?

I would like to see comparison of the C stock, density, accumulation rates to other realigned and natural marshes both globally and in the UK. You mention cores were collected from a near by natural marsh how do the values compare?

The manuscript does not deal with C sequestration rather it OC accumulation or burial. Assure this is clear.

Lastly, I would like to see greater discussion on the sediment movement. The results highlight that the main mechanism for accretion is the movement of sediment from the intertidal flats or from the river into the marsh. The carbon in this sediment has been sequestered in other environments and the marsh site is acting as a depositional zone. This carbon would likely have been remineralized in these other environments so by storing it the marsh is providing a climate regulation service, but it is not the same a sequestration from the atmosphere. Additionally, the movement of this sediment will also be degrading the OC. Discussion of the nuances is vital to this study.

Line by Line (typos and grammar not included)

Introduction

Line 32-34 Maxwell et al. 2024 calculated that the global store is estimated to be 1.44 Pg. This work is the best constrained global figure. <https://doi.org/10.1038/s41467-024-54572-9>

Line 49: "Following tidal reinstatement, rapid deposition of allochthonous carbon-rich sediment facilitates development" – What is carbon rich in this context?

Methods

Line 107 – 108: The study utilises Lidar data from 2003 – 2022, the horizontal accuracy is state (0.5m) what is the vertical accuracy.

Line 108 – 109: Do you account for timing in the tidal cycle. You mention the issue with seasonal dewatering the same can occur depending on the point in the tidal cycle you measure.

Line 157: A core compaction correction factor was applied if the compaction was <2 cm. State how this was done, the methodology in Howard et al. does not work if there are multiple units in the soil profile as you don't know the compaction across the different units. Could soil profile be added to the supplementary material to confirm this is not an issue. There is growing body of work on this:

- <https://doi.org/10.1007/s40641-016-0038-6>
- <https://doi.org/10.1016/j.geoderma.2020.114180>

Line 174: The OM fraction was removed, was there carbonate material in the sediments and if so, why did you choose not to remove it.

Line 197 – Do you ever use the IC data if not remove the text.

Line 214 – 227: TGA analysis does not measure organic carbon, it is a measure of OM you cannot compare the Labile and recalcitrant data to the total OC. Additionally TGA is a proxy measurement of lability, when discussing it make sure you highlight it is thermal lability being discussed not biological.

Line 214 – 227: Reference Capell et al., 2006 (<https://doi.org/10.1016/j.orggeochem.2006.07.025>), Smeaton and Austin, 2022 (<https://doi.org/10.1029/2021GL097481>)

Results

Lines 273 – 284: Errors need to be reported here, what is the vertical resolution of the lidar?

Lines 285 – The sediment properties section is overloaded with stats could these be placed in a table or in the sup mat to improve readability.

Discussion

Throughout the manuscript make sure accumulation and burial and sequestration are used interchangeable. The manuscript is discussing accumulation/burial not sequestration.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The authors have responded fully to three rigorous reviews. I have no further comments.

Reviewer #2

(Remarks to the Author)

I would like to thank the authors for their replies to the reviewers' comments and for their efforts to improve the manuscript. After reviewing the revised version, I still have a few comments and suggestions to strengthen the manuscript.

- Lines 231–232: Is this statement incomplete?
- I found the comparison with the "Tier 1" stock calculation based on literature mean C density interesting. I was wondering

whether it would also be possible to estimate a value using the mean derived from a smaller subset of cores collected at the study site, perhaps selected according to different criteria. This could help demonstrate the robustness of the study's conclusions and support the idea that a smaller number of samples, combined with a carefully designed sampling strategy, may still provide comparable results (see Lines 242–245 and Lines 566–571).

- Line 287: This paragraph seems somewhat redundant with the explanation already provided in Lines 238–242.
- Figure S2: In my opinion, the colour scale used in the figure is not very intuitive. For consistency, could the same colour scale used in Figure 1 be adopted here as well? In addition, I would suggest indicating the breach location in Figure S2. It might also be useful to show the initial elevation prior to breaching.
- Lines 389–390: This sentence appears to be interrupted; perhaps there should be a comma instead of a full stop?
- Lines 551–553: "Consequently, equal depths sampled across elevations may reflect different depositional conditions, so fixed-depth comparisons should be interpreted with caution". In this regard, was the possibility of integrating the analyses with facies analysis considered? This could help define different depositional conditions and the related C accumulation dynamics (see, for example, Puppini et al., 2025 <https://doi.org/10.1029/2024JG008327>)

Reviewer #3

(Remarks to the Author)

Burrell et al., have dealt with all my concerns and I believe the manuscript to be suitable for publication after a few minor updates.

"sequester" is still used in the text - line 77

Recently I came across Gore et al., 2023, that used TGA analysis in saltmarsh it would be useful to acknowledge this technique being used in other UK marshes - <https://www.sciencedirect.com/science/article/pii/S0272771424000520>

I also believe comparing the accumulation rates and stocks to the UK average for natural marshes would be beneficial and give the results some context. A quick search highlights that on average UK saltmarshes accumulate 110 g/m²/yr of OC with a range of 27.2 - 303.1 g/m²/yr. The data presented here show rates of 1500 g/m²/yr. You discuss reasons for this rate being 5 to 50x larger but comparing them to natural system provides important context that is missing

<https://www.sciencedirect.com/science/article/pii/S0048969724022472#ec0005>

It is less clear how the results presented here could be compared to natural OC stocks. One potential route would be to compare the depth integrated OC value (lines 452 onwards). Here the average is 297.8 tonne/ha. In UK natural marshes the average is 110 tonne/ha for saltmarsh soils with values ranging between 22.4 - 405.1 tonne/ha. If you extend the stocks down 1m (not all saltmarsh include paleo tidal flat) then the number range from 50.5 - 731.9 tonnes/ha.

<https://www.frontiersin.org/journals/marine-science/articles/10.3389/fmars.2023.1229486/full>

The data from this paper falls within these ranges and should be highlighted, inline with natural marsh stocks but far exceed accumulation - provide reasons.

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Response to Reviewer Comments

We thank the three reviewers for the positive comments and constructive feedback. We have numbered the comments from the editor and reviewers and provide detailed responses and descriptions of the revisions we have made. We cross reference between comments because several reviewers have commented on the similar points.

Reviewer Comments

Reviewer #1 (Remarks to the Author):

This manuscript details soil and associated organic carbon deposition following managed realignment of a coastal impoundment 19 years post management action (e.g. reconnecting the wetland to the ocean). Through extensive sediment sampling (thousands of 5 cm sediment increments covering accretion throughout the 80 ha site) and change in elevation (based on lidar), a total volume of soil and associated carbon was determined. The authors claim that using a constant rate of accretion would not result in accurate C accounting when considered as a natural climate solution due to heterogeneity across the site.

Response: We thank the reviewer for your constructive comments on our manuscript. Our detailed, point- by- point responses to each comment are provided below.

Comment 4 Sediment accretion that is highly dependent on elevation within the tidal frame is well known and this paper would benefit from better integrating that literature in the Introduction and Discussion.

Response:

Thank you for this comment. We agree that elevation within the tidal frame is a well- established control on sediment accretion. In the Introduction, we previously noted that managed realignment sites are typically positioned low within the tidal frame, creating substantial accommodation space, and we describe how post- breach allochthonous sediment deposition drives rapid early accretion, with OC burial patterns shifting as elevation increases. This reflects the classical elevation–inundation–sediment delivery framework described by Friedrichs & Perry (2001). We have now added reference to a wider range of literature and made the implications of initial low elevation for sedimentation and carbon clearer (New lines 51-53). In the Discussion, elevation-dependent accretion is addressed more explicitly. We have referred to a wider range of literature and made some minor clarifications to ensure that the role of elevation is clearer.

Revisions Lines 546 - 551:

‘Carbon density in natural intertidal habitats, while variable, is constrained by packing effects between organic and lithogenic sediment fractions [59]. As a result, variability in carbon stocks is driven primarily by differences in sediment accretion rate rather than carbon density alone [60-62], reflecting strong elevation-dependant controls on sediment burial within the tidal frame. Consequently, saltmarshes that are low-lying at the time of restoration typically experience rapid early accretion following breaching [14].’

Comment 5 Evaluating sediment accretion through lidar is somewhat novel in a coastal wetland, but largely because rates of accumulation at this site were large because it is a disturbance ecosystem.

Response:

Thank you for this comment. We agree that the use of LiDAR to quantify sediment accretion in coastal wetlands is less common than in terrestrial geomorphology. At Paull Holme Strays, however, the unusually rapid elevation gains following the breach, meant that LiDAR- derived elevation change provided particularly valuable, site- scale constraints on accretion patterns.

Comment 6 The accuracy of the lidar flights and how they changed in time is an omission in this paper, as without it no conclusions about when deposition happened relative to the management action can be made.

Response: Thank you for this comment. We now explicitly document the vertical accuracy of all LiDAR datasets, assess their temporal consistency, and clarify how elevation- change magnitudes compare to known LiDAR uncertainty (Lines 131-139, 332-346). We also include additional contextualisation of accretion timing relative to the 2003 breach. These revisions ensure that conclusions regarding post- breach deposition timing are supported by the documented accuracy and stability of the LiDAR record.

Comment 7 The authors reference lidar data throughout the 19 years, but do not use any but the two extreme time points.

Response: Thank you for raising this point. In the revised manuscript, we now include a concise description of year- on- year elevation change derived from all available LiDAR DTMs and include a cumulative elevation- change map (Supplementary Fig. S2, referred to at line 333). These additions demonstrate that multiple LiDAR surveys were used to characterise accretion timing and confirm that rapid infilling occurred immediately after tidal reinstatement, followed by slower, spatially variable accretion.

Comment 8 Taking thousands of sediment samples to determine how C density is changing across the site is a huge undertaking. The authors do not demonstrate that this approach was a significant improvement over using Tier 1 (e.g. constant C density) values.

Response:

We agree that the sampling effort undertaken here is substantially greater than that required for routine carbon stock estimation. The purpose of this intensive approach was to quantify how carbon density actually varies in space and with depth.

Our results demonstrate that carbon density varies by more than an order of magnitude across elevation, sedimentation history, and depth within the site, indicating that Tier 1 approaches would lead to substantial over- or under-estimation depending on location. This improvement over Tier 1 is therefore not incremental, but structural: the intensive dataset reveals systematic heterogeneity that Tier 1 approaches are unable to represent.

Importantly, the value of the intensive sampling lies in identifying the dominant controls on this heterogeneity. Elevation within the tidal frame, as a proxy for sedimentation regime, emerged as a primary driver of carbon density variability. This allows our results to inform more efficient, lower-intensity Tier 2 applications, for example through stratified sampling based on LiDAR- or UAV-derived elevation data, combined with a limited number of representative, depth-resolved sediment cores per stratum. We have clarified this interpretation and its implications in the Discussion, emphasising that the intensive sampling serves as a calibration framework to improve how Tier 1 and Tier 2 approaches are applied, rather than as a template for routine monitoring

Revision:

Line 599 - 619

“This variability has direct implications for reporting frameworks that rely in constant carbon density defaults (Tier 1 approaches) [29, 59]. At Paull Holme Strays, recalculating site-mean stocks using standard assumptions, ranging from lower-end temperate values ($50\text{--}100\text{ t C ha}^{-1}\text{ m}^{-1}$; [20, 28]) to the most up to date global median ($230\text{ t C ha}^{-1}\text{ m}^{-1}$; [1]), resulted in consistent underestimation of carbon storage (~ 80 to $\sim 207\text{ t C ha}^{-1}$). This discrepancy highlights that uniform density values cannot account for the strong spatial and vertical heterogeneity observed across the site, which varies substantially with elevation, sedimentation history, and depth, ranging from $<5\text{ mg cm}^{-3}$ in rapidly accreting mudflats to $>25\text{ mg cm}^{-3}$ in densely vegetated high-elevation areas.

The intensive sampling conducted in this study was designed to quantify this heterogeneity and provide a robust dataset capable of developing more accurate, lower-intensity Tier 2 approaches. By identifying elevation within the tidal frame and associated sedimentation history as the primary controls on carbon density, our findings support stratified sampling strategies in which sites are partitioned using LiDAR or UAV-derived elevation data, with a limited number of representative, depth-resolved sediment cores collected within each stratum and scaled by areal extent. This methodology retains sensitivity to key environmental drivers of carbon storage while substantially reducing sampling effort relative to the high-resolution strategy adopted here, providing a practical pathway for restoration monitoring and site-scale carbon stock assessment.”

Comment 9 Numerous studies have demonstrated that C density in coastal wetlands varies little due to sediment packing between organic and lithogenic fractions (see <https://doi.org/10.1002/2015EF000334>, [10.1088/1748-9326/aae157](https://doi.org/10.1088/1748-9326/aae157), and <https://doi.org/10.1029/2024JG008254>) and thus rate of accretion is the biggest driver of C stocks, as this manuscript demonstrates.

Response: We appreciate this comment and agree that many existing, mature coastal wetlands exhibit relatively constrained carbon densities, and we have added some new comment in line 546 - 551. However, our study finds both highly variable sedimentation rates which produced far greater spatial and vertical variability in C density than typically observed in stable existing/natural intertidal habitats.

Comment 10 The authors do not assess what the Tier 1 stock value would be.

Response: To explicitly evaluate the performance of Tier 1 approaches, we have now calculated SOC stocks using a range of constant carbon density assumptions. These included (i) lower-end temperate saltmarsh SOC densities ($50\text{--}100\text{ t C ha}^{-1}\text{ m}^{-1}$), consistent with values commonly reported for mineral-dominated temperate marsh soils in synthesis and regional studies (e.g. McLeod et al., 2011; Ouyang & Lee, 2014), and (ii) a higher density of $230\text{ t C ha}^{-1}\text{ m}^{-1}$ corresponding to the most recent global median estimate of tidal-marsh SOC storage to 1 m depth (Maxwell et al., 2024). When applied as constant densities across the measured post-restoration sediment thickness, these Tier 1-style calculations yield site-mean SOC stocks ranging from ~80 to ~207 t C ha^{-1} . All estimates substantially underestimate the depth-integrated SOC stock derived from measured carbon density profiles (~298 t C ha^{-1}), demonstrating that Tier 1 approaches fail to capture SOC storage at this site across the full range of plausible carbon density assumptions. Our discussion has been amended to address this lines 600 – 620.

Comment 11 Also, monitoring costs post restoration are a significant barrier to blue carbon implementation on a market-basis, so would be good to include in this manuscript whether such intense field efforts are needed.

Response:

We fully acknowledge that most blue- carbon studies cannot feasibly undertake sampling at this intensity, nor is it cost- effective to do so routinely. Based on the patterns identified in this study, we now propose reduced-intensity Tier 2 sampling strategies that retain sensitivity to key drivers of OC variability while substantially lowering monitoring effort and cost (lines 609 - 619).

Comment 12 An important finding would be that remote sensing approaches, such as lidar, are sufficient for soil organic C accounting in these types of restorations.

Response:

Thank you for this thoughtful comment. We agree that remote- sensing approaches, particularly airborne LiDAR, can provide highly valuable spatial information on sediment accretion in restored saltmarshes. At Paull Holme Strays, the LiDAR datasets used in this study have a reported vertical RMSE of $\pm 15\text{--}20$ cm and inter- annual consistency was confirmed using fifteen RTK- GNSS- surveyed benchmark plates (-2 to $+2$ cm between 2024–2025), demonstrating excellent vertical stability. This is in the context of average elevation change of 130 cm (range 11 - 250 cm). This supports the use of LiDAR- derived elevation change to quantify site-wide sediment gain, where such gains are larger than the resolution of the technique to scale up localised measurements.

However, LiDAR performance in coastal wetlands depends on vegetation structure, surface complexity, inundation, and site geomorphic state. Prior work shows that LiDAR can systematically under- or over- estimate marsh elevations in vegetated or saturated environments and generally benefits from ground- truth validation (<https://doi.org/10.1371/journal.pone.0259033> <https://doi.org/10.5194/isprs-annals-X-G-2025-109-2025> <https://www.nrcs.usda.gov/publications/ceap-wetland-2014-LiDARMappingWetlandResourcesAssessment.pdf>).

Comment 13 Soil C source is important, as in the NCS literature there is still debate over whether the ecosystem should credit carbon that is buried or removed from atmosphere (e.g. the autochthonous versus allochthonous issue, see <https://doi.org/10.1111/gcb.70022>). This needs to be discussed in this manuscript.

Response:

Thank you for highlighting this important point. We agree that this is an important debate. Although not the focus of this study, we have added a short section to the Discussion clarifying that the majority of early- stage carbon accumulation at managed realignment sites is dominated by allochthonous, estuarine- derived material, whereas autochthonous plant- derived carbon becomes increasingly important as vegetation develops. We also note that current NCS accounting frameworks differ in whether, and how, allochthonous carbon is credited. We have incorporated this nuance into the Discussion to ensure that the implications of our findings for carbon accounting are presented transparently.

Revision:

Discussion line 534 - 544

“Early post- breach accumulation in managed realignment sites is widely recognised to be dominated by allochthonous estuarine material, with autochthonous, plant- derived inputs becoming increasingly important as vegetation establishes (<https://10.1371/journal.pone.0259033>). This distinction is central to ongoing debate regarding whether allochthonous carbon should be credited as a climate benefit, or whether only autochthonous carbon—representing net atmospheric CO₂ drawdown—should count (<https://doi.org/10.1111/qcb.70022>; <https://doi.org/10.1111/qcb.70022>). For this reason, we emphasise that the values reported here represent sedimentary OC burial rather than net sequestration from the atmosphere. Our results therefore characterise the persistence and vertical distribution of OC irrespective of origin, while acknowledging that the accounting relevance of allochthonous versus autochthonous pools depends on the specific framework applied.”

Please see the attached pdf file for the full comments, which were made in line.

Comment Line 54 Meaning greater extent temporally or spatially compared to similar habitats? Anoxic means absence of O₂, so there isn't really a condition that has less oxygen, which could be one way to read "more anoxic". Please clarify.

Response:

We have clarified the phrasing to remove ambiguity around “more anoxic” and to specify the nature of the differences relative to existing marshes. Our intention was to highlight that restored sites often exhibit more prolonged or spatially extensive reducing (low- oxygen) conditions in subsurface sediments due to historic land use and altered drainage.

Revision:

Line 59-61: historic land use, including, reduced porosity, altered drainage, and more prolonged or spatially extensive sub-oxic to anoxic subsurface conditions, shaping long-term sediment dynamics, redox processes, and vegetation development.

Comment Line 59 Importantly, in coastal settings methanogenesis is also limited since sulfate reduction is the primary remineralisation pathway, limiting emissions of methane, which is a more potent GHG than CO₂.

