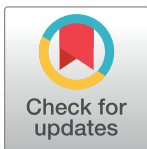


## RESEARCH ARTICLE

## Identifying priority areas to manage mobile bottom fishing on seabed carbon in the UK

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## Abstract

Mobile bottom fishing using trawls and dredges may cause significant reductions in seabed sediment organic carbon stores, limiting the oceanic carbon sink. Although uncertainties remain about the fate of disturbed carbon, protecting the most important and highly disturbed seabed carbon sinks for climate change mitigation represents a sensible precautionary policy. Using spatial modelling of best available datasets relating to seabed carbon stocks and fishing disturbance in the UK Exclusive Economic Zone (EEZ), we estimate the cumulative disturbance of organic carbon by mobile bottom fishing to be 109 Mt per year. Areas with high carbon stocks and disturbance are geographically restricted enabling identification of potential priority areas for precautionary carbon management and/or future research. By targeting areas with the highest 1%, 5% and 10% of carbon values, while also accounting for fisheries displacement, we examined three management levels ranging from 3–12% of the area of the EEZ. These areas encompass between 7–29% of organic carbon stocks. If all mobile bottom fishing disturbance in priority areas was eliminated it would reduce seabed carbon disturbance across the EEZ by 27–67%. Eliminating this fishing effort would be estimated to affect fisheries landings worth between £55m and £212m per year. In contrast, if all mobile bottom fishing was displaced from priority areas to other areas within the study region, our modelling predicts net reductions of organic carbon disturbance between 11% and 22%. Further research is needed to quantify how much of this carbon is remineralised following disturbance and therefore the magnitude of carbon emissions/savings. We also find that to offset the carbon and financial impacts of fisheries displacement, complementary management will be necessary to protect more carbon, including gear modifications to reduce seabed disturbance, overall effort reductions, and incentives to switch to alternative fishing methods.

## OPEN ACCESS

**Citation:** Epstein G, Roberts CM (2022) Identifying priority areas to manage mobile bottom fishing on seabed carbon in the UK. *PLOS Clim* 1(9): e0000059. <https://doi.org/10.1371/journal.pclm.0000059>

**Editor:** Renata Hanae Nagai, Federal University of Parana, BRAZIL

**Received:** March 17, 2022

**Accepted:** July 30, 2022

**Published:** September 13, 2022

**Peer Review History:** PLOS recognizes the benefits of transparency in the peer review process; therefore, we enable the publication of all of the content of peer review and author responses alongside final, published articles. The editorial history of this article is available here: <https://doi.org/10.1371/journal.pclm.0000059>

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**Data Availability Statement:** All data and associated code are available in the [supplementary material](https://www.seanoe.org/data/00784/89590/) or in the SEANOE data repository at <https://www.seanoe.org/data/00784/89590/>.

## Introduction

The ocean has absorbed ~40% of anthropogenic CO<sub>2</sub> emissions since the industrial revolution acting as a major brake on climate change [1, 2]. However, under all future predicted climate scenarios the oceanic carbon sink is projected to become less effective at absorbing CO<sub>2</sub> from the atmosphere [3]. One way to improve the ocean's ability to absorb excess atmospheric CO<sub>2</sub> is to conserve marine organic carbon (OC) stores and promote natural carbon sequestration

**Funding:** GE & CMR were funded for this work by Blue Marine Foundation through the Barclays Ocean Climate Impact grant. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

**Competing interests:** The authors have declared that no competing interests exist.

[4]. These processes, generally referred to as blue carbon, are well established for marine vegetated habitats [5], but it is the functioning of the entire marine ecosystem which maintains the ocean as a sink for anthropogenic CO<sub>2</sub> [6].

Subtidal marine sediments contain the ocean's biggest organic carbon store, estimated to hold ~2.3 Tt in the top 1 m [7] and accumulate globally an additional 126–350 Mt of organic carbon per year [8–10]. However, it is increasingly apparent this store may be vulnerable to remobilisation and mineralisation by human disturbance [8, 11–13]. By far the most widespread human disturbance to the seabed is the use of mobile bottom trawls and dredges to catch fish and shellfish [14–16]. A global first-order estimate suggested that annually, mobile bottom fishing activities may cause ~590–1470 Mt of CO<sub>2</sub> to be released into the water column due to disturbance and remineralisation of organic carbon from seabed sediments [11]. This is equivalent to 15–20% of the atmospheric CO<sub>2</sub> absorbed by the ocean each year [11]. By significantly increasing seawater inorganic carbon concentrations, it would slow the rate of CO<sub>2</sub> uptake from the atmosphere, and possibly release more oceanic CO<sub>2</sub> back to the atmosphere [11, 17–19]. Although there is considerable uncertainty in the magnitude of organic carbon which is remineralised following disturbance from mobile bottom fishing [13], protecting seabed sediment carbon from human disturbance would appear to be an important step in global efforts to mitigate climate change.

