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## RESEARCH LETTER

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## Quality Not Quantity: Prioritizing the Management of Sedimentary Organic Matter Across Continental Shelf Seas

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### Key Points:

- Within most shelf sediments organic matter (OM) is generally of low reactivity (i.e., low labile OM content) and resistant to remineralization
- Muddy nearshore sediments hold large quantities of high reactivity OM which is at risk of remineralization when disturbed
- Policy interventions that seek to protect reactive OM should prioritize near-shore sediment OM over the resilient OM in many shelf seas

### Supporting Information:

Supporting Information may be found in the online version of this article.

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**Abstract** Disturbance of marine sediments results in the remineralization of sedimentary organic matter (OM) and impacts upon natural burial processes. Management interventions which restrict or remove activities that cause seabed disturbance may offer effective strategies to protect the most vulnerable of these shelf sea OM stores, offering new opportunities to deliver climate mitigation actions. While the largest quantities of OM are often stored in the expansive offshore regions of continental shelves and might therefore suggest appropriate zones for management interventions to protect vulnerable OM stores, our results highlight that these offshore regions generally contain OM of low reactivity. Conversely, inshore and coastal sediments store significant quantities of highly reactive OM that is at greater risk of remineralization when disturbed. The marked spatial disparities between OM reactivity across shelf sea sedimentary environments highlights the need to focus emergent policy and future management interventions toward the protection of inshore and coastal sediments.

**Plain Language Summary** If disturbed, the organic carbon within seafloor sediments can potentially be converted to carbon dioxide and a portion lost to the atmosphere, where it potentially contributes to climate change. Our results highlight that the reactivity (biodegradability) of sedimentary carbon across shelf seas is highly variable with low reactivity organic matter found in the offshore region, while organic matter within inshore and coastal sediments can be highly reactive and potentially vulnerable to break-down when disturbed. These differences in organic matter reactivity highlight the need to focus emergent management interventions that can deliver protection toward the most vulnerable organic matter stores in inshore and coastal sediments.

## 1. Introduction

Natural systems such as forests, peatlands and intertidal wetlands have the potential to mitigate global climate change through the capture and long-term storage of carbon (C) (Duarte et al., 2013; Keenan & Williams, 2018). These habitats provide effective CO<sub>2</sub> sinks, but can also release significant quantities of CO<sub>2</sub> due to natural and anthropogenic disturbance (Goldstein et al., 2020; Leifeld & Menichetti, 2018). Marine sediments which trap and store C on geological timescales (Atwood et al., 2020; Hedges & Keil, 1995; Smeaton et al., 2017; Smith et al., 2015) are integral components of the global C cycle (Bauer et al., 2013; Bianchi et al., 2018), yet until recently have been largely overlooked in relation to their role in climate regulation. Furthermore, the potential to exacerbate the impacts of climate change through the release of CO<sub>2</sub> from anthropogenic disturbance of these sedimentary C stores is a growing concern (Atwood et al., 2020; Luisetti et al., 2019, 2020; Sala et al., 2021).

Continental shelf sediments represent 8.9% of the seafloor (P. T. Harris et al., 2014) yet are estimated to store 266 Gt of OC within the top 1m of sediment (Atwood et al., 2020). Annually, a further 146 Mt OC is buried in continental shelf sediments, far exceeding the burial rates of other marine sedimentary environments (e.g., slope, abyssal plains, Hadal trenches) (Hedges & Keil, 1995). The magnitude and rate at which continental shelf sediments store (Atwood et al., 2020; Smeaton et al., 2017) and bury (Bernier, 1982; Hedges & Keil, 1995; Smith et al., 2015) OC has generated calls for new governance and management of the marine environment that would protect (and hence potentially reduce emissions from) the OC held within shelf sediments (Atwood et al., 2020; Luisetti et al., 2019; Sala et al., 2021) including calls for their inclusion in national greenhouse gas (GHG) accounting and natural capital assessments (Avelar et al., 2017; Luisetti et al., 2019, 2020).

A simple argument underpins many of these calls, namely that anthropogenically disturbed shelf sea sediments release CO<sub>2</sub> back into the water column with a portion being lost to the atmosphere (Bauer et al., 2013; Goldstein et al., 2020; Lotze et al., 2006; Sala et al., 2021; Wainright & Hopkinson, 1997) which potentially exacerbates

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current global climate warming. Anthropogenic pressures, particularly the impacts of bottom trawling, are perceived to be the greatest threat (Atwood et al., 2020; Dunkley & Solandt, 2020; Luisetti et al., 2019, 2020; Sala et al., 2021) because mobile bottom fishing gear remobilizes the top layer of sediment (Oberle et al., 2016) where the most biodegradable forms of OC are found. Within European waters bottom trawling annually disturbs 28%–85% of the continental shelf (Eigaard et al., 2017). However, with only 4% of the global seafloor within a Marine Protected Area (MPA) and even less (2.7%) protected from bottom disturbance (Atwood et al., 2020; Sala et al., 2021), the majority of these global sedimentary C stores are regularly exposed to trawling disturbance. The reduction and/or exclusion of bottom trawling to protect existing shelf sea sedimentary OC stores has therefore been discussed as a component of future shelf sea management strategies (Atwood et al., 2020; Dunkley & Solandt, 2020; Luisetti et al., 2019, 2020; Sala et al., 2021).

However, the majority of OC that accumulates in marine sediments (~90%) is degraded (Middelburg, 2019). This fundamental aspect of the modern marine C cycle appears to have been overlooked in current claims regarding the role of (and risks to) marine sediments in climate regulation (Atwood et al., 2020; Luisetti et al., 2019, 2020; Sala et al., 2021). Overestimating the quantity of labile OM remaining in the sediments and under-accounting for natural degradation of OC in marine sediments (Arndt et al., 2013; Larowe et al., 2020) suggests that current estimates of global CO<sub>2</sub> emissions owing to anthropogenic disturbance (Sala et al., 2021) may have been significantly overestimated.