Response:

Thank you for this helpful comment. We have clarified the manuscript to explain that high sulfate concentrations in coastal wetland sediments typically suppress methanogenesis by favouring sulfate-reducing bacteria. However, we also note that recent work demonstrates that methylotrophic methanogenesis can occur even under sulfate-rich conditions (<https://doi.org/10.1111/gcb.15046>, <https://doi.org/10.1016/j.agrformet.2020.108309>). and that methane dynamics in saltmarshes remain an active area of research. Our revised text reflects this nuance while maintaining focus on sediment OC burial, which is the primary scope of this study.

Revision:

Line 67-70:

“Additionally, high sulfate concentrations in intertidal sediments generally suppress microbial CH₄ production (methanogenesis) by favouring sulfate-reducing bacteria, limiting methane emissions, a greenhouse gas ~30 times more potent than CO₂ (Capooci et al., 2023).”

Comment Line 106 The vertical resolution is likely more relevant to this study. What was done to ensure the lidar collections across years were comparable? Was a location of known (and unchanging) elevation evaluated in each data set? Lidar in coastal environments can be biased in vegetated areas. Was any RTK ground-truthing done?

Response:

Thank you for these detailed questions. We now provide explicit information on LiDAR vertical accuracy (Environment Agency RMSE ±15–20 cm), describe steps taken to ensure temporal comparability across surveys, and report the installation and RTK-GNSS surveying (±1–2 cm) of fifteen fixed benchmark plates used to assess inter-year LiDAR stability. These benchmarks demonstrated –2 to +2 cm variation between the 2024 and 2025 LiDAR datasets, confirming consistency well within published RMSE values. We also clarify that vegetation-related LiDAR bias is acknowledged and that

our interpretation focuses on elevation patterns validated against ground- control points. These revisions have been incorporated into the Methods section at Line 131-139 onwards:

Revision:

“The Environment Agency reports a vertical RMSE (Root Mean Square Error) of $\pm 15\text{--}20$ cm for all LiDAR surveys used in this study, referenced to Ordnance Datum Newlyn (ODN). Fixed-elevation benchmarks were not present during the original study period; however, as part of a subsequent long-term monitoring programme, fifteen aluminium benchmark plates were installed in 2023 and surveyed using RTK-GNSS ($\pm 1\text{--}2$ cm accuracy). Elevations extracted for these locations from the 2024 and 2025 LiDAR surveys differed by -2 to $+2$ cm (Supplementary Table S1), confirming inter-year vertical consistency well within the published RMSE. LiDAR surveys are conducted during Low Water Spring tides to ensure maximum sediment exposure and minimise elevation bias from surface water or tidal stage.”

Comment Line 106 Is Paul Holme Strays the name of the full MR study site introduced in the first section of Methods? I would introduce the name there first.

Response:

Thank you for this suggestion. We have now added “Paull Holme Strays” at the first mention of the study site in the Methods.

Comment Line 182 Graphical method repeated in sentence, please edit.

Response:

We have deleted the repeated phrase ‘graphical method’

Comment Line 205 Could be shortened to "at 5 cm depth intervals"

Response:

We have deleted the repeated ‘5cm intervals’

Comment Line 284 Since there are multiple DTMs since restoration, why was the elevation change analysis only done 2002 to 2023? Such an analysis would be very useful for determining when the accretion happened. Has it been gradual over the 19 years since tidal introduction or was it rapid at first, then leveling off? This rate of change is very relevant to C accounting and likely relevant also to framing the labile/recalcitrant analysis.

Response:

Thank you for this comment. We now include an explicit description of temporal elevation- change patterns derived from all available DTMs, rather than only the two end- member years. The revised Results section (lines 131-139 and 332-346) presents year- on- year elevation change and shows that accretion was rapid immediately after the 2003 breach, followed by slower and more spatially variable accumulation. We also include a cumulative elevation- change figure (Supplementary Fig. S2) to illustrate when the majority of sedimentation occurred. These additions directly clarify the timing of elevation gain, which is relevant for interpreting carbon accumulation and depth- related patterns in labile and recalcitrant OC. These revisions fully resolve the concern raised here.

Comment Line 316 Separating the bulk density and OC content sections is a big confusing. The relationship between BD and OC typically follows a mixing relationship between mineral and OM end members based on sediment particle packing theory (see the review of this by Morris et al 2016 doi: 10.1002/2015EF000334 (. Likely the carbon density doesn't not change as much as BD or wt%C and interpreting changes in wt%C as a decline in carbon content is not straightforward if carbon density itself does not change, as ultimately it is C density that defines a stock. Likely the greatest control on C stock across the MR site will be the volume/depth of sediment added in each area, which was highly dependent on the pre-restoration elevation.

Response:

We agree that bulk density and wt% OC should not be interpreted independently, as both reflect a mixing relationship between mineral and organic endmembers governed by sediment packing theory (Morris et al., 2016; doi:10.1002/2015EF000334). In response, we have merged the bulk density and OC content sections in the Results to reflect their coupled behaviour more clearly. We now emphasise that while wt% OC declines with depth, carbon density (g C cm^{-3}) is the more appropriate measure for determining carbon stocks because it captures both OC concentration and sediment packing. We also clarify that the primary control on total OC stock across the MR site is the volume of sediment accreted (accommodation space), which was strongly dependent on pre- restoration elevation. These revisions are implemented into the Results (lines 372-373) and Discussion (line 505-511).

Revision line 399-401:

“This reflects a mineral–organic mixing relationship, whereby changes in wt.% OC covary with sediment compaction and grain packing rather than directly tracking changes in carbon mass per unit volume.”

Comment Line 329 This makes sense with what is know about sediment transport through marsh systems. Low elevation areas typically have coarser sediments, since deposition energy is higher. I think this manuscript could improve by adding additional context from the extensive sediment transport literature in coastal wetlands. Some good refs for this are:

Friedrichs, C. T., & Perry, J. E. (2001). Tidal salt marsh morphodynamics: a synthesis. *Journal of Coastal Research*, 7-37.

Hans Burchard, Henk M. Schuttelaars, David K. Ralston. 2018. Sediment Trapping in Estuaries. *Annual Review Marine Science*. 10:371-395.
<https://doi.org/10.1146/annurev-marine-010816-060535>

Response:

Thank you for this helpful suggestion. Our grain- size analyses represent true mineral particle- size distributions (following peroxide digestion and chemical dispersion), and our statistical results show that grain size becomes a weak predictor once elevation and core depth are included. This reflects the fact that sediment texture is largely mediated by elevation- driven hydrodynamic processes. In accordance with the reviewer's comment, we have added context, noting that coarser sediments typically accumulate in lower- elevation, frequently inundated zones due to higher bed shear stresses and enhanced particulate delivery, consistent with established marsh morphodynamic theory (Friedrichs & Perry, 2001; Burchard et al., 2018).

Revision: Results Line 416:

"Consistent with established sediment-transport behaviour in intertidal systems."

Discussion Line 508-510

"This is consistent with established sediment- transport dynamics in tidal marshes, where lower elevations experience higher inundation frequency and bed shear stress, enhancing mineral sediment delivery and trapping [14, 59]."

Comment Line 358 How much of this is a live root signature?

Response:

We thank the reviewer for highlighting the potential contribution of live roots to the observed labile OC signal. We agree that even with sieving it is not possible to fully separate root-derived OC from sediment-bound pools. In the revised manuscript (lines 513-517), we have therefore explicitly contextualised the observed ~40 cm breakpoint using published data on saltmarsh rooting depth and marsh elevation within the tidal frame.

We now note that multiple studies show that fine root biomass in temperate saltmarshes is predominantly concentrated within the upper 20–40 cm of the sediment profile, with root density declining sharply below this depth (<https://doi.org/10.3389/fpls.2018.00098>, <https://doi.org/10.3389/fevo.2019.0015>, <https://doi.org/10.5194/bg-22-4851-2025>). The breakpoint identified in our segmented regression coincides closely with the lower boundary of this biologically active root zone.

Comment Line 365 Is this 2.47 % of the total carbon was recalcitrant or total 2.47 wt%C was recalcitrant? I think adding clarity here is important. Including both the total wt% and then the proportion of the total C pool would be useful.

Response:

Thank you for noting this ambiguity. The value of 2.47% refers to the absolute concentration of recalcitrant OM (wt% C) in the surface sediments of the reference marsh, not the proportion of the total OC pool. To improve clarity, we now report both the total OC concentration and the proportion represented by the recalcitrant fraction in this horizon.

Revision line 436-439

“Surface concentrations of recalcitrant OM were highest in the reference marsh (top 30 cm: median recalcitrant OC = 2.47 wt% C), representing approximately 62% of the total OC pool in this horizon (median total OC = 4.0 wt%)”

Comment Line 411 Accretion in restored coastal wetlands is highly variable in time as the systems respond rapidly to initial changes, with change rates typically decreasing with time since restoration. When comparing these MR sites, it is important to provide temporal context in addition to suspended sediment concentrations.

Response:

We agree that accretion rates in managed realignment systems are strongly time- dependent, with the most rapid infilling typically occurring soon after restoration. We now include a figure highlighting elevation change over the 19 year period at Paull Holme Strays (Supplementary Figure 1), and have clarified in the Discussion, explicitly distinguishing between early- stage sites (e.g., Steart Marsh), more mature MR sites (e.g., Blackwater Estuary sites), and long- established tidal marshes (e.g., upper Bay of Fundy). The Bay of Fundy example demonstrates that high suspended sediment supply can sustain elevated carbon accumulation rates even in mature systems, reinforcing our

conclusion that sediment availability is a dominant control on carbon accumulation magnitude across MR and tidal- marsh systems.

Revision line 570 – 572:

“While Steart Marsh reflects early post- restoration characterised by high accretion rates, the Blackwater Estuary sites are more mature systems.”

Comment Line 451 For carbon accounting, especially as related to markets, it matters if the source of the C is the local environment (e.g., auto versus allo). Rapid deposition of sediment after restoration is likely all externally sourced and could be "credited" to another ecosystem. It is an ongoing question in the C accounting realm if an ecosystem takes credit for the C it fixes and removes from the atmosphere or the C it keeps from returning to the atmosphere, which would allow for accounting of externally-fixed C. This work does not tackle C source, and likely needs to be mentioned given framing in introduction around C accounting.

Response:

We agree that whether carbon is autochthonous or allochthonous is highly relevant for certain carbon- accounting frameworks. While this study did not directly quantify carbon sources, we now explicitly acknowledge this in the Discussion and clarify the implications for carbon accounting. Specifically, we added a new paragraph (Lines 619-630) noting that early- stage carbon accumulation in managed realignment sites is typically dominated by allochthonous estuarine sediment (e.g., Mossman et al., 2022), and that accounting frameworks differ in whether such externally derived carbon is credited (e.g., GCB, <https://doi.org/10.1111/qcb.70022>). We also emphasise that our depth- resolved profiles provide empirical context for how both allochthonous and autochthonous inputs contribute to long- term OC preservation, even though source partitioning was beyond the scope of this study. Please see revisions to reviewer comment number 13.

Comment Line 452 Not a complete sentence.

Response:

We have revised the text to correct the structure and improve clarity.

Revision line 505 – 508:

“The long- term fate of this initial influx has previously been uncertain. Our depth- resolved analysis revealed a sharp decline in labile OC below ~40 cm (Figure 6), confirmed by segmented regression (breakpoint at 40.5 cm, 95% CI: 38.4–42.7).”

Comment Line 455 Does this coincide to the elevation of MLW? In many marsh systems, porewater drainage below MLW is rare. Also, some mention of the rooting depth would be useful here, as even with sieving it is difficult to say that all OC signals are sediment bound rather than roots (there are a lot of fine roots)

Response:

We thank the reviewer for this helpful comment. We have amended the Discussion to explicitly place the observed ~40 cm decline in labile OCM within the local tidal frame and to clarify the role of rooting depth and pore-water drainage. Specifically, we now state that Paull Holme Strays occupies a high-intertidal position (between mean high-water neaps and springs), such that mean low water corresponds to a shallow subsurface water table. At this elevation, sediments below ~40 cm are expected to remain persistently saturated, limiting pore-water drainage, oxygen penetration, and active root development. We further clarify that fine roots are not entirely separable from the sediment matrix and are therefore likely to contribute to labile OC in surface layers, such that near-surface OC reflects an integrated pool of root-derived and sediment-associated carbon. Below ~40 cm, the sharp reduction in labile OCM is interpreted as a transition to persistently saturated, biologically inactive sediments where long-term carbon storage is increasingly controlled by depositional history and mineral association. These additions are now incorporated at Lines 114-117 and 511-517) of the revised manuscript.

Figure 1 The site outline is the same color as the 2.31-2.9 m elevation change. Suggest different colors here.

Response: *Thank you for highlighting this. We have amended elevation change colour.*

Reviewer #2 (Remarks to the Author):

The manuscript presents the first high-resolution, full-depth assessment of organic carbon (OC) accumulation across a restored intertidal habitat in the UK, Paull Holme Strays, located on the north bank of the Humber Estuary. The site, breached in 2003 as part of a managed realignment scheme designed for both coastal flood protection and habitat restoration, provides a valuable long-term case study of post-restoration sediment and carbon dynamics.

Drawing on an extensive dataset comprising 234 sediment cores and 3,987 sediment samples collected across vegetated saltmarsh and intertidal mudflat habitats, the authors aim to: (1) quantify site-level OC stocks and habitat-specific accumulation rates since site creation; (2) characterise vertical OC profiles by

partitioning labile and recalcitrant fractions in order to assess the extent and rate of labile OC loss with depth; (3) define an empirically derived surface layer to enable consistent spatial comparisons across heterogeneous elevations; and (4) evaluate how environmental variables (e.g., elevation) and sedimentological characteristics (e.g., grain size) correlate with spatial variability in OC storage.

The study integrates repeated Digital Terrain Models derived from airborne LiDAR (from 2003 to 2022) to estimate net sediment accretion and erosion, which inform core depth selection and carbon stock calculations. Sampling was stratified across three elevation bands, with additional reference cores collected from adjacent natural salt marshes. Sediment cores were sectioned at 5 cm intervals and analysed for dry bulk density, grain size, total, inorganic and organic carbon (via elemental analysis and loss-on-ignition procedures), and thermogravimetric partitioning of labile and recalcitrant OC fractions. Sediment properties were subsequently modelled as a function of elevation zone and depth within cores.

Overall, the study is ambitious and methodologically robust. The sampling intensity is exceptional, and the integration of long-term topographic data with detailed geochemical analyses represents a substantial empirical contribution to the understanding of carbon accumulation in managed realignment systems. However, while the dataset is impressive and the analytical framework appears sound, the analysis and discussion of the results could be further strengthened to fully exploit the richness of the data and maximise the broader relevance of the findings.

Response:

We thank the reviewer for their detailed, and constructive comments. Your positive assessment of the study's ambition, methodological rigour, and empirical contribution is very much appreciated. Individual responses to each comment are provided below.

General comments

Study site

Comment 14 While the site description is generally clear, the manuscript would benefit from additional contextual information on the local tidal regime. In particular, providing details on tidal range and general hydrodynamic setting within the Humber Estuary would help readers better interpret the elevation-stratified sampling design. Because much of the manuscript's argument hinges on the interaction between elevation, inundation frequency, sediment supply, and OC preservation, a clearer description of the tidal framework would strengthen the conceptual grounding of the study and make the elevation bands more ecologically meaningful to readers who are less familiar with the site.

Response:

Thank you for this suggestion. We have now expanded the Study Site description to include tidal range, typical inundation patterns, the ODN

elevations for MHWN and MHWS relative to the Hull (Albert Dock) tide gauge to place the site in the tidal frame, and key hydrodynamic characteristics that influence sediment delivery and accretion at Paull Holme Strays.

Revisions: Line 110-117:

“The Humber Estuary is a macrotidal environment with a mean tidal range of ~4–7 m [30], producing strong bidirectional currents that deliver large volumes of suspended sediment. Suspended sediment concentrations are among the highest in the UK (typically 19–27 g L⁻¹) [31], enabling rapid deposition during both flood and ebb tides. Mean high-water neaps and springs at the nearest long-term tide gauge (Hull, Albert Dock) occur at approximately 4.5 m and 6.0 m ODN respectively, providing a reference for placing restored marsh elevations within the local tidal frame.”

Line 511 - 513

“Because the site occupies a high-intertidal setting (between MHWN and MHWS), sediments below ~ 40 cm are expected to remain persistently saturated, limiting pore-water drainage, oxygen penetration, and root development.”

Methods

Comment 15 The methodological framework is extensive and appears rigorous; however, in some sections the explanation could be made clearer, particularly for a multidisciplinary audience. Specifically, the procedures used to calculate OC accumulation rates and carbon sequestration are not fully transparent in the current text.

Response:

“Thank you for this comment. We have revised the Methods section to provide a more explicit, step- by- step description of how OC density, per- core OC stocks, and accumulation rates were calculated (lines 242-250). This includes clarifying how bulk density and %OC were used to derive OC density, how depth- integrated stocks were calculated, and how site- level annual accumulation rates were estimated. We also explicitly distinguish between sedimentary OC accumulation (burial) and atmospheric carbon sequestration to avoid ambiguity. These revisions improve transparency and accessibility of the methodological framework.”

Revision (Lines 242-250):

“Soil OC density was multiplied by the thickness of each subsection (5 cm) to derive the OC mass per unit area (g C cm⁻²), summed across each individual core length to obtain total OC stock per core (g C cm⁻²), and then scaled to tonnes per hectare (t C ha⁻¹). Site-level mean stocks and standard deviations were calculated across all cores.

Time-averaged annual OC accumulation ($\text{t C ha}^{-1} \text{ yr}^{-1}$), per-core OC stocks were divided by the number of years since site creation (19 years). This represents sedimentary OC accumulation (burial), not atmospheric CO_2 sequestration. Total site-wide OC accumulation (t C yr^{-1}) was obtained by multiplying mean per-core accumulation rates by the total restored area (79.8 ha)."

Comment 16 Although the statistical approach appears appropriate and sophisticated, the data analysis section may be challenging for readers without a strong statistical background. In particular, the paragraph describing the use of Generalised Additive Models could benefit from a brief introductory sentence explaining, in general terms, what the method is designed to achieve (e.g. modelling non-linear relationships and depth-dependent patterns while accounting for spatial structure). This does not require substantial expansion, but a concise framing sentence would make the modelling strategy more accessible and facilitate interpretation of the results section.

Response:

Thank you for this helpful suggestion. We have now added a brief introductory sentence to the statistical methods section to clarify, in general terms, the purpose of Generalised Additive Models (GAMs). This framing explains that GAMs are used to capture non- linear relationships and depth- dependent patterns while accounting for spatial structure and repeated measurements within cores.

Revision: Data analysis lines 290-293

"GAMs capture complex, non- linear changes with depth and elevation while also handling repeated measurements from the same core and the natural correlation between successive depth increments, features that standard linear models cannot accommodate."