To provide climate change mitigation potential, conservation or restoration actions must cause emission reductions or removals that are additional to what would occur in a business-as-usual scenario [20]. Information on the standing stock of organic carbon in seabed sediments is therefore not sufficient to quantify the carbon benefits from increasing protection. There is a need to quantify the magnitude of organic carbon disturbed, the potential to manage this disturbance and the societal and financial cost-benefits. Additionally, the net effect in any conservation action must also be calculated. If protection of some areas of the seabed leads to equivalent disturbance to organic carbon elsewhere due to displaced human activities then no carbon benefits are achieved [20]. It is therefore vital to consider and quantify, when designing a management strategy, how fisheries displacement may affect organic carbon stocks.

Here, we use the UK exclusive economic zone (EEZ) as a case study to outline a procedure to identify areas where precautionary protection from mobile bottom fishing activities could have significant carbon benefits. Using data on seabed sediment carbon stocks and fishing disturbance we model the magnitude and distribution of seabed organic carbon disturbance across the EEZ. Further, by considering additionality of carbon benefits, fisheries displacement and landings value, we identify priority areas for future research and potential fisheries management.

## Materials and methods

### Analysis software

All analyses were undertaken in R 4.0.5 [21]. Manipulation and display of raster and spatial vector data was carried out using the *raster*, *terra* and *sf* packages [22–24]. The *fasterize* package was used to convert spatial polygon data into raster layers for further manipulation [25]. Further editing and display of spatial data was also carried out in QGIS [26]. A list of input data sources required to run the analyses is shown in [S1 Table](#).

### Seabed sediment organic carbon stock

Due to data availability, estimates of organic carbon standing stock in seabed sediments across the UK EEZ were constrained to the top 10 cm of the seabed. Four previously published spatial analyses of organic carbon stocks in the top 10 cm were identified, each covering varying

spatial extents and resolutions across the Northeast Atlantic [27–30]. All datasets, except Diesing, Kroger [27] and Diesing, Thorsnes [28], were available as estimated organic carbon stock ( $\text{kg m}^{-2}$ ) in each spatial pixel for their respective extents. Data from Diesing, Thorsnes [28] were converted from  $\text{kg m}^{-3}$  to  $\text{kg m}^{-2}$  in the top 10cm by dividing all values by 10. Publicly available data outputs from Diesing, Kroger [27] only contain estimates for the content of organic carbon as a percent of sediment dry weight. This was converted to stock values ( $\text{kg OC m}^{-2}$ ) using data from Smeaton, Hunt [29] who modelled dry bulk density ( $\text{kg dry sediment per m}^3$ ) across the study area. Final estimates of organic carbon in  $\text{kg m}^{-2}$  were made at a resolution of 500 x 500 m, as this is approximately the highest resolution of the 4 published datasets. All datasets were projected onto a 500 m resolution grid covering the UK EEZ with Lambert Azimuthal Equal Area coordinate system. Projections used bilinear interpolation and the mean stocks of organic carbon across the datasets was calculated where overlap occurred. Stock data ( $\text{kg OC m}^{-2}$ ) was converted to  $\text{t km}^{-2}$  (1000 kg) for further analysis.

### Mobile bottom fishing disturbance

Data on the extent and disturbance from mobile bottom fishing was primarily derived from published outputs by the International Council for the Exploration of the Sea (ICES). ICES calculate the annual surface swept area from mobile bottom fishing as hours fished within a given year multiplied by average fishing speed multiplied by gear footprint [31]. The annual swept area ratio (SAR) is the sum of the swept areas divided by the area of a given spatial pixel [31]. SAR values are used to indicate the theoretical number of times the entire pixel is impacted by mobile bottom fishing within a year if effort was evenly distributed within that pixel [31, 32]. Therefore, as an example, a SAR of 3 is assumed to mean that the entire pixel is trawled three times per year, while a SAR of 0.4 is assumed to mean that 40% of the pixel is trawled once per year. In ICES (2019) [31] the total SAR from mobile bottom fishing vessels carrying vessel monitoring systems (VMS) registered to European vessels (Belgium, Denmark, France, Germany, Ireland, The Netherlands, Norway, Sweden and the UK) was available for each year from 2009 to 2017 at a resolution of  $0.05^\circ$  for four gear categories: otter trawls, beam trawls, dredges and seines [31]. The mean SAR across years was calculated for each gear type in each pixel.