The quality (i.e., reactivity) of the organic matter (OM) and associated OC within natural C stores determines the role the store plays in climate regulation and, equally, determines the vulnerability of the store to disturbance both natural and anthropogenic (Goldstein et al., 2020). Using a new carbon reactivity index (CRI) calculated from the proportion of labile, recalcitrant and refractory fractions of the OM, we quantify a novel measure of the quality and reactivity of the OM and associated quantity of OC in inshore, coastal and offshore sediments across the United Kingdom's Exclusive Economic Zone (EEZ).

## 2. Materials and Methods

### 2.1. Study Area

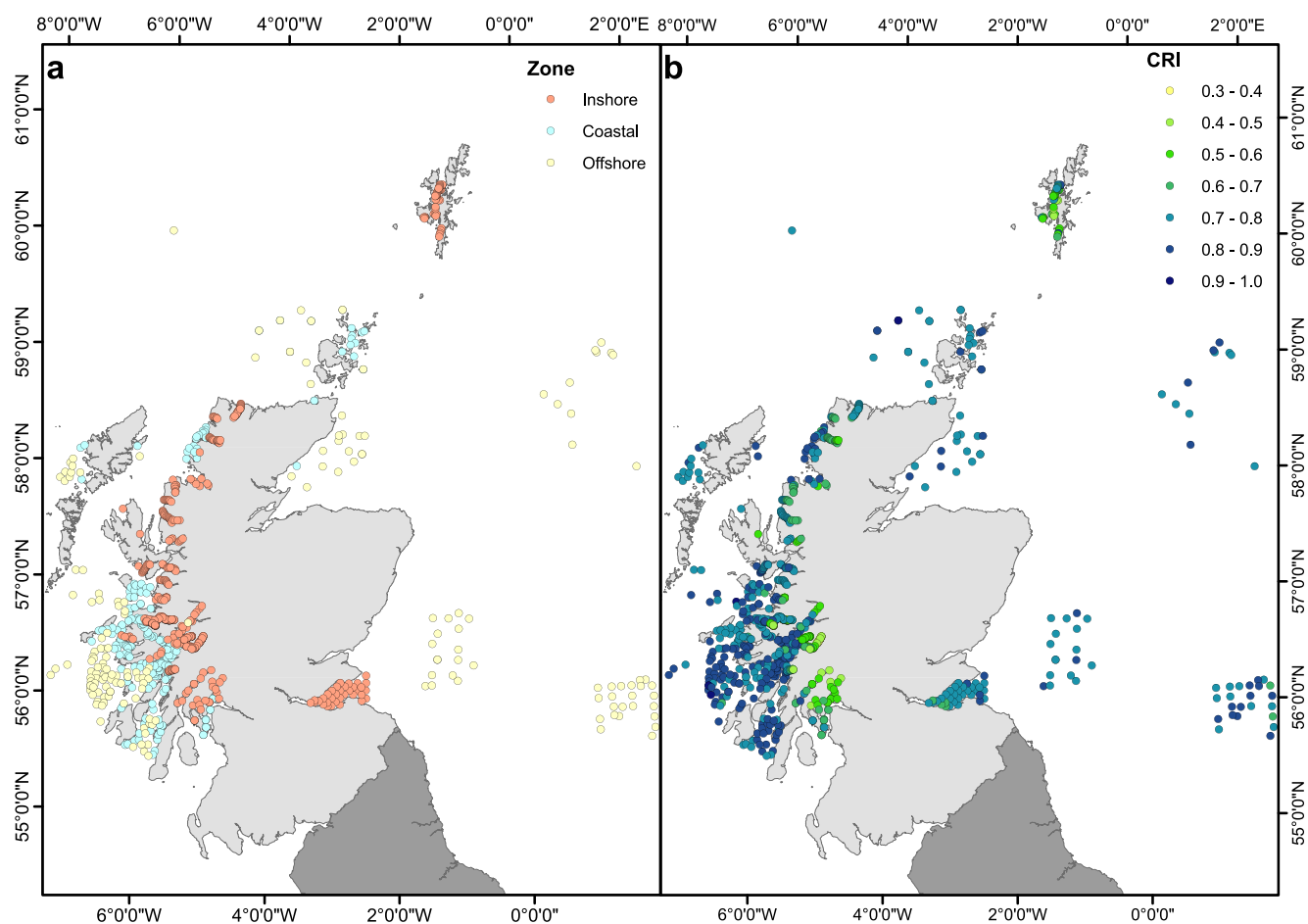
The surficial sediments within the Scottish portion of the UK EEZ (Figure 1a) are the primary focus of this study. The sediments have been subdivided into three zones following the methodology of Smeaton, Hunt et al. (2021) and Smeaton, Yang, and Austin (2021), these zones represent inshore (fjords and estuaries), coastal (<5 km from land) and offshore (>5 km from land) sedimentary environments. Fjords, for example, are characteristic as hotspots for the burial (Bianchi, Cui, Blair, Burdige, & Eglinton, 2018; de Haas et al., 2002; Hedges & Keil, 1995; Smeaton, Hunt et al., 2021; Smeaton, Yang, & Austin, 2021) and the long-term (>10<sup>3</sup> years) storage (Smeaton et al., 2017) of OC. The three zones of the UK EEZ are representative of common sedimentary environments on continental shelves (P. T. Harris et al., 2014) which allows the findings of this study to be used to understand the reactivity of OM across global continental shelves.