Results and discussion

Comment 17 The manuscript presents a rich and carefully generated dataset and offers several interesting interpretations regarding the controls on OC accumulation and preservation across elevation gradients. However, some aspects of the discussion could be further developed to strengthen the mechanistic interpretation and broaden the relevance of the findings. While the discussion appropriately highlights spatial variability in sedimentation and links it to hydrodynamic forcing and proximity to the breach, the hydrodynamic framework remains somewhat implicit. A more explicit characterisation of internal site dynamics would improve interpretation. For example: Where within the managed realignment area is sediment transport and tidal energy expected to be highest?

Response:

Thank you for this suggestion. While we did not measure hydrodynamic energy or flow paths directly, the spatial pattern of sedimentation across the

site provides a clear basis for interpreting internal site dynamics. The greatest accretion (~250 cm) occurs immediately adjacent to the western breach where post restoration elevation was lowest and is consistent with expectations that tidal energy and suspended- sediment delivery are highest near breach openings in managed realignment systems. In contrast, eastern and higher- initial elevation areas, which are more sheltered from direct tidal forcing, exhibit very limited accretion (~11–40 cm). These observed gradients in sedimentation underpin our interpretation of within- site hydrodynamic structure and are used throughout the Discussion to contextualise differences in OC density, fraction-specific depth patterns, and OC accumulation. We emphasise that this interpretation reflects established geomorphic understanding rather than direct hydrodynamic measurement, and we have revised the text to ensure this is clear.

Comment 18 Is the system approaching a ecogeomorphological equilibrium, and if so, what trajectory is anticipated?

Response:

Thank you for this thoughtful question. Rapid sediment infilling adjacent to breaches (Supplementary Figure 1) and limited accretion on higher marsh surfaces are consistent with mid-stage managed realignment development (10.1016/j.margeo.2006.10.009; 10.1177/0309133312451351). Previous studies suggest that whole-system equilibrium typically develops over multi-decadal timescales and remains strongly influenced by sediment supply and sea-level rise (10.1016/S0272-7714(02)00361-1; 10.1002/esp.3926).

Comment 19 A clearer conceptual model linking elevation, hydrodynamics, sediment supply, and vegetation development would help contextualise the spatial patterns described.

Response:

Thank you for this suggestion. The manuscript discusses the key components of the ecogeomorphic framework. Specifically, how elevation controls inundation frequency, how hydrodynamics and sediment supply influence accretion patterns, and how vegetation development contributes to OC inputs and preservation at different elevations. However, we agree that making these linkages more explicit would help readers unfamiliar with saltmarsh dynamics. We have therefore added clarifying text in the Discussion to summarise the conceptual relationships between elevation, hydrodynamics, sediment delivery, and vegetation development, without extending interpretation beyond the scope of our data (10.2112/1551-5036-27.sp1.7; 10.1016/S0272- 7714(02)00361- 1; 10.1016/j.margeo.2006.10.009; 10.1038/s43247-024-01829-2). This addition provides the clearer conceptual

framing requested, while keeping the focus on the measured sediment and OC patterns.

Revisions: Lines 622 - 625.

“These results are consistent with established ecogeomorphic models, in which elevation determines inundation regime, inundation governs hydrodynamic energy and sediment supply, and vegetation development subsequently reinforces feedback between elevation and sediment accretion.”

Comment 20 The manuscript recognises the importance of vegetation in shaping OC dynamics, but its role could be explored more explicitly. It remains unclear whether vegetation composition is homogeneous within elevation bands or whether species turnover may contribute to differences in OC inputs and preservation.

Response:

Thank you for raising this point. Vegetation is recognised as an important driver of OC inputs, but detailed vegetation composition surveys were not undertaken as part of this study. Consequently, we do not attempt to link species- level patterns to OC variability. Instead, vegetation enters our interpretation indirectly through elevation- related processes (e.g., biomass inputs, oxygenation), which we now clarify in the Discussion. This avoids overstating vegetation effects beyond the scope of the dataset.

Revision: Line 530 – 533:

“While detailed species-level surveys were not conducted, elevation-based patterns effectively encompass vegetation effects by acting as a proxy for increasing biomass and structural complexity found in higher-elevation communities.”

Comment 21 Are there differences in dominant plant communities across elevation bands?

Response:

Vegetation communities at Paull Holme Strays do vary across elevation bands, broadly reflecting typical intertidal zonation patterns, with low- elevation areas dominated by pioneer and mudflat communities and higher elevations supporting more established marsh vegetation. However, we did not conduct quantitative vegetation mapping or species- level surveys as part of this study and therefore cannot formally analyse differences in community composition or dominance across elevation bands. Instead, vegetation effects are incorporated indirectly through elevation- related processes that influence biomass inputs, inundation frequency, and sediment oxygenation. We have clarified this explicitly in the Discussion (Line 518 - 533 onwards), which addresses the reviewer’s question while avoiding over- interpretation beyond the scope of the available data.

Comment 22 Do rooting depths vary among vegetation types? If so, could variation in the depth distribution of live roots influence the observed vertical patterns of labile OC?

Response:

We thank the reviewer for this helpful comment. Yes, rooting depth and root biomass distribution vary among saltmarsh vegetation types and along environmental gradients such as elevation and inundation frequency. However, published studies consistently show that, across dominant temperate saltmarsh species and zones, the majority of fine root biomass is concentrated within the upper ~20–40 cm of the sediment profile, with only limited root penetration below this depth. We have revised the Discussion to acknowledge this variability explicitly and to clarify that fine roots are not entirely separable from the sediment matrix and may contribute to the labile OC signal in surface layers.

These additions are now incorporated at Lines 513 - 517 of the revised manuscript.

Comment 23 In addition, were potential pre-breaching differences in soil properties considered? Such legacy effects could partly explain present-day OC patterns.

Response:

We have revised the Discussion to explicitly consider potential pre-breach (legacy) effects and to clarify pre-breach land use at Paull Holme Strays. Prior to breaching, the site comprised reclaimed agricultural land with broadly uniform land use across the embanked area. We now note that, while pre-breach soil properties may influence early post-restoration trajectories, studies of managed realignment in the Humber Estuary (<https://doi.org/10.1016/j.scitotenv.2016.11.032>) demonstrate that post-breach sedimentation and tidal processes rapidly overprint legacy soil characteristics in this high-sediment, macrotidal setting. Consequently, legacy effects are unlikely to explain the strong and consistent depth-dependent OC patterns observed, which are interpreted as being dominated by post-breach depositional and biological controls. These clarifications are now included in the revised manuscript (Discussion, Lines 501 - 505).

Comment 24 If available, LiDAR data or historical aerial imagery could provide useful information on vegetation structure, development, and temporal evolution across the study area.

Response:

We agree that LiDAR data and historical aerial imagery can provide valuable insights into vegetation structure, extent, and temporal development in restored coastal wetlands. However, while LiDAR data were available for assessing elevation change at Paull Holme Strays, these datasets were not suitable for analysing vegetation structure or composition due to limitations in point- cloud classification, canopy penetration, and temporal consistency for vegetation metrics. Similarly, historical aerial imagery was not available at sufficient spatial resolution or temporal frequency to support robust vegetation mapping across the study period.

Vegetation surveys or remote- sensing- based vegetation analyses were not incorporated into the original sampling design, and accordingly our analysis focuses on sedimentary processes and depth- resolved OC patterns rather than vegetation dynamics. Instead, vegetation effects are considered indirectly through elevation- related processes, which are explicitly acknowledged in the Discussion.

Comment 25 The sharp decline in labile OC below ~40 cm is interpreted primarily in terms of remineralisation. However, it would be valuable to consider whether this depth also corresponds to the typical rooting zone of the dominant vegetation. Distinguishing between loss of labile OC due to post-depositional remineralisation and reduced fresh root inputs with depth would strengthen the interpretation of the vertical profiles.

Response:

We agree with the reviewer that both post-depositional remineralisation and depth-dependent reductions in fresh root inputs are likely to influence the observed vertical patterns of labile OC. The Discussion has been revised to explicitly incorporate rooting depth alongside remineralisation processes. We now note that the ~40 cm breakpoint coincides with the depth range over which the majority of fine root biomass is reported for temperate saltmarsh vegetation, and with the lower boundary of the biologically active root zone under conditions of persistent saturation. We also clarify that, despite coarse root removal, fine roots are not readily separable from the sediment matrix and may contribute to the labile OC signal in surface sediments. Below ~40 cm, both reduced fresh root inputs and progressive post-depositional degradation during burial contribute to the sharp decline in labile OC, while recalcitrant and mineral-associated fractions are preferentially preserved at depth. These amendments are now included in the revised manuscript (Discussion, Lines 513 - 517).

Comment 26 The inclusion of a natural saltmarsh reference site is commendable. However, given that both saltmarsh and mudflat habitats are analysed within the managed realignment area, it would be useful to clarify whether natural mudflat reference sites were considered. Such comparisons could help disentangle restoration-stage effects from habitat-specific carbon dynamics.

Response:

We agree that comparison with natural mudflat reference sites would provide valuable additional context for distinguishing restoration- stage effects from habitat- specific carbon dynamics. Unfortunately, due to access restrictions on the seaward intertidal zone immediately outside the managed realignment site, it was not possible to obtain external natural mudflat cores during the period of this study. Consequently, mudflat OC patterns within the managed realignment area were interpreted relative to internal elevation and sedimentation gradients rather than against an external mudflat control.

While this limits direct comparison with natural mudflats, the internal gradient approach still allows us to resolve habitat- related differences in OC dynamics across mudflat- to- marsh transitions within the restored system. We recognise the added value of external natural mudflat references, and incorporating accessible mudflat control sites will be a priority for future work aimed at separating restoration trajectory effects from broader intertidal habitat controls.

Comment 27 The discussion rightly notes the importance of allochthonous sediment inputs in rapidly accreting zones. However, the potential influence of OC source characteristics on fraction stability deserves more explicit consideration. For example, could imported (allochthonous) OC already be partially stabilised and therefore relatively more recalcitrant?

Response:

We agree that allochthonous OC delivered via suspended sediment may already contain a mixture of thermally labile and thermally recalcitrant material, and some fraction of this imported OM may be partially stabilised prior to deposition. However, because we did not measure OC source (e.g., isotopes, biomarkers), we cannot distinguish stabilised allochthonous inputs from autochthonous contributions within the thermal fractions. Our interpretation therefore remains based solely on the observed depth- dependent patterns in thermally labile and recalcitrant OM.

Comment 28 To what extent might differences in OC source explain variation in labile vs. recalcitrant fractions across elevations?

Response:

Differences in OC source may contribute to variation in thermally labile and recalcitrant fractions across elevations; for example, low- elevation zones receiving mainly allochthonous suspended sediment may introduce OC with different thermal characteristics than vegetation- driven inputs at higher elevations. However, because OC source was not quantified, we cannot partition thermal fractions by origin. As such, we interpret fraction patterns in relation to measured depth profiles and site hydrodynamics, rather than attributing them to specific OC sources.

Comment 29 Relatedly, it would be appropriate to acknowledge that allochthonous OC inputs may not necessarily represent net carbon sequestration at the system scale, but rather redistribution of carbon within the broader estuarine environment. Even a brief discussion of this accounting issue would improve conceptual clarity, particularly in the context of blue carbon assessment and its implication for carbon crediting.

Response:

We agree with this point and have added a short clarification in the Discussion acknowledging that allochthonous OC inputs represent redistribution of carbon within the broader estuarine system rather than guaranteed net carbon sequestration at the system scale. We now explicitly state that our estimates quantify sedimentary OC accumulation and burial, not net atmospheric CO₂ removal. This distinction improves conceptual clarity for blue- carbon assessment and ensures that site- scale accumulation rates are interpreted appropriately in the context of carbon accounting and potential crediting frameworks.

Revision: Line 539 - 544:

“For this reason, we emphasise that the values reported here represent sedimentary OC burial rather than net sequestration from the atmosphere. Our results therefore characterise the persistence and vertical distribution of OC irrespective of origin, while acknowledging that the accounting relevance of allochthonous versus autochthonous pools depends on the specific framework applied.”

Comment 30 The manuscript states that the combination of high-resolution sampling, elevation stratification, and fraction-specific depth analysis “disentangles short-term turnover from longer-term carbon preservation” and clarifies a pattern “previously unexplained” in managed realignment systems. While the dataset is indeed exceptional in resolution and scope, the degree of conceptual novelty could be more carefully framed.

Response:

Thank you for this thoughtful suggestion. We agree that the conceptual framing should avoid implying that the processes described here are entirely novel. Rather than identifying a new mechanism, the contribution of this study lies in empirically resolving patterns that have been previously hypothesised or inferred from lower- resolution observations but not explicitly demonstrated with full- depth, elevation- stratified, and fraction- specific datasets.

We have therefore revised the Discussion to clarify that our findings provide high- resolution empirical confirmation of established conceptual expectations: namely, that rapidly accreting zones tend to accumulate volumetrically important but carbon- poor sediments; while more slowly accreting, vegetation- rich zones accumulate thinner but carbon- dense deposits. Our results show how these contrasting pathways can yield similar annual OC accumulation rates, a pattern noted in previous studies but not previously quantified across full sediment profiles at this spatial and vertical resolution. We have adjusted the wording accordingly to reflect this refinement in emphasis.

Revision: Line 620 – 625:

“Our findings provide high-resolution empirical confirmation of the linkages between elevation, sedimentation rate, and OC quality in structuring carbon storage within restored intertidal systems. These results are consistent with ecogeomorphic models, in which elevation determines inundation regime, inundation governs hydrodynamic energy and sediment supply, and vegetation development subsequently reinforces feedback between elevation and sediment accretion [69, 77].”

Comment 31 The empirical identification of a “dynamic surface layer” is potentially useful, however, the concept of an “Evidence-Based Surface Depth for OC Analysis” would benefit from clearer definition and justification. For example, is this depth expected to be transferable to other restored sites? Does it depend on sedimentation rate, vegetation type, or site age? A more explicit conceptual explanation of how this threshold should be interpreted and applied would enhance its practical and theoretical value.

Response:

Thank you for this insightful comment. We agree that clearer definition and conceptual justification of the evidence-based surface depth would strengthen the manuscript. We have therefore expanded the Discussion to clarify that the identified ~40 cm dynamic surface layer represents a process-based, site-specific threshold, rather than a universally applicable depth. We now explicitly emphasise that the position of this dynamic surface

layer is expected to vary among restored saltmarshes depending on sedimentation rate, vegetation development, and time since restoration, and should be interpreted as the depth below which sediments transition from biologically active, rapidly cycling OC to burial-dominated, longer-term carbon storage.

To address application beyond this site, we clarify that this threshold is intended to provide a conceptual framework for interpreting vertical OC dynamics, rather than a prescriptive sampling depth transferable across all restored sites. Its value lies in guiding the identification of comparable dynamic surface layers in other systems, based on site-specific sedimentation and ecological context.

Revision: Line 626 - 632:

“By pairing near unprecedented sampling resolution with elevation stratified cores and depth resolved OC fractionation, we identified a ~40 cm dynamic layer within which biological inputs, rooting depth, and oxygen availability drive high variability and rapid cycling of labile OM, and below which persistent saturation and burial processes favour the preservation of recalcitrant and mineral associated carbon. This distinction explains how contrasting combinations of accretion and OC density can yield similar burial rates, a pattern frequently reported but rarely resolved.”

Specific comments

- Figure 1: Please clarify whether the vertical datum is correctly reported as Ordnance Datum Newlyn (ODN). The abbreviation appears inconsistent (ODN vs ODM).

Response:

Thank you for noting this. The correct vertical datum is Ordnance Datum Newlyn (ODN). The appearance of “ODM” was a typographical error, which has now been corrected in Figure 1 and the accompanying text.

Comment Line 107: There appears to be a typographical error (semicolon after “for”).

Response:

We have removed the unnecessary semicolon to improve clarity.

Comment Line 140: A full stop appears to be missing at the end of the sentence.

Response:

A full stop has now been added to the end of the sentence.

Comment Line 182: “using the graphical method of Folk and Ward [37] graphical method...”

There is a repetition (“graphical method”).

Response:

Repetition removed from manuscript.

Comment Line 182 Additionally, the authors state that grain-size analysis was conducted using a Malvern Mastersizer 2000, but statistical parameters were calculated using Gradistat. As the Mastersizer software provides grain-size statistics directly, could the authors clarify why Gradistat was used?

Response:

The Malvern Mastersizer 2000 software provides grain- size distributions and some basic descriptive statistics; however, it does not calculate Folk & Ward graphical parameters, which remain standard in sedimentology for comparability with previous studies. To maintain consistency with widely used sedimentary classification approaches, we exported the raw grain- size distributions from the Mastersizer and applied the Folk & Ward graphical method using GRADISTAT. This allowed us to compute mean, sorting, skewness, and kurtosis on the phi scale following the established procedure described in Folk & Ward (1957).

Comment Lines 222–225: The methodological description would benefit from an additional reference to support or contextualise the robustness of the approach.

Response:

We have added an additional reference to support the use of thermogravimetric analysis (TGA) for partitioning labile and recalcitrant organic carbon in coastal sediments. The revised text now cites established applications of TGA for distinguishing thermally labile and more stable organic matter fractions (<https://doi.org/10.1007/s10933-021-00209-6> and <https://doi.org/10.3390/f14071469>), thereby strengthening the methodological context. The paragraph has been updated accordingly (lines 267-279).

Comment Lines 323–324: “Models confirmed elevation (as of 2022) and depth (change in elevation since restoration) were the primary controls on OC content”. The definition of “depth” is unclear here. In this sentence, depth appears to refer to change in elevation since restoration (i.e., accumulated sediment thickness), whereas elsewhere in the manuscript it seems to refer to depth below the present sediment surface. Please clarify terminology and ensure consistent usage throughout the manuscript to avoid confusion.

Response:

Thank you for highlighting this ambiguity. In our analysis, this variable refers to the thickness of sediment accumulated since the 2003 breach (i.e., post- restoration sediment thickness), rather than depth below the present- day surface. Because pre- restoration topography was

heterogeneous, elevation change since restoration does not directly map to present- day surface elevation.

We agree that the phrasing “depth (change in elevation since restoration)” in Lines 390-391 was unclear and potentially misleading. We have therefore revised the text to refer explicitly to “post- restoration sediment thickness (i.e., the depth of sediment accumulated since restoration, 2003–2022)” and removed the ambiguous parenthetical. Throughout the remainder of the manuscript, the term “depth” is now used consistently to refer only to core depth below the present sediment surface, ensuring clear and consistent terminology.

Comment Figure 3: For improved comparability, it may be helpful to use the same OC% scale for both restored habitats and the reference station. A consistent axis range would facilitate direct visual comparison.

Response:

Thank you for this suggestion. We agree that consistent axis ranges can often aid comparison; however, the reference station exhibits a wider range in OC% values than the restored habitats. Standardising the axis across panels would compress the variability in the reference data and obscure important differences in its vertical profile. For this reason, we have retained the original axis scaling to accurately represent the observed variation.

Comment Line 390 and associated paragraph (dynamic surface layer ~40 cm): The section describing the identification of a ~40 cm “dynamic surface layer” is presented as central to the manuscript, yet the concept of an “Evidence-Based Surface Depth for OC Analysis” remains somewhat unclear. Although the segmented regression analysis appears to support the breakpoint statistically, the conceptual framing and practical implications of this threshold would benefit from clearer explanation.

Response:

We agree that further clarification of the evidence- based surface depth and its conceptual basis would improve the manuscript. We have revised the text to more clearly explain (i) the empirical criteria used to identify the dynamic surface layer, (ii) how these indicators converge around ~40 cm, and (iii) the practical purpose of defining this depth. We have also clarified that the segmented regression breakpoint supports, rather than solely determines, this depth threshold. Revision to the results and discussion now provides stronger conceptual framing and clearer explanation of its relevance.

Revision: Results Line 474-488

“Independent empirical criteria converged on a dynamic surface layer near ~40 cm, defined here as the depth interval dominated by active OC turnover. This depth interval corresponds to the depth of greatest variability in sediment properties, the depth at which labile OM stabilised, and the layer encompassing ≥90% of cumulative OC (Figure 6a). To validate this empirically derived estimate, segmented regression was applied to the aggregated labile-OM profile (Figure 6b), identifying a breakpoint at 40.5 cm (95% CI: 38.4–42.7 cm) (Figure 6b). This breakpoint reflects the transition from a rapid decline in thermally labile OM in the upper sediments, to a slower rate of change in deeper layers (Figure 6b). This closely aligns with the empirical estimate and supports ~40 cm as a representative, site-specific ‘dynamic surface layer’ for consistent comparison across the site, while illustrating an evidence-based approach to identifying functionally comparable surface layers in other restored intertidal systems.”

Revision: Discussion Line 626 - 639:

“By pairing near unprecedented sampling resolution with elevation stratified cores and depth resolved OC fractionation, we identified a ~40 cm dynamic layer within which biological inputs, rooting depth, and oxygen availability drive high variability and rapid cycling of labile OM. Below this layer, persistent saturation and burial processes favour the preservation of recalcitrant and mineral associated carbon. This distinction explains how contrasting combinations of accretion and OC density can yield similar burial rates, a pattern frequently reported but rarely resolved.

Furthermore, by demonstrating the limitations of constant-density Tier 1 defaults, these results advocate for stratified, depth-resolved Tier 2 methodologies that account for tidal elevation and sedimentation history. Integrating long-term topographic data with detailed geochemistry addresses longstanding uncertainties regarding the vertical structure and persistence of organic carbon. Together, these advances strengthen the scientific foundation for standardised monitoring and accounting in coastal restoration projects.”

Comment Lines 409–428 (comparisons with other sites): The comparative discussion with other managed realignment sites is interesting and potentially valuable. However, for consistency and interpretability key contextual parameters (e.g., tidal range, suspended sediment concentration) should also be explicitly reported for the present study site. In addition, where possible, comparisons across sites should be standardised (e.g., consistent units for sediment concentration, consistent reporting of tidal range for all sites mentioned).

Response:

We have revised the comparative section to ensure clear and consistent reporting of key contextual parameters across sites. Specifically, we now explicitly report tidal range and suspended sediment concentrations for the

Humber Estuary, the present study site. We have also standardised all sediment concentration units to mg L^{-1} for comparability (Lines 555 - 570). These revisions improve interpretability and consistency across cross-site comparisons. The paragraph has been updated accordingly.

Comment Line 453: “While the long-term fate of this initial influx has previously been uncertain”. The sentence appears incomplete if standing alone. It should be linked to a main clause. Please verify sentence structure.

Response:

We have revised the text to correct the structure and improve clarity.

Revised sentence 505 – 508:

“The long-term fate of this initial influx has previously been uncertain. Our depth-resolved analysis revealed a sharp decline in labile OM below ~40 cm (Figure 6), confirmed by segmented regression (breakpoint at 40.5 cm, 95% CI: 38.4–42.7).”

Reviewer #3 (Remarks to the Author):

Burrell et al. “Buried Potential? Evaluating Long-Term Sequestration in a Restored Intertidal Habitat” reports on research focused on a realigned saltmarsh in the Humber estuary. The sampling resolution is extremely high and allows the site to be investigated at an unprecedented resolution.

The data set is highly impressive but their issues that require resolving prior to publication.

Response:

We thank the reviewer for their constructive assessment of our manuscript and for acknowledging the strength of the dataset and sampling resolution. We appreciate the clear identification of issues requiring attention, and we have addressed each point carefully. Individual responses to all comments are provided below.

My main concerns are methodological.

Comment 32 TGA analysis is a mass loss measurement so does not measure carbon rather it is a proxy for Organic Matter. The authors combine the TGA data with the bulk OC data this is not possible. Text is required to clearly state. For this section I strongly suggest you discuss the TGA data as OM (Labile, recalcitrant and total).

Response:

Thank you for highlighting this important methodological point. We agree that TGA quantifies mass loss associated with thermally decomposed

organic matter (OM), rather than directly measuring organic carbon (OC). In the revised manuscript, we now describe TGA- derived fractions explicitly as thermally labile OM and thermally recalcitrant OM and clarify that these represent proxies for OM stability rather than direct carbon measurements. We also make clear that these fractions are expressed relative to the total OM detected by TGA, not to elemental OC concentrations. Text throughout the Methods and Results has been updated accordingly to avoid implying that TGA partitions carbon itself. We further clarify that “labile” and “recalcitrant” refer specifically to thermal lability as determined by TGA heating ranges. These revisions ensure correct interpretation of the TGA data and alignment with the reviewer’s concerns (lines 267-279). Additionally Figures 2 and 6 have been amended.

Comment 33 Additionally, when discussing lability make clear it is thermal.

Response:

Thank you for this clarification. We have revised the manuscript to explicitly refer to thermally labile and thermally recalcitrant OM throughout the text, rather than using “labile” or “recalcitrant” in isolation. This change ensures that lability is clearly defined in terms of the thermal fractionation approach employed in this study (Specifically lines 19, 21, 268, 274, 276, 278, 429, 430, 436, 440, 447, 448, 477, 482, 498, 507, 509, and 629).

Comment 34 For the accretion data the readers need to understand the errors involved in the approach. What is the vertical accuracy of the Lidar?

Response:

We agree that uncertainty associated with the LiDAR- derived accretion data should be made explicit. We now report the vertical accuracy of the LiDAR datasets (root- mean- square error of $\pm 15\text{--}20$ cm) and describe how stability was assessed using RTK- GNSS benchmark plates. These clarifications have been added to the Methods section to improve transparency (lines 131-139, and 332-346).

Comment 35 Has this changed through the years.

Response:

To improve context around the timing of accretion, we have now included a concise description of year- on- year elevation change in the Results and added a cumulative elevation- change map (Supplementary Fig. S2). This shows rapid infilling immediately post- breach followed by slower, spatially variable accretion, information now cross- referenced in the Discussion to link elevation dynamics to OC depth patterns. These revisions collectively improve

transparency around LiDAR accuracy, temporal stability, and the elevation- change context that underpins our interpretation of OC accumulation.

Results (Line 331-336, revised text):

“Temporal patterns show rapid accretion immediately following the 2003 breach, with substantial elevation increases during the first four years (Supplementary Fig. S2). Accretion continued throughout the 19-year period but at slower and more spatially variable rates (11–250 cm). Accretion was strongly associated with initial pre-restoration elevation (GAM: adjusted $R^2 = 0.78$, deviance explained = 81.3%; edf = 7.16, $F = 8.71$, $p < 0.001$): low initial elevations exhibited both higher rates and greater spatial variability in sediment deposition, where elevation gains ranged from 40 to 250 cm. The largest gains occurred near the western breach (Figure 1b), where adjacent low-lying areas accumulated sediment rapidly, consistent with site morphology and greater tidal exposure. In contrast, areas with higher initial elevations, particularly near the new sea wall at the back of the marsh, showed the lowest elevation gains, ranging from 11 to 79 cm. This progression of rapid early infill followed by slower, spatially heterogeneous deposition provides important context for interpreting both OC accumulation and the transition from labile to recalcitrant OC with depth.”

Comment 36 Overall how does the error propagate through the stock calculations?
Response:

We agree that error propagation is an important consideration. Uncertainty in OC stock estimates arises primarily from LiDAR- derived sediment thickness and variability in OC density. Although fixed- elevation benchmarks were not present during the initial 2003–2022 period, we subsequently installed fifteen buried aluminium benchmark plates in 2023 as part of a long- term monitoring programme. These plates were surveyed using RTK- GNSS (± 1 –2 cm), and LiDAR- derived elevations extracted for these control points from the 2024 and 2025 datasets differed by -2 to $+2$ cm, well within the reported RMSE. While installed after the primary study period, they demonstrate strong temporal consistency in LiDAR elevations and support the reliability of the historic elevation- change estimates.

To improve context around the timing of accretion, we have now included a concise description of year- on- year elevation change in the Results and added a cumulative elevation- change map (Supplementary Fig. S2). This shows rapid infilling immediately post- breach followed by slower, spatially variable accretion—information now cross- referenced in the Discussion to link elevation dynamics to OC depth patterns. These revisions collectively improve transparency around LiDAR accuracy, temporal stability, and the elevation- change context that underpins our interpretation of OC accumulation.

Revisions:

Methods (Line 130-139 revised text):

“The Environment Agency reports a vertical RMSE (Root Mean Square Error) of $\pm 15\text{--}20$ cm for all LiDAR surveys used in this study, referenced to Ordnance Datum Newlyn (ODN). Fixed-elevation benchmarks were not present during the original study period; however, as part of a subsequent long-term monitoring programme, fifteen aluminium benchmark plates were installed in 2023 and surveyed using RTK-GNSS ($\pm 1\text{--}2$ cm accuracy). Elevations extracted for these locations from the 2024 and 2025 LiDAR surveys differed by -2 to $+2$ cm (Supplementary Table S1), confirming inter-year vertical consistency well within the published RMSE. LiDAR surveys are conducted during Low Water Spring tides to ensure maximum sediment exposure and minimise elevation bias from surface water or tidal stage.”

Results (Line 331-336, revised text):

“Temporal patterns show rapid accretion immediately following the 2003 breach, with substantial elevation increases during the first four years (Supplementary Fig. S2). Accretion continued throughout the 19-year period but at slower and more spatially variable rates (11–250 cm). Accretion was strongly associated with initial pre-restoration elevation (GAM: adjusted $R^2 = 0.78$, deviance explained = 81.3%; edf = 7.16, $F = 8.71$, $p < 0.001$): low initial elevations exhibited both higher rates and greater spatial variability in sediment deposition, where elevation gains ranged from 40 to 250 cm. The largest gains occurred near the western breach (Figure 1b), where adjacent low-lying areas accumulated sediment rapidly, consistent with site morphology and greater tidal exposure. In contrast, areas with higher initial elevations, particularly near the new sea wall at the back of the marsh, showed the lowest elevation gains, ranging from 11 to 79 cm. This progression of rapid early infill followed by slower, spatially heterogeneous deposition provides important context for interpreting both OC accumulation and the transition from labile to recalcitrant OC with depth.”

Other points

Comment 37 Should carbon be in the title?

Response:

We agree and have revised the title to explicitly include carbon.

Comment 38 I would like to see comparison of the C stock, density, accumulation rates to other realigned and natural marshes both globally and in the UK.

Response:

Thank you for this suggestion. The manuscript includes comparisons of carbon stock, density, and accumulation rates with both UK and global restored and natural marshes. In the Discussion, we compare our accumulation rates with managed realignment sites across the UK, including; Orplands, Northey Island, and Tollesbury in the Blackwater Estuary, and Steart Marshes in Somerset, as well as with high- sediment- supply systems such as the Bay of Fundy. We also compare OC densities and depth- resolved patterns with the natural reference marsh sampled for this study (Results: Bulk Density; OC Content and Drivers; Labile/Recalcitrant OM sections), showing that high- elevation MR areas approach natural- marsh characteristics while MR mudflats remain distinct. These existing comparisons situate Paull Holme Strays within the wider context of both restored and natural marsh systems, regionally and internationally.

Comment 39 You mention cores were collected from a nearby natural marsh how do the values compare?

Response:

Thank you for this question. Comparisons between the existing/natural saltmarsh reference site and the MR sediments are already presented in the Results (lines 353-356, 386-389, 409-411, 437-441, figures 2, 3 and 5). Parametric contrasts indicate that OC values in the Reference marsh are closer to those of high- elevation, vegetated MR areas than to Mid or Low MR zones. Finally, recalcitrant OM concentrations are highest in the natural marsh, consistent with its more mature state, whereas MR sediments show lower concentrations. These comparisons are reported in the Results section (Bulk Density; OC Content and Drivers; Labile and Recalcitrant OMC). Together, they demonstrate that the natural marsh most closely resembles the high- elevation, well- vegetated areas of the MR site, while the MR mudflat areas remain distinct due to their earlier successional stage.

Comment 40 The manuscript does not deal with C sequestration rather it OC accumulation or burial. Assure this is clear.

Response:

Thank you for this important clarification. We agree that the manuscript quantifies sediment OC accumulation/burial rather than carbon sequestration in the climate- mitigation sense. We have therefore revised the manuscript to ensure that “accumulation” and “burial” are used consistently when referring to measured sediment OC stocks and rates. The term “sequestration” has been removed or replaced throughout, except when referring more generally to long- term carbon storage potential in a conceptual sense. These revisions ensure that the terminology accurately reflects the measurements undertaken and avoids implying atmospheric CO₂ removal or permanence, which were not quantified in this study. In addition, we now explicitly acknowledge that allochthonous OC may be partially stabilised prior to deposition, which may contribute to the relative recalcitrance of deeper fractions, although OC source and pre- depositional processing were not directly measured. This distinction is now clear in the revised text.

Revisions:

- Line 55 amended to: “...with OC burial shifting over time from deposition of external inputs...”
- Line 83 amended to: “...long- term carbon storage potential...”
- Line 584 amended to: “...in determining long- term carbon burial potential.”

Comment 41 Lastly, I would like to see greater discussion on the sediment movement. The results highlight that the main mechanism for accretion is the movement of sediment from the intertidal flats or from the river into the marsh. The carbon in this sediment has been sequestered in other environments and the marsh site is acting as a depositional zone. This carbon would likely have been remineralized in these other environments so by storing it the marsh is providing a climate regulation service, but it is not the same a sequestration from the atmosphere.

Response:

Thank you for raising this important point. We agree that much of the sediment delivered to the MR site contains allochthonous organic matter that has been sequestered elsewhere in the estuary and is being redistributed rather than newly fixed from the atmosphere. We also agree that the climate- regulation benefit arises from enhanced burial of material that may otherwise have been remineralised. We discuss fully in our responses to Comments 27–29 and, in summary, we now make this distinction explicit in the

Discussion, where we note that our estimates represent sedimentary OC accumulation rather than system- level atmospheric CO₂ sequestration. We also clarify that allochthonous OM may already have undergone partial degradation during transport, and that our interpretation focuses on observed depth- resolved patterns rather than attempting to partition pre- versus post- depositional remineralisation. These clarifications address the nuances of sediment movement and biodegradation highlighted in your comment.

Comment 42 Additionally, the movement of this sediment will also be degrading the OC. Discussion of the nuances is vital to this study.

Response:

Thank you for this comment. We agree that sediment transported into the site is likely to experience some degree of organic matter degradation prior to deposition, and that this is an important nuance when interpreting labile versus recalcitrant fractions. We address this point in our discussion of OC source characteristics (Comments 27–29), where we note that allochthonous OM may already be partially decomposed before entering the MR site and that our depth- resolved results therefore reflect both pre- depositional and post- depositional remineralisation. Because we did not quantify OC source or measure in- transit degradation directly, our interpretation focuses on the observed thermal fraction patterns and their depth trajectories, rather than attributing specific proportions of labile OM loss to transport versus in- situ processes. We have ensured this limitation is clearly stated in the Discussion so that the nuances of OC degradation during transport and burial are transparent to readers.

Line by Line (typos and grammar)

Introduction

Comment Line 32-34 Maxwell et al. 2024 calculated that the global store is estimated to be 1.44 Pg. This work is the best constrained global figure.

<https://doi.org/10.1038/s41467-024-54572-9>

Response:

Thank you for this helpful suggestion. We have updated the global estimate of saltmarsh carbon stocks in the Introduction (line 38) to incorporate the recent assessment by Maxwell et al. (2024).

Comment Line 49: “Following tidal reinstatement, rapid deposition of allochthonous carbon-rich sediment facilitates development” – What is carbon rich in this context?

Response:

We have clarified what is meant by “carbon- rich” in this context. Here, the term refers to fine allochthonous sediments delivered to the site via tidal

exchange, which typically contain appreciable amounts of organic carbon derived from estuarine and riverine sources. We have revised the text to explicitly define this usage and avoid ambiguity.

Revision: Lines 53-57

“Following tidal reinstatement, rapid deposition of allochthonous sediment facilitates marsh development [12], with OC sequestration shifting over time from burial of external inputs to plant- driven autochthonous accumulation as elevation increases [13].”

Methods

Comment Line 107 – 108: The study utilises Lidar data from 2003 – 2022, the horizontal accuracy is state (0.5m) what is the vertical accuracy.

Response:

We agree that the vertical accuracy of the LiDAR data should be explicitly stated. The LiDAR datasets used in this study have a reported vertical root- mean- square error (RMSE) of approximately $\pm 15\text{--}20$ cm, consistent with Environment Agency specifications for coastal LiDAR surveys. We have now added this information to the Methods section and clarified how vertical accuracy was accounted for in interpreting elevation change. Additional detail on LiDAR accuracy, temporal consistency, and validation using RTK- GNSS benchmarks is provided in our response to Comment 36.

Comment Line 108 – 109: Do you account for timing in the tidal cycle. You mention the issue with seasonal dewatering the same can occur depending on the point in the tidal cycle you measure.

Response:

We agree that both LiDAR-derived elevations and sediment properties can be influenced by the timing of measurement within the tidal cycle. LiDAR surveys were conducted at Low Water Spring tides following Environment Agency specifications, minimising elevation bias from surface water. In addition, all sediment cores were collected during low-tide conditions to minimise variability associated with tidal inundation or short-term sediment dewatering.

Revision:

Lines 180-182

“ All sediment cores were collected during low-tide conditions to minimise variability associated with tidal inundation or short-term sediment dewatering”

Lines 137-139

“LiDAR surveys are conducted during Low Water Spring tides to ensure maximum sediment exposure and minimise elevation bias from surface water or tidal stage.”

Comment Line 157: A core compaction correction factor was applied if the compaction was <2 cm. State how this was done, the methodology in Howard et al. does not work if there are multiple units in the soil profile as you don't know the compaction across the different units.