### 2.2. Sampling

Archival sediment samples ( $n = 434$ ) were acquired from the British Geological Survey (BGS) sample repository (Keyworth, UK) all were obtained using a day-grab from the Scottish portion of the UK EEZ (Figure 1a). These samples were described according to the Folk classification scheme (Folk, 1954). Additionally, over a five-year period between 2016 and 2021, 451 day-grab and multi-core sediment samples were collected from around Scotland (Figure 1a). The upper layer (0–1 cm) of the multi-cores and surface scrapes from the day-grabs were used to represent the surficial sediments.

### 2.3. Elemental Analysis

Samples were freeze dried and homogenized; approximately 10 mg of processed sediment was placed into tin capsules and sealed for N analysis. A further 10 mg was placed into a silver capsule; the samples encapsulated in silver underwent acid fumigation to remove carbonate (D. Harris et al., 2001). The acidified samples were dried for 48 hr at 40°C and the capsules sealed. The OC and N content of the samples were determined using an Elementar Vario EL following standard methodology (Verardo et al., 1990).



**Figure 1.** Map of study area. (a) Location of surface samples collected as part of this study, split into three zones—Inshore (fjords and estuaries), coastal and offshore. (b) Spatial distribution of carbon reactivity index values across the study area.

#### 2.4. Thermogravimetric Analysis (TGA)

Milled samples of approximately 20 mg were placed into 70 mL aluminum oxide crucibles before being placed into a Mettler Toledo TGA2 and heated from 40°C to 1000°C at a ramp heating rate of 10°C min<sup>-1</sup> under a constant stream of N<sub>2</sub>. The thermograms produced from these analyses were adjusted to a common temperature scale and clipped to the range 200°C–650°C to remove interference from absorbed water and non-organic material. The thermograms were normalized to the mass loss, to assure all thermograms were comparably scaled.

#### 2.5. Carbon Reactivity Index (CRI)

The CRI is a modification of the Rp index which has previously been used in the characterization of OM (Kristensen, 1990). Utilizing the TGA data the OM can be grouped into three thermal fractions indicative of lability or biodegradability (Capel et al., 2006). These OM fractions are thermally defined as labile (200°C–400°C), recalcitrant (400°C–550°C) and refractory (550°C–650°C). Using the updated thermal ranges for labile OM (OM<sub>L</sub>) (200°C–400°C) and recalcitrant and refractory OM (OM<sub>R</sub>) (400°C–650°C) the CRI can be calculated following the Rp Index methodology (Kristensen, 1990). The CRI is calculated as follows:

$$\text{CRI} = \frac{\% \text{OM}_R}{\% \text{Total OM}} \quad (1)$$

Conceptually the CRI represents a continuum of reactivity (Figure S1 in Supporting Information S1) with value of 0 indicating that the material is fully biodegradable (fully reactive) and a value of 1 indicating that the substance is non-biodegradable (not reactive). Yet, in reality no natural molecule can be fully biodegradable or

non-biodegradable (Larowe et al., 2020), rather the CRI represents the range of OM reactivity between these two points. To determine the reliability of the CRI, several analytical standards and natural materials were analyzed. The most biodegradable substance measured was fucoid sugar standard with a CRI <0.1 while the highest CRI values of 0.8–0.9 were observed in glacial sediments deposited in the mid-latitude fjords of Scotland and on the continental shelf at the end of the last glacial period. This data set captures the natural range of OM reactivity from the CRI values (0.06–0.90) observed. The full data set used to calibrate the CRI can be found in Figure S2 and Table S1 in Supporting Information S1.

### 3. Results and Interpretation

#### 3.1. Quality and Reactivity of Sedimentary OM

Annually, ~55 Pg C enters the world's oceans (Field et al., 1998; Meybeck, 1982); of this only 2–3 Pg C yr<sup>-1</sup> reaches the seafloor, with an even smaller fraction still locked away in seafloor sediments (0.2–0.4 Pg C yr<sup>-1</sup>) (Middelburg, 2019). A large proportion of this C burial occurs in coastal and inshore sediments (Bauer et al., 2013; Smith et al., 2015). The rate at which OC is incorporated into marine sediment stores therefore decreases markedly across continental shelf to deep-sea environments (Hedges & Keil, 1995; Middelburg, 2019) due to the enhanced degradation of the OM (Arndt et al., 2013; Middelburg, 2018, 2019) and changing hydrodynamic conditions (C. K. Harris and Wiberg, 2002; Nittrouer & Wright, 1994).

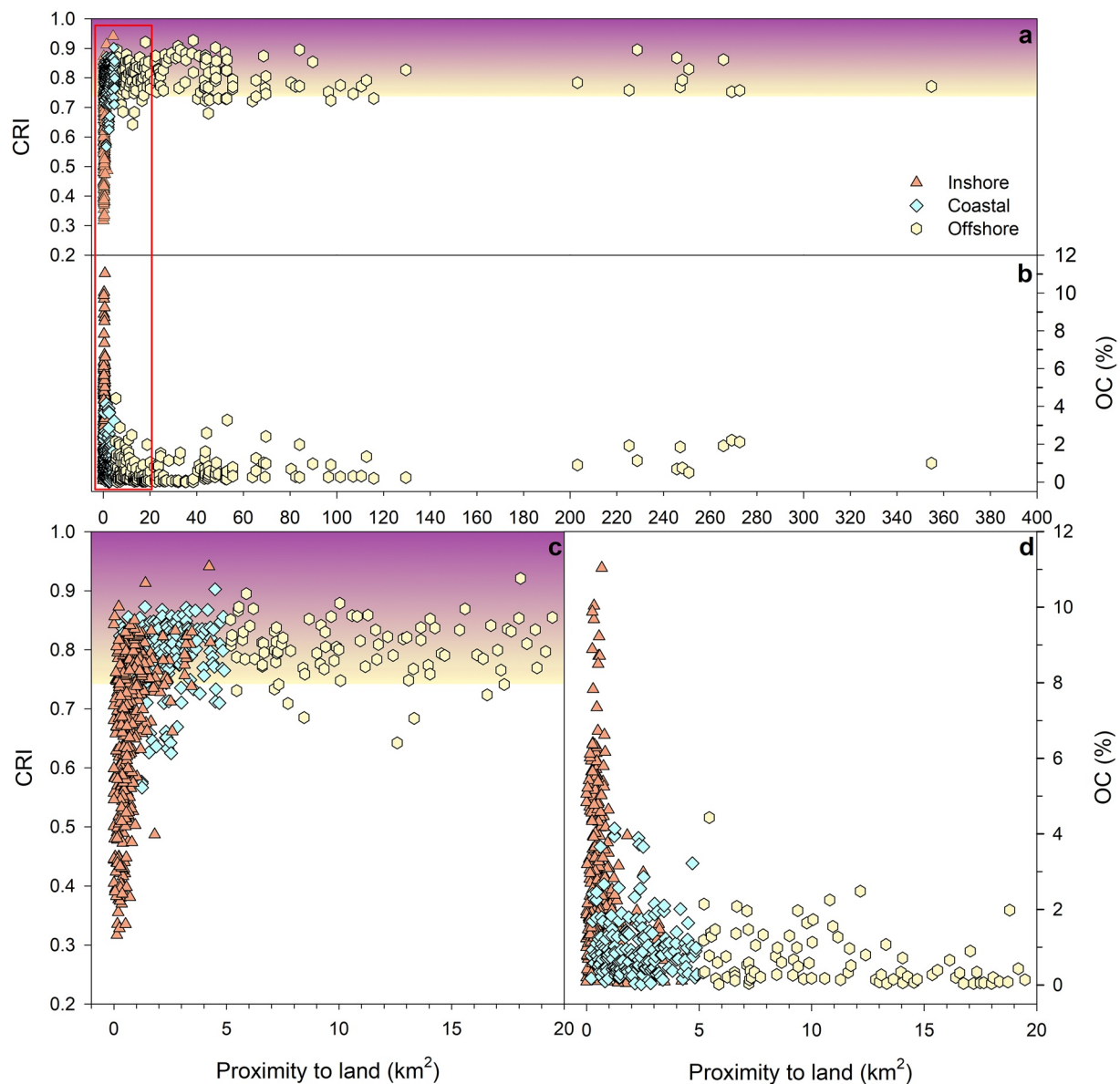
The natural biogeochemical (Arndt et al., 2013; Larowe et al., 2020) and hydrodynamic processes (C. K. Harris and Wiberg, 2002; Nittrouer & Wright, 1994) that govern the transport and storage of OC across the marine environment also drive its decomposition, so that ~90% of the OC that enters the marine sediment store is degraded (Middelburg, 2019). The degree of degradation determines the reactivity of the OM (i.e., OM characteristics which determine OC remineralization potential (e.g., biodegradability) and the associated sedimentary OC. These characteristics in-turn govern the vulnerability of the OC to remineralization, be that due to natural or anthropogenic disturbance. Different mixtures of labile, recalcitrant and refractory components determine the reactivity of OM and the associated OC (Capel et al., 2006). OM<sub>L</sub> is highly reactive and easily remineralized during transport and accumulation in marine settings (Arndt et al., 2013; Keil et al., 1994), recalcitrant and refractory OM<sub>R</sub> is generally resistant to degradation (i.e., low reactivity) reducing the opportunity for the associated OC to be lost through remineralization. The CRI provides a useful measure to assess the reactivity of OM across marine sedimentary environments (Figure S1 in Supporting Information S1).

#### 3.2. Quality Versus Quantity

The surficial marine sediments (top 10 cm) within the UK EEZ are estimated to hold 262 ± 68 Mt OC (Smeaton, Hunt et al., 2021; Smeaton, Yang, & Austin, 2021). Yet within these sediments the quantity and density of OC varies significantly (Smeaton, Yang, & Austin, 2021) with inshore and coastal systems such as fjords, estuaries and coastal mud belts being recognized as globally significant hotspots for the burial and storage of OC (Bauer et al., 2013; Bianchi et al., 2018, 2020).

Across the UK EEZ, there are significant gradients in the reactivity of sediment OM (Figure 1b), with CRI values ranging between 0.31 and 0.94 (Figure 2). The OM with the highest reactivity is found at the land-ocean interface within inshore sediment systems; moving away from land, the quantity of OC and the reactivity of the OM decreases (Figure 2). The transition from OM<sub>L</sub>-rich to OM<sub>L</sub>-poor sediments occurs within remarkably short distances from land (Figures 2c and 2d). The OM with the highest reactivity is found within 5 km of land, further offshore the sediments are characterized by high CRI values (low reactivity) and lower OC contents (Figures 2c and 2d).