Response:

We acknowledge that core compaction is not necessarily distributed uniformly across sedimentary units and that the approach described by Howard et al. (2014) may introduce uncertainty where multiple stratigraphic units are present. In this study, compaction correction was applied only where total compaction represented a small proportion of the recovered core length ($\leq 2-3\%$, depending on core length), corresponding to absolute compaction values ≤ 2 cm. Under these conditions, compaction was corrected by linearly redistributing the measured compaction across the full core length, such that all depth intervals were adjusted proportionally.

Because compaction magnitudes were substantially smaller than the 5 cm sampling resolution, this linear correction does not alter unit boundaries or result in vertical reassignment of samples between sub- sections. No attempt was made to partition compaction among individual sediment units, as such redistribution cannot be resolved reliably at this scale. Given the small magnitude of compaction relative to sampling resolution, the applied correction minimises depth bias without introducing artefacts and has negligible influence on the depth- resolved OC patterns reported here.

Comment Line 157 Could soil profile be added to the supplementary material to confirm this is not an issue. There is growing body of work on this:

- <https://doi.org/10.1007/s40641-016-0038-6>
- <https://doi.org/10.1016/j.geoderma.2020.114180>

Response:

We agree that soil- profile documentation can be useful for transparent evaluation of compaction and stratigraphic integrity, as highlighted in recent studies. During field sampling and core sectioning, all cores were visually inspected for evidence of stratigraphic disturbance, smearing, or collapse.

Total compaction was minimal (≤ 2 cm) and consistent across cores due to sampling method.

Representative photographs of selected cores were taken during processing; however, given the large number of cores collected and the very small magnitude of compaction relative to the 5 cm sampling intervals, systematic photographic documentation of every core was not undertaken. Because no unit- scale distortion was evident and compaction was well below sampling resolution, we did not consider inclusion of partial photographic profiles necessary to validate the applied correction.

We recognise the growing body of work highlighting the value of detailed profile documentation in studies where compaction or lithological contrasts are substantial and agree that such material is particularly important when larger deformation or unit- specific corrections are required. In the present study, we therefore explicitly acknowledge this limitation and justify our correction approach based on the observed minimal compaction and consistent sediment structure.

Comment Line 174: The OM fraction was removed, was there carbonate material in the sediments and if so, why did you choose not to remove it.

Response:

Carbonates were not removed during the grain size analysis for two primary reasons. First, previous studies in the Humber Estuary indicate that the minerogenic fraction is dominated by fine silts and clays with very low carbonate content, typically originating from the erosion of Holderness cliffs. Second, we chose not to acid-treat the samples to avoid the potential 'pseudosand' effect, where secondary calcium carbonate can act as a cementing agent; removing it can artificially alter the natural grain size distribution. This approach ensures the reported grain size reflects the hydrodynamic conditions at the time of deposition.

Comment Line 197 – Do you ever use the IC data if not remove the text.

Response:

Yes, the IC data are required and are used in the calculation of organic carbon content. Specifically, organic carbon (OC %) is calculated by subtracting inorganic carbon (IC %) from total carbon (TC %) for each sample. As IC is an essential part of this calculation, we have retained this text.

Comment Line 214 – 227: TGA analysis does not measure organic carbon, it is a measure of OM you cannot compare the Labile and recalcitrant data to the total OC.

Response:

We agree with this point and clarify that thermogravimetric analysis (TGA) quantifies organic matter fractions based on mass loss over defined temperature ranges, rather than measuring organic carbon directly. In the revised manuscript, we make explicit that labile and recalcitrant fractions derived from TGA represent relative organic matter pools, and that these fractions are interpreted in relation to depth- resolved OC patterns rather than directly compared quantitatively to absolute total OC concentrations. We have revised the text to avoid implying equivalence between TGA- derived organic matter fractions and total organic carbon. For more detail please see response to comment number 32 and 33.

Comment Line 214 - 227 Additionally TGA is a proxy measurement of lability, when discussing it make sure you highlight it is thermal lability being discussed not biological.

Response:

We agree and have revised the manuscript to consistently specify that the labile and recalcitrant fractions identified by TGA represent thermal lability, rather than biological or biochemical lability. This clarification is now made explicit wherever TGA- derived fractions are discussed, ensuring that lability is clearly framed as a proxy based on thermal decomposition behaviour, not direct biological availability. For more detail please see response to comment number 32 and 33.

Comment Line 214 – 227: Reference Capell et al., 2006 (<https://doi.org/10.1016/j.orggeochem.2006.07.025>), Smeaton and Austin, 2022 (<https://doi.org/10.1029/2021GL097481>)

Response:

We thank the reviewer for these references. Our methodology has been updated with a current best practice journal article for defining thermally labile vs recalcitrant OM using the same temperature steps used in this study

<https://doi.org/10.1007/s10933-021-00209-6> and <https://doi.org/10.3390/f14071469>.

Results

Comment Lines 273 – 284: Errors need to be reported here, what is the vertical resolution of the lidar?

Response:

We agree that uncertainty associated with the LiDAR- derived elevation change should be explicitly stated in the Results. We have now clarified that the airborne LiDAR datasets used in this study have a reported vertical root- mean- square error (RMSE) of approximately $\pm 15\text{--}20$ cm. This

information has been added to the Results section to provide appropriate context for the reported elevation- change magnitudes. Further details on LiDAR accuracy, inter- annual consistency, and validation using RTK- GNSS benchmarks are provided in our response to Comment 36.

Comment Lines 285 – The sediment properties section is overloaded with stats could these be placed in a table or in the sup mat to improve readability.

Response:

We agree that the Sediment Properties section contains a high density of statistical detail, which can reduce readability for a multidisciplinary audience. In fact, full statistical outputs for these analyses are already consolidated in Supplementary Table 2, which summarises all GAM results (edf, F- statistics, p- values, and depth- trend descriptors) for bulk density, grain size, and textural fractions across elevation bands. To improve clarity in the main text, we have streamlined the Results section to focus on the principal spatial and depth- related patterns, while explicitly directing readers to Supplementary Table 2 for full statistical details. This approach retains complete transparency while improving readability.

Revision lines 349-380:

“Bulk density, grain size, and sand–silt–clay composition exhibited significant spatial variation across elevation bands and non- linear trends with depth across the site (Figure 2; full GAM outputs in Supplementary Table 21). Bulk density was lowest at Low and Mid elevations (median = 0.88 and 0.98 g cm⁻³, respectively) and highest at High elevations (median ± SE = 1.01 ± 0.07 g cm⁻³), with no significant difference between High elevations and the reference station (Figure 2a). Across all elevation bands, bulk density declined non- linearly with depth, with the highest values occurring in the upper ~10–15 cm of High- elevation cores and consistently lower densities at depth.

Grain size and textural composition showed contrasting spatial and vertical patterns (Figure 2b–d). Low- elevation sediments were coarser (median = 9.36 μm) than those at High elevations (median = 7.43 μm), with the coarsest material concentrated in the upper ~10 cm of Low- elevation cores. Grain size decreased with depth across all elevations, with the strongest depth- related variation observed at Mid elevations (range = 5.1–11.3 μm). Textural fractions reflected these trends: Low elevations were characterised by higher silt content (~86 %) and lower clay (~9 %), whereas High elevations

contained higher clay fractions (~14 %), with Mid elevations intermediate (~10 %). Full statistical support for these patterns, including elevation contrasts and depth- related non- linearities, is provided in Supplementary Table 2.

Depth- dependent non- linear patterns indicate rapid changes in sediment properties within the upper layers, transitioning to more stable conditions below ~30–40 cm. With increasing depth, Mid- elevation sediments increasingly resemble those at lower elevations, particularly in grain size, whereas High- elevation cores remain more distinct, retaining higher bulk density and finer textures (Figure 2c–d). This pattern suggests that deeper Mid- elevation sediments may represent older deposits formed under hydrological conditions similar to those currently observed in lower- lying areas.”

Discussion

Comment Throughout the manuscript make sure accumulation and burial and sequestration are used interchangeable. The manuscript is discussing accumulation/burial not sequestration.

Response:

We agree with this comment and have revised the manuscript to ensure consistent usage of terminology throughout. Specifically, we now use “accumulation” and “burial” when referring to measured increases in sedimentary organic carbon within the system and avoid using “sequestration” except where explicitly discussing accounting frameworks or conceptual distinctions. Where the term “sequestration” was previously used inappropriately, it has been replaced or clarified to reflect sedimentary OC accumulation/burial rather than net atmospheric CO₂ removal. These revisions align the Discussion with the scope of the data presented and are consistent with our response to Comment 40.

Response to Reviewers

We thank the three reviewers for the positive comments and constructive feedback. We have numbered the comments from the reviewers and provide detailed responses and descriptions of the revisions we have made.

Reviewers' comments:

Reviewer #1 (Remarks to the Author):

The authors have responded fully to three rigorous reviews. I have no further comments.

Response: We thank the reviewer for their positive assessment of the revised manuscript.

Reviewer #2 (Remarks to the Author):

I would like to thank the authors for their replies to the reviewers' comments and for their efforts to improve the manuscript.

After reviewing the revised version, I still have a few comments and suggestions to strengthen the manuscript.

Comment 1: Lines 231–232: Is this statement incomplete?

Response: We thank the reviewer for highlighting this point. The original wording was potentially unclear regarding how the inorganic carbon content of the original sediment sample was derived from the elemental analyser measurement of the ash fraction. We have revised the text to clarify that the measured carbon content of the ash was scaled according to the ratio of ash weight to original dry sample weight before calculating organic carbon content by difference.

Lines 212-214 “The inorganic carbon content of the original sample was then calculated by scaling the measured ash carbon content according to the ratio of ash weight to original dry sample weight. Organic carbon content (%) was subsequently determined by subtracting inorganic carbon from total carbon.”

Comment 2: I found the comparison with the “Tier 1” stock calculation based on literature mean C density interesting. I was wondering whether it would also be possible to estimate a value using the mean derived from a smaller subset of cores collected at the study site, perhaps selected according to different criteria. This could help demonstrate the robustness of the study's conclusions and support the idea that a smaller number of samples, combined with a carefully designed sampling strategy, may still provide comparable results (see Lines 242–245 and Lines 566–571).

Response: Thank you for this suggestion. We agree that identifying the optimum sampling effort required to produce carbon stock estimates comparable to those presented here would provide valuable insight into the robustness of the study's conclusions. Such an analysis could also help determine whether a smaller number of samples, combined with a carefully designed sampling strategy, can generate reliable site-scale estimates, thereby informing more efficient future monitoring programmes. However, robustly addressing this question would require substantial additional analyses, including the evaluation of multiple subsampling approaches, sample sizes, and selection criteria across sites. The amount of work required to undertake this assessment is beyond the scope of the present manuscript. To acknowledge this important point, we have added text to the Discussion highlighting the need for future research to determine the minimum sampling effort required for reliable carbon stock estimation. This topic is currently being investigated as part of a separate study and is intended to form the basis of a standalone manuscript.

Comment 3: Line 287: This paragraph seems somewhat redundant with the explanation already provided in Lines 238–242.

Response: We thank the reviewer for this observation. We agree that aspects of this paragraph repeated methodological details already described in the "Calculation of organic carbon stock and Tier 1 comparison" section. To improve conciseness, we have revised the text to focus on the bootstrap uncertainty analysis and refer readers to the earlier methodological description of stock and accumulation calculations.

Comment 4: Figure S2: In my opinion, the colour scale used in the figure is not very intuitive. For consistency, could the same colour scale used in Figure 1 be adopted here as well? In addition, I would suggest indicating the breach location in Figure S1 . It might also be useful to show the initial elevation prior to breaching.

Response: Thank you for this helpful suggestion. Figure S1 has been revised to use the same colour scale as Figure 1 to improve consistency and facilitate comparison between figures. We have also added the breach location to the figure for clarity. While we agree that pre-breach elevation data could provide additional context, we have not included it because no survey was available sufficiently close to the breaching date, and substantial earthworks undertaken prior to breaching significantly altered site topography. Consequently, the available pre-breach data are not representative of conditions immediately prior to restoration and may therefore be misleading.

Comment 5: Lines 389–390: This sentence appears to be interrupted; perhaps there should be a comma instead of a full stop?

Response: We thank the reviewer for highlighting this issue. We agree that the sentence was awkwardly phrased. It has been revised for clarity and now reads: "Models confirmed that elevation (as of 2022) and core depth (representing the depth of sediment accumulated since restoration between 2003 and 2022) were the primary controls on OC content (%)."

Comment 6: Lines 551–553: “Consequently, equal depths sampled across elevations may reflect different depositional conditions, so fixed-depth comparisons should be interpreted with caution”. In this regard, was the possibility of integrating the analyses with facies analysis considered? This could help define different depositional conditions and the related C accumulation dynamics (see, for example, Puppini et al., 2025 <https://doi.org/10.1029/2024JG008327>)

Response: We thank the reviewer for this valuable suggestion. We agree that facies analysis could provide additional insight into depositional environments and their influence on carbon accumulation dynamics, particularly where sedimentary units reflect contrasting hydrodynamic conditions. However, the objectives of the present study were focused on quantifying organic carbon accumulation, preservation and spatial variability using elevation-stratified sampling across the restored site. Sediment facies were not characterised during sample collection and therefore a robust facies-based analysis is beyond the scope of the current dataset. We have nevertheless added text to the Discussion acknowledging facies analysis as a potentially valuable avenue for future research. We have also added the Puppini et al. (2025) reference to strengthen the paper.

Reviewer #3 (Remarks to the Author):

Burrell et al., have dealt with all my concerns and I believe the manuscript to be suitable for publication after a few minor updates.

Comment 7: "sequester" is still used in the text - line 77

Response: We thank the reviewer for identifying this remaining use of the term. To maintain consistency with the distinction between sedimentary organic carbon burial and atmospheric CO₂ sequestration discussed elsewhere in the manuscript, we have replaced "sequester OC" with "accumulate and store OC". Line 64.

Comment 8: Recently I came across Gore et al., 2023, that used TGA analysis in saltmarsh it would be useful to acknowledge this technique being used in other UK marshes - <https://www.sciencedirect.com/science/article/pii/S0272771424000520>

Response: We thank the reviewer for this helpful suggestion. Gore et al. is already cited in the manuscript (Reference 19) in relation to organic carbon persistence. To further acknowledge the application of thermogravimetric

analysis within UK saltmarsh systems, we have now also cited Gore et al. in the Thermogravimetric Analysis section of the Methods.

Comment 9: I also believe comparing the accumulation rates and stocks to the UK average from natural marshes would be beneficial and give the results some context. A quick search highlights that on average UK saltmarshes accumulate 110 g/m²/yr of OC with a range of 27.2 - 303.1 g/m²/yr. The data presented here show rates of 1500 g/m²/yr. You discuss reasons for this rate being 5 to 50x larger but comparing them to natural system provides important context that is missing

<https://www.sciencedirect.com/science/article/pii/S0048969724022472#ec0005>

Response: We thank the reviewer for this helpful suggestion. To provide additional context, we have added a comparison with published UK saltmarsh organic carbon accumulation rates to the Discussion. We now note that natural UK saltmarshes accumulate organic carbon at an average rate of approximately 1.1 t C ha⁻¹ yr⁻¹ (range: 0.27–3.03 t C ha⁻¹ yr⁻¹), whereas the mean accumulation rate observed at Paull Holme Strays was substantially higher (15 t C ha⁻¹ yr⁻¹). Lines 519-521.

Comment 10: It is less clear how the results presented here could be compared to natural OC stocks. One potential route would be to compare the depth integrated OC value (lines 452 onwards). Here the average is 297.8 tonne/ha. In UK natural marshes the average is 110 tonne/ha for saltmarsh soils with values ranging between 22.4 - 405.1 tonne/ha. If you extend the stocks down 1m (not all saltmarsh include paleo tidal flat) then the number range from 50.5 - 731.9 tonnes/h.

<https://www.frontiersin.org/journals/marine-science/articles/10.3389/fmars.2023.1229486/full>

The data from this paper falls within these ranges and should be highlighted, inline with natural marsh stocks but far exceed accumulation - provide reasons.

Response: We thank the reviewer for this valuable suggestion. We agree that comparison with natural saltmarsh carbon stocks is informative and complements the accumulation-rate comparison above. We have therefore expanded the Discussion to note that the depth-integrated organic carbon stocks measured at Paull Holme Strays (297.8 t C ha⁻¹) fall within the range reported for UK saltmarsh soils. We now explicitly highlight the contrast between the relatively high accumulation rates observed at Paull Holme Strays and stock values that remain within the range reported for natural UK saltmarsh systems. Lines 524-526.

Buried Potential? Evaluating Long-Term Sequestration in a Restored Intertidal Habitat

Burrell, E.J¹., Mazik, K¹., Mossman, H²., and Taylor, M³

¹School of Environmental Science, University of Hull, Hull, United Kingdom. ²Ecology and Environment Research Centre, Department of Natural Sciences, Manchester Metropolitan University, Manchester, United Kingdom. ³School of Engineering, University of Hull, Hull, United Kingdom.

Abstract

Restoration of intertidal habitats is increasingly promoted as a nature-based solution for climate mitigation, yet uncertainties remain around their carbon dynamics. This study provides the first full-depth, site-wide assessment of 20 years of sediment organic carbon (OC) accumulation in a UK restored intertidal habitat (Paull Holme Strays), based on 3,987 sediment samples across saltmarsh and mudflat. We integrate depth-resolved sampling, OC fractionation, and elevation-stratified modelling to quantify stocks and characterise variability. Since breaching in 2003, the site has accumulated ~125,000 m³ of sediment, with 11–250 cm of elevation gain closely linked to initial elevation. OC declined non-linearly with depth (adj. R² = 0.62); labile OC was largely confined to an upper surface layers, while deeper layers were dominated by more persistent recalcitrant OC, consistent with breakpoint analysis. Elevation and depth were the primary correlates of OC variability, with bulk density and grain size acting as secondary influences. Annual OC accumulation averaged ~15 t C ha⁻¹ yr⁻¹, with roughly one third labile and two thirds recalcitrant, reflecting the combined effects of sediment volume and carbon concentration. These analyses disentangled near-surface turnover from deeper, persistent storage and clarified why rapidly accreting, low-elevation areas with lower OC concentrations, and OC-dense high-elevation areas with limited accretion can yield comparable annual accumulation. An empirically defined surface horizon, paired with elevation-stratified, fraction-resolved profiles, provides a scalable basis for consistent comparison and strengthens transparent, standardised blue-carbon assessment.

Introduction

Despite their relatively small spatial scale, saltmarsh and intertidal mudflats are globally significant carbon sinks, storing an estimated 0.4–6.5 Gt of organic carbon (OC) worldwide [1]. Alongside biodiversity support, flood protection and nutrient cycling [2], their capacity to sequester atmospheric carbon dioxide makes them critical components of nature-based solutions in climate change mitigation [3, 4]. However, global saltmarsh and intertidal habitat extent continues to decline due to coastal development, sea-level rise, and increasing storm activity [5, 6]. Global net losses of ~76 km² yr⁻¹ between 2000-2019 reduced carbon burial capacity by an estimated 0.045 Tg CO₂e yr⁻¹ [7].