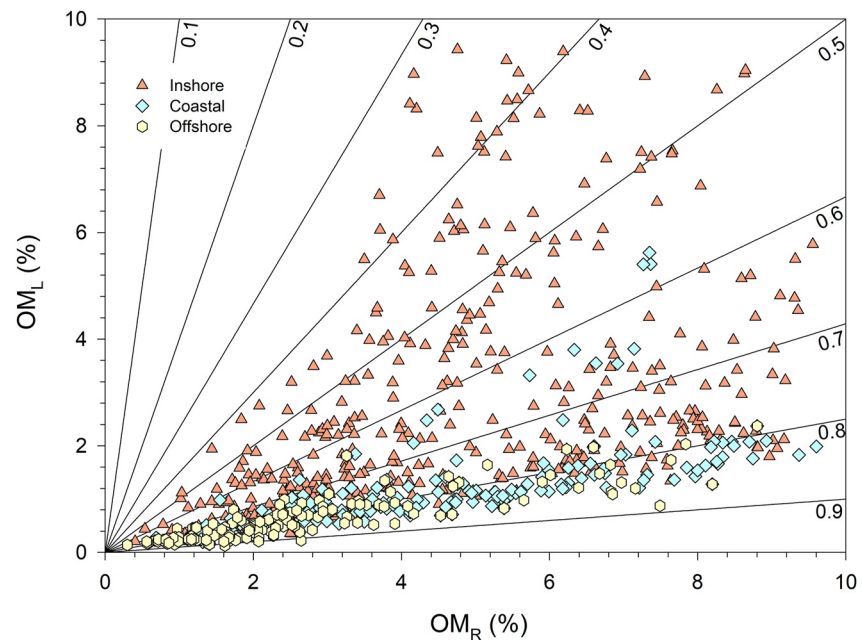
The greatest variability in the OM reactivity is found in inshore sediments, where CRI ranges between 0.3 and 0.9. Within the sample set, sediments with a CRI of between 0.3 and 0.45 are exclusively found in inshore areas, specifically in upper fjord basins with low oxygen bottom waters (Friedrich et al., 2014), where the hypoxic conditions help reduce OC degradation (Arndt et al., 2013; Jessen et al., 2017; Larowe et al., 2020) and enhance OM<sub>L</sub> preservation. Outside of these nearshore hypoxic sedimentary basins, inshore sediment CRI values range between 0.45 and 0.9. The combination of high terrestrial OC input combined with high OC burial rates in inshore environments (Bianchi et al., 2020; Smith et al., 2015) results in large quantities of OM<sub>L</sub> being rapidly



**Figure 2.** Gradients of carbon reactivity index (CRI) and OC (%) across UK Exclusive Economic Zone (EEZ) sediments. The plots represent changes in (a) CRI (b) OC (%) of inshore (orange triangle), coastal (blue diamonds) and offshore (yellow hexagons) sediments with distance from land and terrestrial OC sources. The red box illustrates the location of the zoomed views, 0–20 km from land: (c) CRI (d) OC (%). Sediments with a CRI >0.75 are highlighted by the yellow-purple with the transition indicating OM of decreasing reactivity.  $N = 885$ .

trapped and stored, significantly decreasing degradation (and loss) of the overall sedimentary OM stock (Bianchi et al., 2020; Smith et al., 2015). CRI values >0.75 are found in the outer reaches of the inshore zone where these sediments are dominated by  $OM_R$ , much as they are across the wider continental shelf (Figure 3).

In contrast to inshore sediments, the OM in coastal and offshore sediments is largely derived from marine sources (i.e., marine primary production; Field et al., 1998; Middelburg, 2019) as indicated by sediment C/N ratios (Figures S3 and S4 in Supporting Information S1). Marine-derived OM is significantly more labile than terrestrial equivalents, providing a source of high reactive OM to the seafloor. Continental shelf seas are characterized by well-oxygenated bottom waters (Laffoley & Baxter, 2019), low sedimentation rates (Bernier, 1982; de Haas et al., 2002; Hedges & Keil, 1995), extended OM transport times (Bao et al., 2014; Bröder et al., 2018), enhanced biological OM consumption (Legendre & Rassoulzadegan, 1995) and widespread natural sediment resuspension (Coughlan et al., 2021; Fanning et al., 1982), all of which contribute to high rates of  $OM_L$  degradation. These