In recognition of their functional and societal value, large-scale restoration and conservation efforts have been undertaken [8]. Over the past three decades, approximately 35 km² of intertidal habitat have been restored in the UK alone [9]. Across Europe, restoration is predominantly achieved through managed realignment (MR), which involves relocating flood defences landward and reinstating tidal flooding to previously reclaimed land [10]. MR sites are often low lying within the tidal frame due to land compaction and relative sea level rises following reclamation, meaning they often have substantial accommodation space for sediment accretion [11]. Following tidal reinstatement, rapid deposition of allochthonous carbon-rich sediment facilitates development [12], with OC sequestration shifting over time from burial of external inputs to plant-driven autochthonous accumulation as elevation increases [13]. Realigned intertidal habitats often differ from existing/natural systems in both biotic and abiotic characteristics due to historic land uses, including reduced porosity, altered drainage, and more anoxic subsurface conditions, shaping long-term sediment dynamics, redox potential and vegetation development [14, 15].

The largest carbon deposits in intertidal habitats are in the sediment [16], and its long-term persistence depends not only on rates of accumulation but also on the extent to which deposited carbon is protected from remineralisation [17].

Waterlogged, anoxic conditions in sediments slow down organic matter decomposition, enhancing long-term OC preservation [18]. The effectiveness of these preservation processes varies greatly among sites and is influenced by regional environmental controls such as sediment supply, tidal regime [19], vegetation composition [20], hydro-geomorphic setting [21], and marsh age [22].

While previous research has demonstrated the potential for restored coastal and estuarine systems to sequester OC [3, 4, 23], reported values vary widely between sites on a global scale (1.8–19.4 t C ha⁻¹ yr⁻¹) [1], reflecting both genuine spatial heterogeneity and methodological inconsistencies. Estimates at both local and national scales often rely on global averages of OC accumulation rates [24], commonly based on total organic carbon (TOC) measurements [25], or from limited datasets with surface extrapolations [26, 27]. Such approaches provide little insight into how carbon readily degraded by microbes, known as labile carbon, declines with depth, or how recalcitrant carbon that resists decomposition persists over decadal timescales [28]. This uncertainty in persistence and long-term sequestration potential of OC in restored intertidal habitats limits the robustness and reliability of current estimates for inclusion in carbon markets and climate policy frameworks.

Here, we present the first high-resolution assessment of OC accumulation across a restored intertidal habitat in the UK, Paull Holme Strays. Drawing on 3987 sediment samples, collected across both vegetated saltmarsh and intertidal mudflat, we aim to (1) quantify site-level OC stocks and habitat-specific accumulation rates since creation in 2003; (2) characterise vertical OC profiles, partitioning labile and recalcitrant fractions, to quantify the extent and rate of labile organic carbon loss with depth; (3) identify an empirically defined surface layer to enable consistent spatial comparisons across heterogeneous elevations; and (4) test how environmental characteristics such as elevation, which influence sediment and allochthonous carbon supply [11], and sedimentary characteristics such as grain size, that affect the preservation of OC

stock [20], correlate with OC variability. By explicitly distinguishing saltmarsh and mudflat contributions, we aim to reduce methodological bias from prescribed depths or full-core averaging and provide a reproducible framework for restored intertidal systems. While site-specific, our findings have broad relevance across NE Atlantic saltmarsh systems and provide a robust empirical foundation for developing accurate, standardised protocols for OC stock assessments.

Methods

Study site

Sediment samples were collected from the MR site (Figure 1; 53°44'N, 0°16'W), located on the north bank of the Humber Estuary, UK. Breached in September 2003, it was the first MR site on the Humber and was designed to serve a dual role of coastal flood protection and habitat restoration due to coastal defence works and sea level rise [29]. The site was created by breaching the existing sea wall in two locations (Figure 1 a and b) restoring ~80 ha of intertidal habitat, part of which compensates for habitat loss elsewhere in the estuary. The site lies adjacent to Paull Holme Sands mudflat and forms part of a landscape covered by several national and international conservation designations [30].

Quantifying sediment deposition and erosion

Multiple Digital Terrain Models (DTMs) derived from airborne LiDAR data at 50 cm horizontal resolution [31] were obtained for the MR site at Paull Holme Strays. DTMs were available for the years 2003 (immediately post-breach) and for; 2004, 2005, 2007, 2010, 2012, 2013, 2014, 2016, 2017, 2019, and 2022. Where multiple flights existed, data was selected from similar seasons to minimise seasonal variations, such as dewatering or sediment reflocculation. The raster geoprocessing tool in ArcGIS Pro 3.3 was used to merge downloaded DTM tiles before being clipped by the MR site area (defined manually with a polygon around the crest of the flood embankment). The first DTM available after the breach (26/09/2003) was clipped by the site boundary, and the resulting polygon (with an area of 79.8 ha) used to clip the remaining DTMs. Elevation change (in metres relative to Ordnance Datum Newlyn, m ODN) between DTMs was calculated to estimate net sediment accretion or erosion over time. Mean elevation change across raster pixels was calculated and then converted to total change in sediment volume by multiplying by the area covered by the raster DTM. Naturally accreted marsh areas that have risen above the highest astronomical tide were retained in the analysis, as these areas are part of the system's development and reflect long-term sediment and carbon accumulation processes. Any artificially elevated features such as the flood embankment were excluded from analysis of marsh sediment dynamics.

Field sampling design

Elevation varied considerably across the site as a function of initial elevation pre restoration elevation, combined with flooding, drainage and sedimentation dynamics over the past two decades. To capture this variation, we selected three sampling elevation bands, stratified by elevation from the 2022 lidar-derived DTM and in-situ vegetation composition (Figure 1a). High elevation bands comprised current elevations > 3m ODN, with dense vegetation including *Juncus maritimus*,

Phragmites australis. Mid elevation bands comprised current elevations 2.5-3m ODN, with vegetation including *Cochlearia officinalis*, *Puccinellia maritima*, and Low elevation bands comprised current elevations <2.5m ODN, consisting of mainly bare mud with sporadic *Salicornia spp* and *Spartina anglica*. An area of approximately 3.4 ha near the eastern breach was modified in 2021/22 by the Yorkshire Wildlife Trust, involving excavation and adjacent piling of soil to create nesting habitat for Marsh Harriers and Redshank (pers. comm.). This activity altered the sediment surface through both removal and addition of material, but resulted in no net loss overall, so LiDAR-derived elevation calculations were unaffected. However, no sediment cores were collected from this area

Twenty-four sampling locations were randomly selected at each elevation band. In addition, a further six sampling locations were selected in the pre-existing saltmarsh seaward of the MR, with plant communities similar to those within the MR, to act as a natural reference (Figure 1a). At each sampling location, three replicate sediment cores (internal diameter 10cm) were taken to the depth of the pre-restoration agricultural surface, i.e. the full depth of the sediment accreting since restoration. This core length was calculated based on elevation change at each sampling stations from the differences in the 2003 and 2022 DTMs (Figure 1b). Sediment cores were sampled at each location between April and September 2023.

Sediment collection

Cores up to 1.2m depth were collected by hand, with a PVC core, 10cm internal diameter, a wall thickness of 0.5cm, and length of 1.5m, with sharpened edges to cut through root material. Cores over 1.2m were collected with a vibrocore, using aluminium cores (7.6cm in diameter, 3m in length). The height of the corer above the sediment was measured on the outside, for calculating core penetration, and on the inside for estimating core compaction. In cases of minimal compression (<2cm), cores were retained, and compaction correction factor applied [32]. If compression was >2cm, the corer could not be inserted to the required depth, or there was significant sample loss another core was taken in close proximity.

Sediment preparation

All cores were processed the day of collection and sub sectioned into 5 cm lengths, to quantify variation in sediment carbon. In total 234 cores were collected, ranging in length from 40 to 250cm, resulting in 3987 samples. Each subsample was analysed in triplicate for physical and chemical properties; replicate measurements were averaged to minimise instrument-level variability before statistical analysis

Dry bulk density (sediment density) was determined by drying 30cm³ of each of the 3987 sediment subsamples to a constant weight at 60°C for 72 hours [33]. At temperatures exceeding 60°C, fractions of sediment organic matter may oxidise and cause an under-estimation of OC [34]. Dry bulk density (DBD), the relationship between the mass of the dry solids (M) and the volume (V), was calculated from the equation $DBD(g/l)=M(g)/V(l)$ [35].

Sediment particle size analysis

Dried sediment samples were treated with 10% hydrogen peroxide to remove organics, and further treated with 3% sodium hexametaphosphate (Calgon) as a dispersant [36]. After treatment, samples were stirred and sonicated for 15 minutes to aid disaggregation. A subsample was analysed for grain size using laser diffraction with a Malvern Mastersizer Hydro 2000 MU (Malvern, Worcestershire, UK), with three replicate measurements per sample. The instrument measured particle sizes across a 0.017–2000 µm range, reporting full particle size distributions and volumetric sand, silt, and clay fractions (sediment classes). Grain size statistics were calculated using the graphical method of Folk and Ward [37] graphical method on the logarithmic phi scale in GRADISTAT [38]. For analysis, we used: 1) mean grain size as the geometric mean (µm), obtained by back-transforming the phi-scale mean, and 2) sand, silt and clay fractions following the Wentworth scale as implemented in GRADISTAT. Because sand, silt, and clay percentages are compositional data (summing to 100%), fractions were transformed using the centred log-ratio (CLR) transformation prior to analysis.

Quantifying organic carbon content of the sediment

Total organic carbon content (TOC) analysis was performed using Elemental Analysis LECO CHN628 (LECO Corporation, USA), calibrated using EDTA as a standard. Dried, ground and sieved sediment samples (63 µm) [39] were weighed into tin foil cups, sealed and combusted in the presence of oxygen (Air Liquide, 99.999%) to generate CO_x, NO_x and H₂O at 950 °C. Total carbon was reported as wt.% mass of initial sample [40, 41]. Aliquots of the same samples analysed for TC were weighed and heated to 550°C for 4 hours, at this temperature, carbon is removed leaving the inorganic carbon in the ash [42]. The ash was weighed to the nearest milligram and analysed on the Elemental Analyser (as outlined above) to determine the inorganic carbon content of the ash. The inorganic carbon content of the original sample was calculated by scaling the elemental analyser result by the ratio of ash weight to original dry weight. Organic carbon content (%) was then derived by subtracting the inorganic carbon from the total carbon content of each sample.

Calculation of organic carbon stock

Sediment organic carbon stocks were calculated from full-depth cores sampled at 5 cm intervals using 5 cm depth intervals, dry bulk density (DBD), and total organic carbon (TOC). For each subsample, SOC density (g C cm⁻³) was calculated as:

$$\text{SOC density (g OC cm}^3\text{)} = \text{DBD (g cm}^{-3}\text{)} \times \frac{\% \text{OC}}{100}$$

The organic carbon content of each subsample was multiplied by its thickness and summed across the core to obtain per-core stocks, which were then converted to t OC ha⁻¹. Site-level mean stocks and standard deviations were calculated across cores, and average annual SOC accumulation (t C ha⁻¹ yr⁻¹) was estimated by dividing core stocks by site age (19 yr). Site-wide accumulation was calculated using mean per-core values multiplied by total site area (78.9ha).

Thermogravimetric analysis

Dried and milled sediment samples were analysed using thermogravimetric analysis (TGA) to partition OC into labile and recalcitrant fractions. Analyses were conducted using a Thermogravimetric Analyzer LECO TGA701 (LECO Corporation, USA) under a constant flow of N₂, with samples heated from ambient temperature to 950 °C ([*Moisture Phase* - ambient to 107 °C at 3 °C/min, holding for 15 min], [*Volatile Phase* - 107-950 °C at 5 °C/min, holding for 7 min] and [*Ashing Phase* - 950-600 °C in nitrogen, followed by 600-750 °C in air at 3 °C/min before cooling to room temperature]). Labile OC was quantified as the mass loss between 200–400 °C, representing thermally unstable compounds, while recalcitrant OC was quantified as the mass loss between 400–650 °C, representing more stable organic matter. The proportion of each fraction was expressed relative to the total OC detected by TGA. Labile and recalcitrant OM densities were calculated in the same way as SOC density, detailed above.

Data analysis

All statistical analyses were conducted using R software version 4.3.2 [43]. Data exhibited a moderate positive skew (SK = 0.617), and slight platykurtosis (K = 0.5), and remained non-normal despite transformation. Figures were produced using “ggplot2” [44]. Full code and model outputs are provided in the Supplementary Information.

Site sediment deposition and erosion

Spatial variation in accretion was modelled using Generalised Additive Models (“mgcv” package, Wood [45]), based on the initial post-restoration elevation surface (2003), which was classified into three zones: Low (<2.5 m ODN), Mid (2.5–3.0 m ODN), and High (>3.0 m ODN). Thin plate regression splines were used to capture non-linear accretion trajectories across zones.

Sediment Properties and Organic Carbon Profiles

Sediments properties were modelled as a function of elevation zone, and depth within the core. Organic carbon (total, labile and recalcitrant (%)), bulk density (g cm⁻³), sediment composition (sand/silt/clay%), and median grain size (µm) were modelled using GAMs fitted with the bam() function in the mgcv package [45]. Each model included elevation band as a fixed factor, smooth terms for non-linear depth profiles within elevations, and random intercepts for cores. To account for autocorrelation among successive depth increments, an AR(1) correlation structure was applied to model residuals. Smoothing parameters were estimated via fREML, and model adequacy was confirmed using residual diagnostics (gam.check). Model selection was based on Akaike Information Criterion (AIC), likelihood ratio tests, and cross-validation, with residual diagnostics assessing fit.

Organic Carbon Stock and Accumulation Rates

Uncertainty in site-scale OC accumulation was estimated using non-parametric bootstrapping (100,000 resamples) using the boot package [46]. Mean accumulation rates were calculated per unit area and scaled to the total site (78.9 ha) to estimate annual carbon sequestration (t C yr⁻¹) with associated 95 % confidence intervals.

Evidence Based Surface Depth for OC Analysis

Prescribed-depths or full-core averages, used in many studies can obscure or bias spatial comparisons because vertical accretion varies within and between intertidal habitats. We therefore defined a representative surface layer using a data-driven procedure informed by 3,987 samples to enable robust spatial comparisons across the site. Specifically, we combined four approaches: (1) the depth range exhibiting the greatest heterogeneity in sediment properties, bulk density (g cm^{-3}), grain size (μm), and sediment composition (sand/silt/clay%); (2) the inflection point marking stabilisation of labile OC with depth; and (3) the core depth encompassing $\geq 90\%$ of cumulative OC. The median of these three estimates was taken to reduce bias from any single method; and (4) finally, segmented regression was applied to the site-aggregated profile of labile OC (median values per 5 cm interval) to identify a statistically significant breakpoint where the rate of labile OC decline changes, representing the transition from dynamic surface sediments to more stable subsurface layers.

Results

Sediment deposition and erosion

Since its creation, the MR site has undergone substantial elevation gain, with approximately $125,111 \text{ m}^3$ of sediment accumulated (Figure 1b). Accretion varied considerably across the site (11-250 cm) and was strongly associated with initial pre-restoration elevation (GAM: adjusted $R^2 = 0.78$, deviance explained = 81.3%; edf = 7.16, $F = 8.71$, $p < 0.001$). Areas with low initial elevations exhibited both higher rates and greater spatial variability in sediment deposition, where elevation gains ranged from 40 to 250 cm. The largest gains occurred near the western breach (Figure 1b), where adjacent low-lying areas accumulated sediment rapidly, consistent with site morphology and tidal exposure. In contrast, areas with higher initial elevations, such as near the new sea wall at the back of the marsh, showed the lowest elevation gains, ranging from 11 to 79 cm.

Sediment Properties

Bulk density, grain size, and sand–silt–clay composition, exhibited significant spatial variation across elevation bands and with depth across the site (see Supplementary Table 1 for full GAM outputs; Figure 2).

Bulk density was significantly lower in Low ($\beta = -0.130 \pm 0.016$, $p < 0.001$) and Mid elevations ($\beta = -0.030 \pm 0.015$, $p < 0.05$) compared to High elevations (median $\pm$ SE = $1.01 \text{ g cm}^{-3} \pm 0.07 \text{ g cm}^{-3}$); there was no significant difference between High and reference sampling stations (Figure 2a). Depth-related variation was also significant, with non-linear declines detected in all bands (edf = 5–7, $p < 0.001$). The highest densities occurred in the upper 15 cm of High-elevation cores ($0.8\text{--}1.5 \text{ g cm}^{-3}$), while deeper layers were consistently less dense.

Grain size and textural composition showed contrasting spatial patterns. Low-elevation sediments were coarser (median = $9.36 \mu\text{m}$) than High elevations ($7.43 \mu\text{m}$), consistent with GAM estimates ($\beta = +1.60 \pm 0.17$, $p < 0.001$). Grain size generally decreased with depth across all elevations ($p < 0.001$), with the most

pronounced changes in Mid elevations (range: 5.1–11.3 μm). The coarsest layers were concentrated in the upper 10 cm of Low-elevation cores, while High-elevation cores were more homogeneous throughout the profile. Textural fractions reflected these trends: Low elevations had higher silt (86%) and lower clay (9%) compared to High elevations (14% clay) and Mid elevations (~10%). GAM outputs indicated significant differences between elevations for sand, silt, and clay (all $p < 0.001$), with non-linear depth trends most pronounced for silt in Mid elevations (edf = 10.65, $F = 6.82$, $p < 0.001$) and clay in High elevations (edf = 8.95, $F = 3.72$, $p < 0.001$). Non-linear patterns with depth indicate rapid changes in the upper layers and more stable conditions below ~30–40 cm, with Mid elevations increasingly resembling those of lower lying areas, particularly in grain size, whereas High-elevation cores remained more distinct, retaining higher bulk density and finer grain size (Figure 2c and d). This pattern suggests that deeper Mid-elevation sediments may represent older deposits laid down under hydrological conditions similar to those currently observed in Lower elevations.

Organic Carbon Content and drivers of variation

OC content declined significantly with depth across the site (adj. $R^2 = 0.631$; deviance explained = 65%). High (edf = 5.43, $F = 45.12$, $p < 0.001$) and Mid elevations (edf = 5.91, $F = 24.81$, $p < 0.001$) exhibited pronounced curvature, consistent with complex OC accumulation and decomposition through the sediment profile (Figure 3). Low elevations showed weaker, more gradual changes (edf = 2.55, $F = 12.06$, $p < 0.001$), while the Reference marsh displayed moderate non-linearity (edf = 2.95, $F = 14.14$, $p < 0.001$).