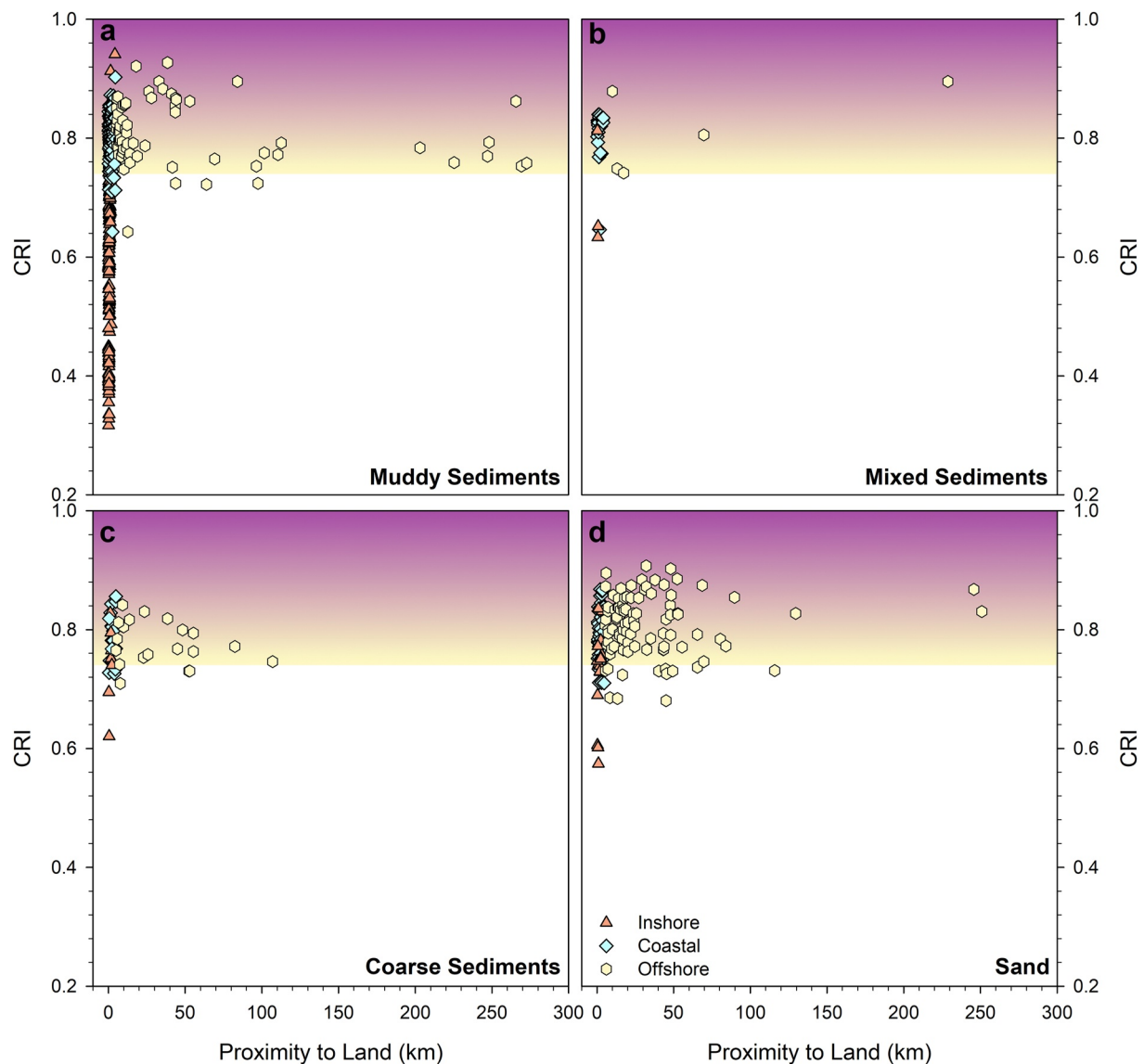
**Figure 3.** Labile ( $OM_L$ ) versus recalcitrant and refractory ( $OM_R$ ) OM cross plot for inshore, coastal and offshore UK Exclusive Economic Zone sediments. The radiating lines represent the carbon reactivity index where 0 = fully biodegradable and 1 = non-biodegradable.  $N = 885$ .

natural processes ensure that the majority of offshore continental shelf sediments fail to retain significant quantities of  $OM_L$  and, consequentially, the OM stored has lower reactivity than that observed in inshore and coastal environments (Figure 3). The largely ubiquitous nature of these natural processes across continental shelf seas results in relatively stable CRI across gradients of water depth and proximity to land (Figure 2; Figure S4 in Supporting Information S1). Where coastal and offshore shelf sediments have a CRI < 0.75, these are often found at the mouths of large estuaries (Figure 1b) where large quantities of  $OM_L$  and OC (Bauer et al., 2013; Bianchi et al., 2018) are available.

Our data indicate that the reactivity of the OM across inshore, coastal and offshore continental shelf sediments is coupled to the sediment's proximity to land (Figures 2c and 2d). High reactivity OM is found in near and inshore areas resulting in low CRI values (Figure 2), primarily driven by the input of highly reactive biospheric OC from the terrestrial environment (Bauer et al., 2013; Bianchi, 2011; Bianchi et al., 2018; Cui et al., 2016) that is rapidly buried (Bauer et al., 2013; Smith et al., 2015), preserving the  $OM_L$  fraction. Sediment type is the other main explanatory variable (Figure 4). Non-muddy, coarser substrates are dominated by  $OM_R$  and consequently have high CRI values (>0.75; Figures 4b–4d). Neither proximity to land nor water depth significantly impacts the CRI of these sediments (Figures 4b–4d; Figure S5 in Supporting Information S1), suggesting that the OM associated with these coarser sediments was originally of low reactivity or has been rapidly processed in an energetic environmental cycle of deposition and resuspension. CRI values < 0.75 are almost exclusively found in muddy shelf sea sediments (Figure 4a).

#### 4. Risk and Management of Anthropogenic Disturbance

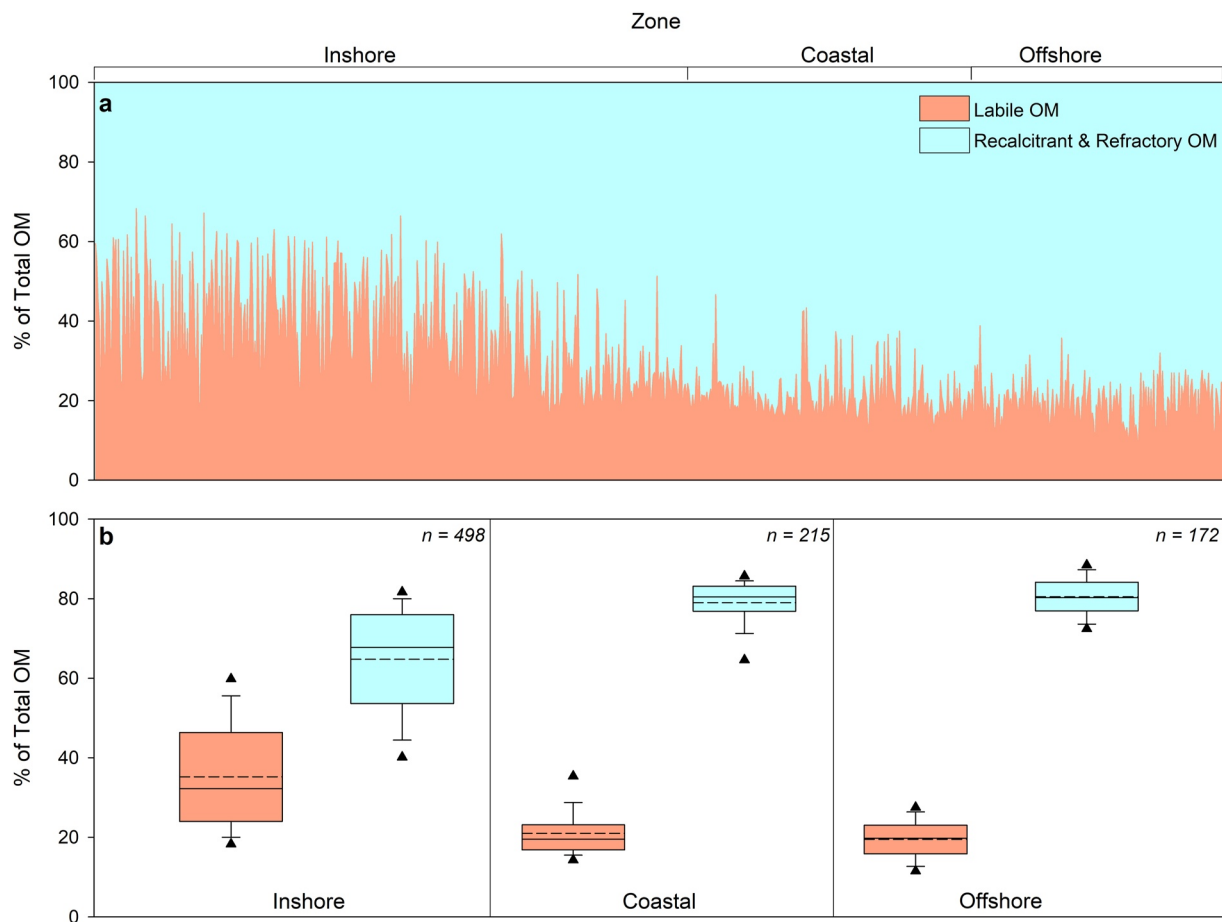
Disturbance of marine sediments, specifically by bottom trawling, is suggested to represent a significant risk to these sedimentary OC stores and a potential pathway for  $CO_2$  to be lost to the atmosphere enhancing global warming (Atwood et al., 2020; Dunkley & Solandt, 2020; Luisetti et al., 2019, 2020; Sala et al., 2021). Bottom trawling undoubtedly damages benthic habitats, their biodiversity and the wider ecosystem functioning of the seabed (Pusceddu et al., 2014). Yet, evidence that seabed disturbance can facilitate the release of  $CO_2$  from sedimentary C stores is sparse. In specific locations, bottom trawling has been shown to negatively impact the OM and OC stored in sediments, as observed in Mediterranean nearshore submarine canyons (>300 m water depth) (Paradis et al., 2018, 2019, 2020). In the last 50 years there has been a shift toward bottom trawling in deeper



**Figure 4.** Carbon reactivity index (CRI) versus sediment type as described by the Folk classification scheme (Folk, 1954). The reactivity of the organic matter (OM) held within four main sediment types on the UK Exclusive Economic Zone (a) muddy sediments, (b) mixed sediments, (c) coarse sediments, and (d) sand. Data are compiled across inshore, coastal and continental shelf sediments. Sediments with a CRI > 0.75 are highlighted by the yellow-purple shading, where the transition indicates an increase in recalcitrant and refractory OM and results in a greater resistance to degradation.  $N = 695$ .

waters (Paradis et al., 2018), but globally, the majority of the bottom trawling effort still remains concentrated on the continental shelf (<250 m water depth; Amoroso et al., 2018). However, radically different OM transport mechanisms and depositional processes (Arndt et al., 2013; de Haas et al., 2002; C. K. Harris and Wiberg, 2002; Larowe et al., 2020; Middelburg, 2018; Nittrouer & Wright, 1994) between these environments makes it difficult to translate the conclusions derived from these submarine canyons (Paradis et al., 2019, 2020) directly to the shallower, highly energetic environments of continental shelf seas.

The UK continental shelf has a long, sustained history of bottom trawling and is among the most heavily trawled seabed's in the world (Amoroso et al., 2018; Eigaard et al., 2017) with current known bottom trawling intensity at its most acute within muddy sediments >5 km for land. However, the risk of OC remineralization due to disturbance and resuspension is low because, as we now show, high CRI values indicate that today these sediments are dominated by  $OM_R$  and the easily biodegradable labile fraction has already been lost (Figure 3) either through natural or sustained anthropogenic disturbance over multiple decades. The ubiquitous nature of the high CRI



**Figure 5.** Composition of the organic matter (OM) across the sediments of the UK Exclusive Economic Zone (EEZ). (a) Percentage of  $OM_L$  and  $OM_R$  across the three zones (inshore, coastal, offshore) of the UK EEZ. Within each zone the samples are arranged from closest to the land (left hand side of each zone) to furthest offshore. (b) Boxplots illustrating the  $OM_L$  and  $OM_R$  fractions across the three zones of the UK EEZ. Dotted and solid lines represent the mean and median values, respectively, and the triangles illustrate the 5th and 95th percentiles.

values of sediments  $>5$  km from land (Figure 3) is likely a product of natural OM degradative processes that take place during the transport and burial (Arndt et al., 2013; de Haas et al., 2002; C. K. Harris and Wiberg, 2002; Larowe et al., 2020; Middelburg, 2018; Nittrouer & Wright, 1994) of OM across continental shelves which drive the loss of the  $OM_L$  fraction, in addition to any significant sustained anthropogenic disturbances. However, the  $OM_L$  rich inshore sediments are considerably more reactive than their offshore counterparts (Figure 3) and the potential for the OC held within these sediments to be remineralized and released as  $CO_2$  is significantly higher.