Models confirmed elevation (as of 2022) and depth (change in elevation since restoration) were the primary controls on OC content (%) (adj. $R^2 = 0.62$; deviance explained = 64%, see table S4 and S5). Consistent with site-wide depth declines (Figure 3), the significant elevation–depth interaction (edf = 11.8, $p < 0.001$) indicates that OC losses with burial were steepest in High elevations, where rapid accretion and vegetation inputs created carbon-rich surface layers, while Low elevations showed more gradual declines. Bulk density and grain size had weak or non-significant effects when elevation and depth were included, suggesting their influence is largely mediated by these primary drivers. When elevation and depth were removed, both properties became significant predictors (bulk density: edf = 2.04, $F = 10.1$, $p < 0.001$; grain size: edf = 1.21, $F = 18.4$, $p < 0.001$), but explanatory power dropped (adj. $R^2 = 0.50$), confirming they act as secondary, correlated controls rather than independent drivers of OC.

Substantial heterogeneity among cores within elevation bands was captured (edf = 71.46, $F = 13.20$, $p < 0.001$), indicating fine-scale variability beyond elevation-level trends. Parametric contrasts confirmed significantly lower median OC in Low ($\beta = -0.680 \pm 0.083$, $p < 0.001$) and Mid ($\beta = -0.576 \pm 0.083$, $p < 0.001$) elevations relative to High, whereas differences for the Reference marsh were smaller and not statistically significant ($\beta = -0.273 \pm 0.153$, $p = 0.075$). Despite these trends, some low-lying areas retained substantial carbon stocks, particularly adjacent to the western breach (Figure 4), where stronger tidal currents during early post-breach

stages promoted rapid and substantial deposition of organic-rich sediment in areas excavated during construction, leading to the greatest elevation gains across the site (Figure 1b). Total OC (integrated over depth) from cores in this area ranged from 1.8 to 4.1 g OC cm⁻², among the highest concentrations recorded across the site (0.8 – 6.56 g OC cm⁻²). Conversely, much lower OC stocks were recorded at the eastern end of the site, where the breach is smaller and initial elevations were higher, limiting tidal exchange and sediment deposition. As a result, elevation gains were minimal (Figure 1b), and total OC typically remained below 3 g cm⁻². The highest total OC stocks were observed in the higher-elevated, densely vegetated areas at the western end of the site (Figure 4). Cores from these elevations frequently exceeded 3.8% OC in the top 30 cm of sediment, with total OC stocks site-wide ranging between 3.0 and 6.6 g cm⁻². These high stocks occurred in areas that experienced substantial elevation gain (often >1 m) and rapid vegetation colonisation following restoration, conditions that promoted sustained organic matter accumulation.

Labile and recalcitrant OC exhibited contrasting depth profiles and elevation patterns (Figure 5). Labile OC was concentrated near the surface, peaking in the top 30 cm of High-elevation cores (median = 2.10%, range = 1.11–3.53%), compared to a site-wide median of 1.77% (range = 0.48–3.53%), and declined steeply with depth across all elevation zones (edf = 9.8–16.4, $p < 0.001$), approaching zero below ~40 cm. In contrast, recalcitrant OC was more persistent with depth, showing weaker non-linear trends (edf = 6.7–12.3, $p < 0.001$) and dominating below ~40 cm, consistent with its greater chemical stability. Surface concentrations of recalcitrant OC were highest in the reference marsh (top 30 cm: median = 2.47%, range = 2.11–3.45%), well above the site-wide median of 1.32% (range = 0.27–3.45%), with lower values in the MR. The higher recalcitrant OC in the reference marsh may reflect greater organic matter inputs associated with its more established vegetation, which could provide more material for stabilisation and humification over time. Elevation contrasts from the fitted models were negative relative to High for both fractions (e.g., Low vs High: labile $\beta = -0.17 \pm 0.03$, $p < 0.001$; recalcitrant $\beta = -0.31 \pm 0.15$, $p = 0.044$; Mid vs High: labile $\beta = -0.04 \pm 0.02$, $p = 0.042$; recalcitrant $\beta = -0.30 \pm 0.14$, $p < 0.05$), reflecting lower surface concentrations in Low/Mid elevation zones. Overall, these patterns suggest that labile OC is strongly influenced by elevation-driven processes and vegetation inputs, while recalcitrant OC represents older, more stable carbon at depth (see Supplementary Table 2 to 4 for full GAM outputs).

Organic carbon stock and accumulation rates

Average annual carbon accumulation across cores was 15 t C ha⁻¹ yr⁻¹ (95% CI: 14.15–16.43), with 4.7 t C ha⁻¹ yr⁻¹ in the labile fraction (95% CI: 4.34–5.08) and 9.3 t C ha⁻¹ yr⁻¹ in the recalcitrant fraction (95% CI: 8.18–10.4).

Scaled to the total site area (~79.8 ha), this equates to a total annual SOC accumulation of 1,206 t C yr⁻¹ (95% CI: 1,117–1,296), including 373 t C yr⁻¹ labile and 732 t C yr⁻¹ recalcitrant carbon. These results account for observed variability among cores in bulk density, OC content, and depth, providing a robust site-wide figure of carbon sequestration at the site.

388

389 *Evidence Based Surface Depth for OC Analysis*

390 Independent empirical criteria converged on a dynamic surface layer near 40 cm,
391 corresponding to the depth interval of greatest variability in sediment properties and
392 the stabilisation of labile OC, and encompassing $\geq 90\%$ of cumulative OC (Figure 6a).
393 To validate this empirical estimate, segmented regression was applied to the
394 aggregated labile OC profile (Figure 6b). Segmented regression on the aggregated
395 labile-OC profile identified a breakpoint at 40.5 cm (95% CI: 38.4–42.7 cm)
396 (Figure 6b), marking a clear transition from rapid OC decline in the upper layers to a
397 more gradual decrease in deeper sediments (Figure 6b). This closely aligns with the
398 empirical estimate and supports ~ 40 cm as a representative surface layer for
399 site-wide comparison.

400

401 Discussion

402 This study provides the first high-resolution, full-depth assessment of OC content in
403 a UK MR site. By resolving vertical profiles, distinguishing labile and recalcitrant
404 fractions, and stratifying by elevation, we avoid biases from prescribed shallow
405 depths or full-core averaging and quantify how near-surface processes differ from
406 deeper, longer-term storage. We estimate site-wide accumulation of $\sim 15 \text{ t C ha}^{-1} \text{ yr}^{-1}$
407 ($1,206 \text{ t C yr}^{-1}$), with deeper strata dominated by recalcitrant OC, consistent with
408 long-term stability.

409 A consistent pattern across studies suggests that rapidly accumulating MR saltmarsh
410 with low sediment carbon content can achieve similar carbon accumulation rates to
411 slowly accreting marshes with higher carbon densities [47, 48]. In MR sites with
412 limited sediment availability, significantly lower carbon accumulation rates have been
413 recorded. For example, in the Blackwater Estuary (Essex), where suspended
414 sediment concentrations range from 50 to 150 mg L^{-1} (Ladd, 2019), accumulation
415 rates were reported at $3.21 \text{ t C ha}^{-1} \text{ yr}^{-1}$ in Orplands and $3.33 \text{ t C ha}^{-1} \text{ yr}^{-1}$ in Northey
416 Island [23]. Even lower rates were observed in Tollesbury ($1.04 \text{ t C ha}^{-1} \text{ yr}^{-1}$), also
417 within the Blackwater Estuary, where reduced sediment delivery compared to other
418 sites and site-specific conditions constrained deposition [3]. In contrast, the Humber
419 Estuary is characterised by large tidal ranges (macrotidal), allowing sediment
420 deposition on both the flood and ebb tides, with one of the highest suspended
421 sediment concentrations in the water column, in the UK (19 - 27 g/L) [49, 50].
422 Incoming sediment is typically composed of fine silts and clays with moderate to high
423 organic content, depending on tidal conditions [29]. Sites with high sediment supply
424 show markedly higher accumulation rates, for instance, Steart Marsh (Somerset),
425 with suspended sediment concentrations ranging from 1,000 to 10,000 mg/L ,
426 recorded an accumulation rate of $19.4 \text{ t C ha}^{-1} \text{ yr}^{-1}$ [12]. Similarly, the upper Bay of
427 Fundy (Canada), where sediment concentrations range from 150 to 300 mg/L [51],
428 reported rates of $13.29 \text{ t C ha}^{-1} \text{ yr}^{-1}$ [52].

Per-hectare values of sediment organic carbon are strongly determined by the depth of the organic horizon [53], which is ultimately determined by the rate and carbon density of sediment supply, as well as root material accumulation, which contributes to elevation gain. Elevation change data (Figure 1) highlights substantial variability in sedimentation across Paull Holme Strays, from ~11 cm in high-elevation areas to ~250 cm in low-lying areas near the western breach (Figure 1). Across Paull Holme Strays High-elevation zones with limited sedimentation exhibited higher OC densities but lower overall accumulation rates (Figure 1 and 4), whereas rapidly accreting zones stored less OC per unit mass yet achieved comparable annual accumulation (~15 t C ha⁻¹ yr⁻¹). This supports the dual role of sediment supply and carbon concentration (i.e. inputs from vegetation), in determining sequestration potential. For example, cores near the western breach contained some of the highest OC stocks (up to 4.1 g cm⁻²), whereas eastern areas rarely exceeded 3 g cm⁻². These patterns are strongly influenced by hydrodynamic controls, where greater tidal energy and proximity to the breach promote rapid accretion in western areas, while eastern areas remain more sheltered and accumulate less sediment. Understanding these spatial differences is critical for predicting long-term carbon storage and designing restoration strategies that optimise both sediment delivery and vegetation development. Consequently, equal depths sampled across elevations may reflect different depositional conditions, so fixed-depth comparisons should be interpreted with caution.

The accommodation space created during restoration is often rapidly infilled with sediments originating from adjacent environments, rather than with autochthonous organic matter produced by in-situ saltmarsh vegetation [54]. While the long-term fate of this initial influx has previously been uncertain. However, our depth-resolved analysis revealed a sharp decline in labile OC below ~40 cm (Figure 6), confirmed by segmented regression (breakpoint at 40.5 cm, 95% CI: 38.4–42.7). This transition marks the dynamic surface layer where most OC turnover occurs and coincides with the depth interval of greatest variability in sediment properties. Below this depth, labile OC approaches zero, while recalcitrant OC persists, indicating that long-term carbon storage is dominated by chemically stable fractions. This pattern, supported by a non-linear decline in OC concentrations with depth (edf = 3.06, $p < 0.001$), is consistent with post-depositional remineralisation, whereby labile carbon in surface layers is progressively degraded during burial.

It is well-established that vegetation plays a key role in determining SOC levels [55, 56], through direct input of OC from plant roots and decaying biomass, as well as indirectly through vegetation structures, (e.g. leaves, stems), facilitating the trapping of sediment and thus the accumulation of allochthonous OC [57]. Areas of high elevation and dense vegetation are likely to lose more labile carbon over time due to two key factors: first, they tend to receive substantial inputs of labile organic matter from vegetation (both during initial colonisation and subsequent biomass production); and second, they are less frequently inundated, resulting in more oxygenated conditions that accelerate microbial degradation [58]. The significant elevation–depth interaction (edf = 11.8, $p < 0.001$) indicates that OC loss with depth was most pronounced in high-elevation zones, consistent with known patterns of microbial

degradation where more chemically or biologically labile organic matter is remineralised rather than preserved in long-term carbon stocks [59]. In contrast, low-elevation areas, although storing less OC initially (Figure 5), exhibited slower rates of OC decline. These areas tend to be more frequently inundated and more anoxic which slows down microbial decomposition, favouring the preservation of labile carbon.

By pairing **near-unprecedented sampling resolution** with elevation-stratified cores and depth-resolved OC fractionation, this study disentangles short-term turnover from longer-term carbon preservation in restored intertidal habitats. The combination of vertical profiles and fraction-specific dynamics clarifies why low-elevation, rapidly accreting sediments with lower OC concentrations, and high-elevation, OC-dense sediments with little accretion can produce similar annual OC accumulation, a pattern widely observed but previously unexplained in managed-realignment systems. Our empirical identification of a ~40 cm dynamic surface layer provides a practical depth for consistent comparison across heterogeneous elevations, reducing the bias introduced by fixed sampling depths or surface extrapolations. Together, these elements offer a scalable, evidence-based approach to interpreting OC stocks and accumulation across restored intertidal environments, directly addressing longstanding uncertainty around vertical OC persistence and improving the reproducibility and transparency of blue-carbon assessments. By resolving the mechanisms that structure OC variability within a realignment site, this study advances the basis for robust monitoring and strengthens the scientific foundation of coastal-restoration carbon accounting.