While  $OM_R$  is generally considered to be stable and therefore likely to be resilient, it must be remembered that there is a continuum of OM reactivity (Larowe et al., 2020) and that there are biogeochemical processes that could drive the degradation and release of  $CO_2$  from sediments rich in  $OM_R$ . One such process is priming where  $OM_R$  can be broken down by microorganisms when sufficient  $OM_L$  is available (Bianchi, 2011). Even in offshore sediments  $\sim 20\%$  of the total OM is labile (Figure 5), therefore the priming effect could play a yet unaccounted for but important pathway for  $CO_2$  release from  $OM_R$  rich sediments which potentially could be enhanced by either natural or anthropogenic disturbances.

Increasingly, strategies designed to manage the continental shelves no longer solely focus on the biodiversity and ecosystem damage that is caused by trawling of the seabed (Pusceddu et al., 2014). Rather, attention is increasingly switching to the potential damage which these anthropogenic activities cause to sedimentary C stores and the potentially negative impacts on the global climate (Dunkley & Solandt, 2020; Sala et al., 2021). However, the low reactivity of OM stored in sediments  $>5$  km from land (Figure 2) brings potential management strategies (Atwood et al., 2020; Dunkley & Solandt, 2020; Luisetti et al., 2019, 2020) designed to protect the OC stored in



shallow (<250 m) continental shelf sediments sharply into question. As previously noted, the highest observed trawling intensities are observed in offshore (>5 km land) areas, both in UK waters and globally (Amoroso et al., 2018; Eigaard et al., 2017). Yet, it is clear that these sediments contain relatively small amounts of OC and are dominated by  $OM_r$  (Figure 5), suggesting that they are potentially far more resilient to disturbance and less likely to be remineralized than some studies suggest, for example, Sala et al. (2021) suggest that up to 70% of the OC in fine-grained sediments is labile and subject to remineralization following trawling disturbance, this is likely a significant overestimation (Figure 5).

We reach the conclusion, supported by our analyses of both the current quality and quantity of sedimentary OC, that management interventions relating to bottom trawling activities are far more relevant to the protection of inshore sediments where there are significant quantities of highly reactive OC is present (Figure 2). Muddy inshore and some coastal sediments trap and store significant amounts of OC (Smeaton & Austin, 2019; Smeaton, Hunt et al., 2021; Smeaton, Yang, & Austin, 2021) and are the most susceptible to remineralization if disturbed, much more so than other sediments across the continental shelf (Figures 3 and 5). The scientific rationale for continental shelf-wide restrictions on trawling (i.e., the argument that anthropogenic disturbance of the seabed will release  $CO_2$ , Dunkley & Solandt, 2020; Sala et al., 2021) is far more likely to be applicable to these inshore and coastal systems. Unlike the wider continental shelf where bottom trawling is common and generally well monitored (Amoroso et al., 2018; Eigaard et al., 2017; Oberle et al., 2016), the data to map the pressures from these activities within inshore and coastal waters is limited.

## 5. Conclusions

Globally, marine sediments and continental shelf sediments (<250 m water depth) in particular hold vast quantities of OC (Atwood et al., 2020; Lee et al., 2019; Smeaton, Hunt et al., 2021; Smeaton, Yang, & Austin, 2021) and there are growing calls for these systems to be managed and policies developed to protect these important C resources. Of particular note have been a growing number of calls to manage and in some cases restrict or exclude bottom trawling from these protected areas (Dunkley & Solandt, 2020). Many of the proponents of these calls to limit bottom trawling across continental shelf seas focus on the size of the C stock rather than the reactivity of the sedimentary OM and, in-turn, they ignore significant cross-shelf differences in the vulnerability of that OC to be remineralized by anthropogenic disturbance.

In the UK EEZ, the offshore continental shelf sediments store the largest quantity (Smeaton, Hunt et al., 2021; Smeaton, Yang, & Austin, 2021) but are the least reactive (Figures 2 and 5). Beyond 5 km from land, natural OM degradation processes which are active during the continuum of transport, deposition, resuspension and burial of sedimentary OC (Arndt et al., 2013; Bao et al., 2014; Bröder et al., 2018; Larowe et al., 2020; Middelburg, 2019) likely become the primary processes driving the net accumulation of low reactivity OM in these sediments. These natural shelf sea processes may very likely negate (and possibly outweigh) any significant potential for large amounts of  $CO_2$  release from anthropogenic disturbance of the seabed across much of the continental shelf.

Current global estimates of 0.58–1.47 Pg of  $CO_2$  yr<sup>-1</sup> emitted from marine sediments as a consequence of bottom trawling (Sala et al., 2021) must be questioned in light of the lability data from the sediments of the UK EEZ (Figure 5). Sala et al. (2021) estimated that 70% and 28.6% of total OM was labile in fine and coarse sediments, respectively. The great spatial heterogeneity in OM reactivity between different sedimentary environments highlights the need to refocus the discussion on managing marine sedimentary OC resources away from the resilient stores of OM in offshore sediments toward the much more vulnerable OM found in inshore and coastal sediments. If marine sedimentary environments are to be managed specifically to protect vulnerable C resources and deliver climate benefits through reduced  $CO_2$  emissions, then we highlight the need to focus research efforts to generate the evidence and understanding necessary to ensure the protection of muddy inshore sediments as a global priority.

## Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

## Data Availability Statement

All data generated in this research can be found at Marine Scotland Data (Smeaton & Austin, 2022) (<https://data.marine.gov.scot/dataset/geochemical-analysis-quality-and-reactivity-organic-matter-held-marine-sediments-united/>).

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