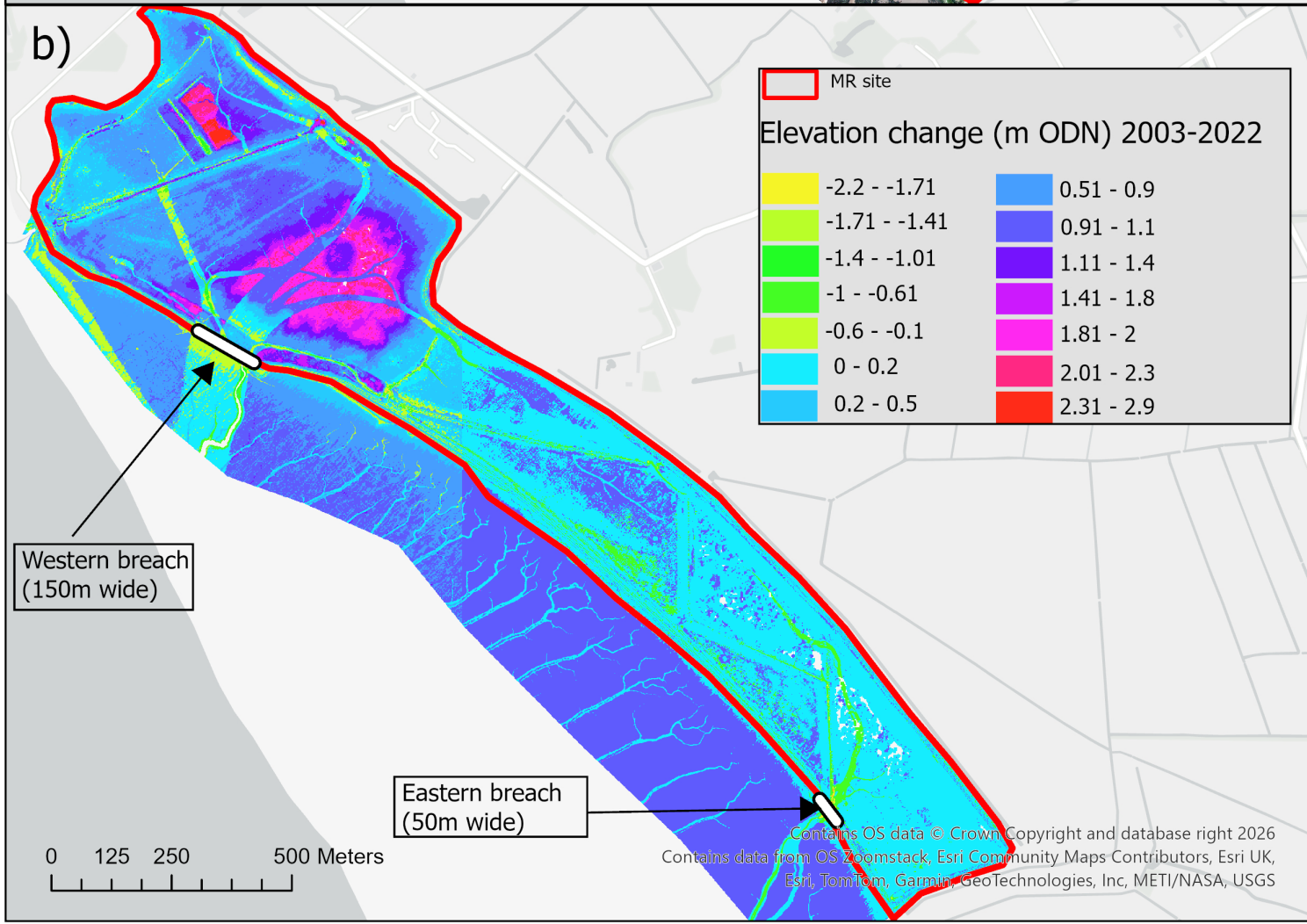
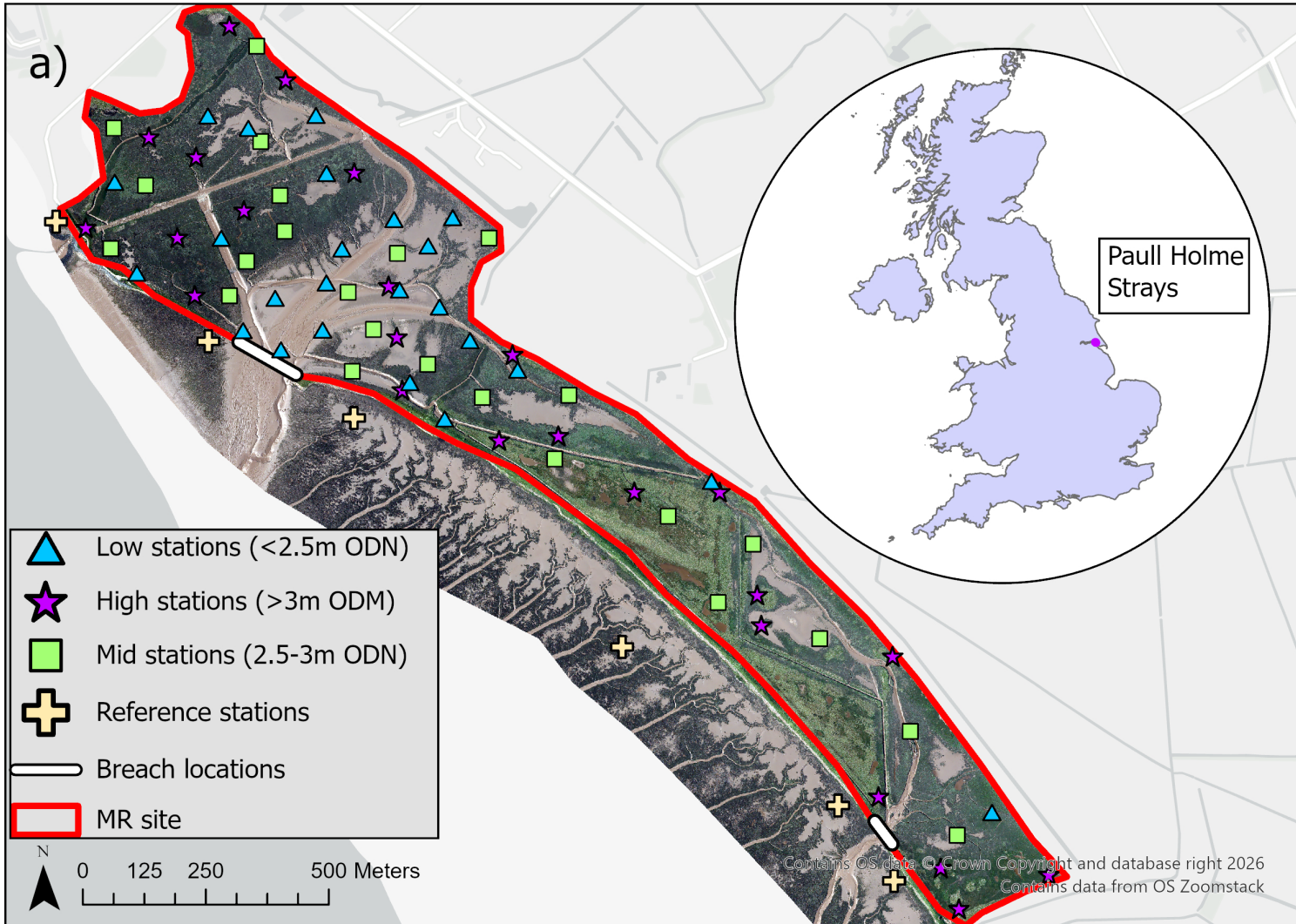
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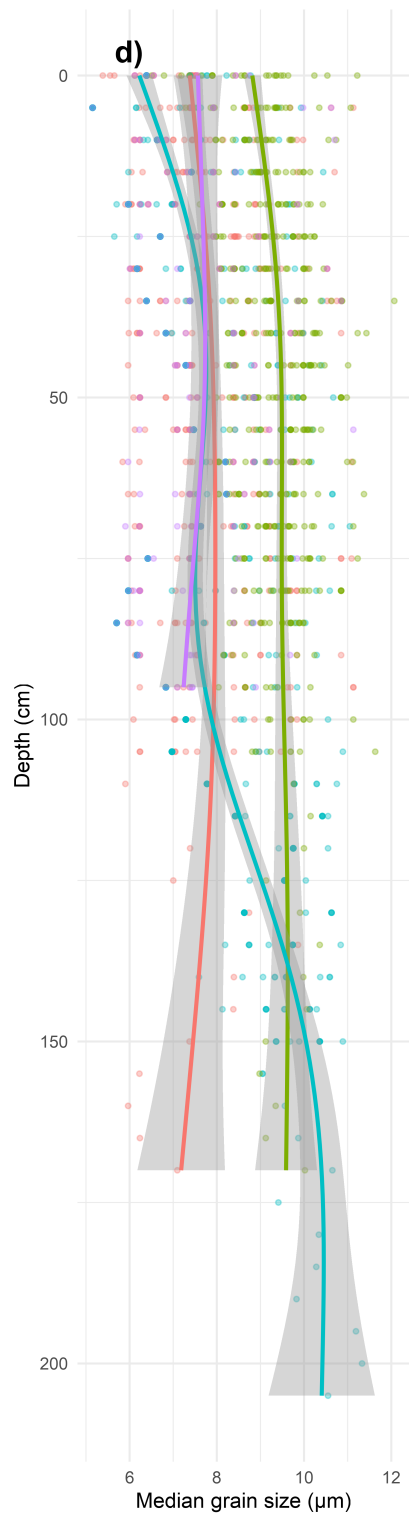
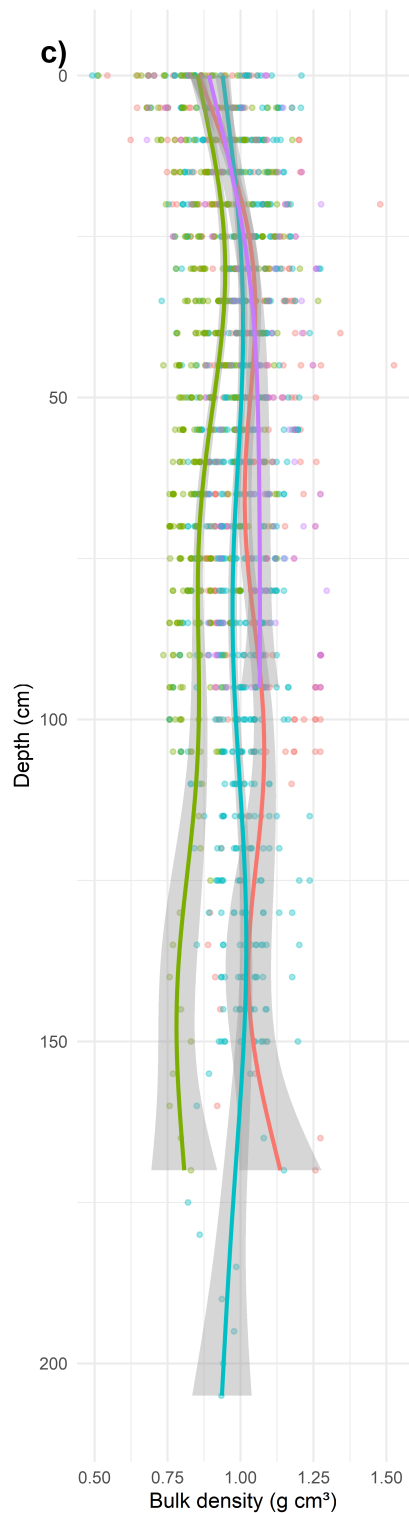
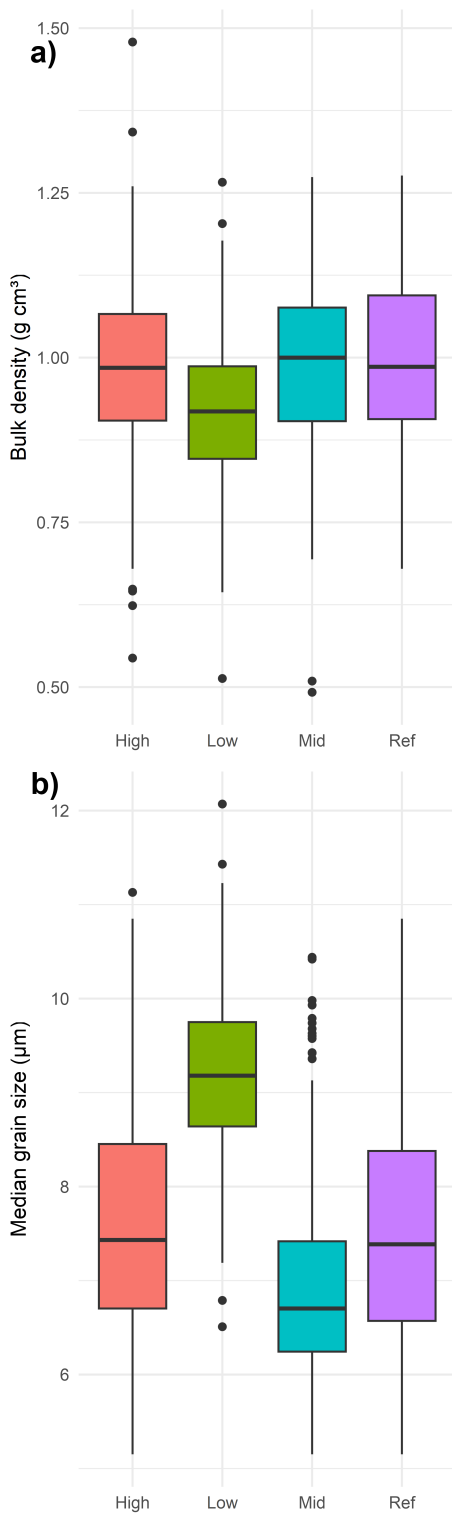
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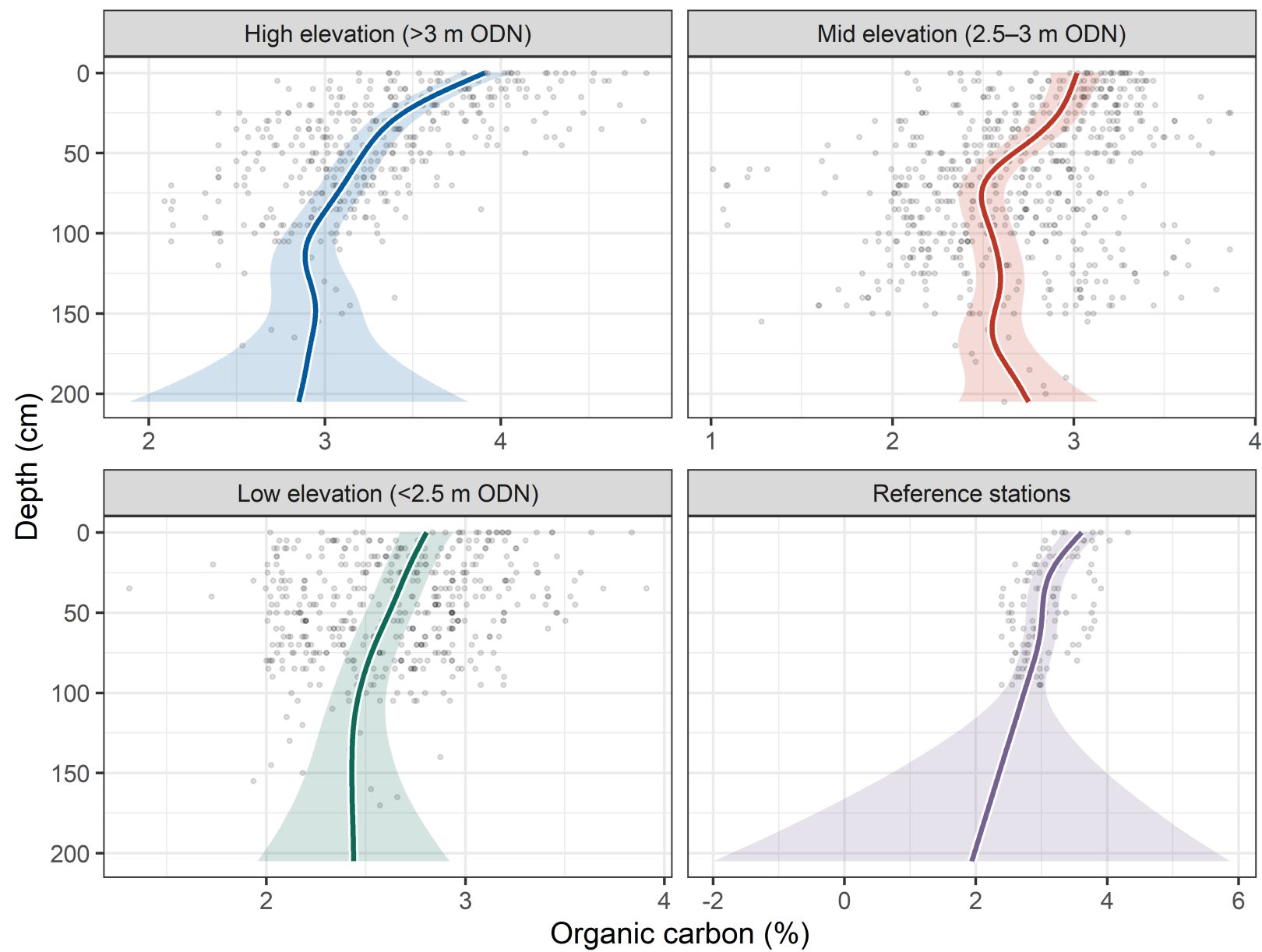
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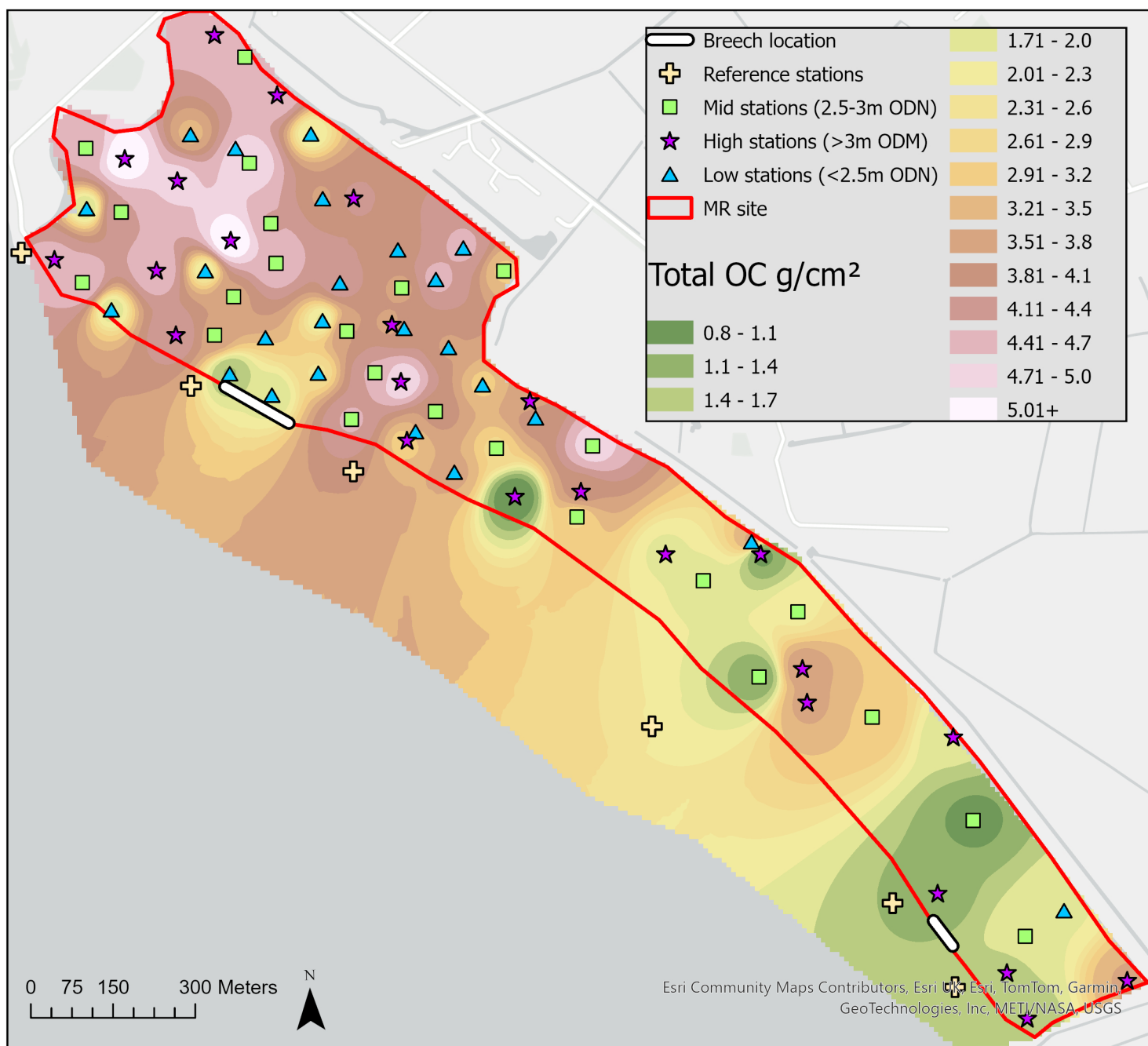
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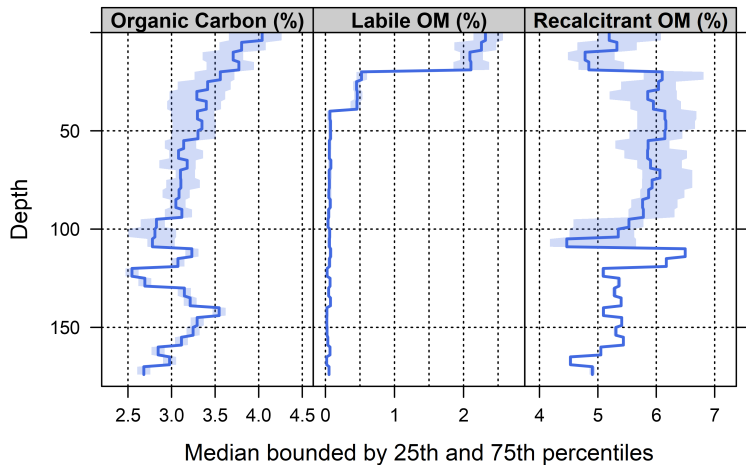


- High Elevation (>3m ODN)
- Mid Elevation (2.5-3m ODN)
- Low Elevation (<2.5m ODN)
- Reference stations

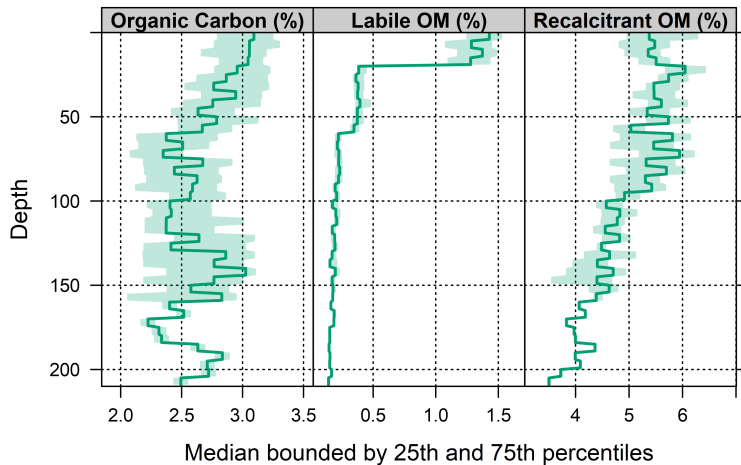




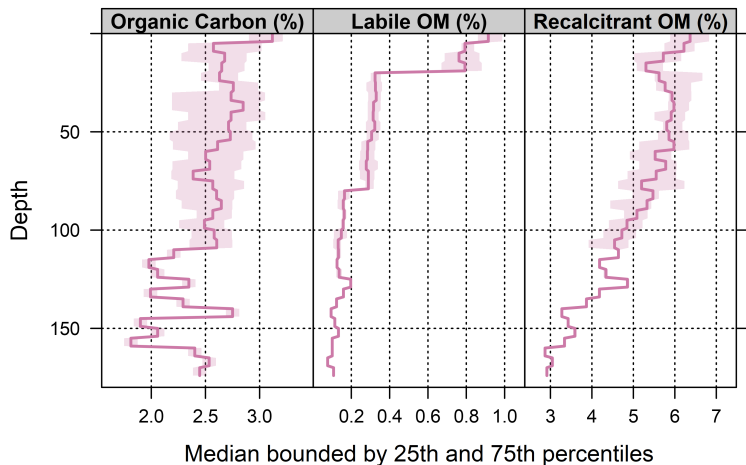
High elevation (>3 m ODN)



Mid elevation (2.5–3.0 m ODN)



Low elevation (<2.5 m ODN)



Reference marsh