Where data from the ICES (2019) [31] publication were lacking for parts of the study area, a less precise average annual SAR value was derived from ICES (2021) [32]. Here, published values for each gear type (otter trawls, bottom trawls, dredges and seines) are present as a mean annual SAR at a resolution of  $0.05^\circ$  for the period 2013–2018 from VMS data provided by all EU vessels, United Kingdom, Faroes, Iceland, and Norway [32]. As SAR data in ICES (2021) [32] are only available as discrete categorical values, the median value within each categorical range was used.

As ICES data only considers those vessels with VMS, a large portion of the inshore, <15m fishing fleet, will not be considered in the calculation of SAR. A conservative proxy SAR value for <15 m fleet was calculated using survey data from ScotMap in Scotland [33], and CEFAS data in England and Wales [34]. Using surveys of fishers who own <15 m Scottish registered vessels, ScotMap contains spatial data displayed at  $0.025^\circ$  resolution, on the number of vessels which identified that they carry out bottom mobile fishing activities within different areas across Scotland's marine zone. Integer values for the number vessels are displayed for three vessel categories—“*Nephrops* trawls”: trawler vessels primarily targeting *Nephrops norvegicus*; “Other trawls”: predominantly targeting squid and flatfish; and “Dredges”: any type of bottom dredge. Where pixels contain <3 vessels, data are only shown as a categorical value (1–3 vessels), therefore a conservative value of one vessel was used here for further analysis. Number of

vessels in Scotland's marine area only were converted to estimated SARs using data from Eigaard, Bastardie [35]. Average values of hourly swept area (SA: km<sup>2</sup> h<sup>-1</sup>) were estimated as 1.2, 0.5 and 0.1 for *Nephrops* trawls, Other trawls and Dredges respectively [35]. Using a conservative estimate that each vessel passes through each pixel once per year, and that vessels are assumed to travel at approximately 3 knots while fishing [35] (and are therefore estimated to travel through 2.75 pixels per hour), the number of vessels per pixel was converted to an average annual SAR using the formula: SAR = n\*(SA/2.75)/A; where n is the number of vessels and A is the estimated surface area of the pixel calculated using the *area* function from the *raster* package.

To estimate inshore fishing disturbance in English and Welsh waters, Vanstaen and Breen [34] calculate a value of sightings per unit effort (SPUE) at a resolution of 0.05° x 0.025° using CEFAS sightings data from fisheries monitoring vessels and overflight in 2007–2009 and 2010–2012. The value of SPUE for all trawler and dredging vessels within 12 nm was used here as a proxy for effort from the <15 m bottom mobile inshore fleet. Although these data may contain some vessels with VMS, and some mobile pelagic vessels, in England and Wales the <15 m fleet makes up over 90% of registered fishing vessels, and activity days data for vessels under 15 m length shows that just 1.76% of all fishing activity days for trawlers was undertaken using midwater trawls, and so 98.24% of activity days by trawlers is expected to be using bottom gears [34]. A mean of the two datasets (2007–2009 & 2010–2012) was taken for both trawls and dredges, and mean SPUE was converted to a coarse value of estimated annual SAR by rescaling the data so the maximum SAR in English and Welsh waters was equal to 2.13 times the maximum SAR calculated above for Scottish <15 m vessels. The 2.13 value was derived from the MMO 2019 UK Fisheries Statistics as the mean difference in total power of English and Welsh small vessels compared to Scottish vessels in 2007–2012 [36].

These processes led to nine distinct SAR data-layers to be used for further analysis (Table 1). All SAR values were converted to a swept volume ratio (SVR) by multiplying by the average penetration depth of the gear using the following formula: SVR = SAR\*(p/10), where p is the penetration depth measured in centimetres, and 10 cm is the depth of sediment under consideration [35, 37]. Penetration depths were derived from Hiddink, Jennings [37] and Eigaard, Bastardie [35], and applied as shown in Table 1. Finally, the SVR values across the nine data-layers were spatially aligned to the carbon stock data using bilinear interpolation and the sum taken to create a total SVR in each pixel across the study area. Overall, total SVR indicates the theoretical mean number of times the top 10cm of seabed sediments is disturbed by mobile bottom fishing each year.

**Table 1. Average mobile bottom fishing gear penetration depths.** Nine datasets on fishing disturbance (measured as swept area ratios) were converted to a swept volume ratio using estimates of the average depth to which different fishing gears penetrate seabed sediments.

Dataset	Component	Average penetration depth (cm)	Justification
ICES	Otter trawls	2.44	Estimated by Hiddink, Jennings [37]
ICES	Beam trawls	2.72	Estimated by Hiddink, Jennings [37]
ICES	Seines	0.5	Conservative value based on Eigaard, Bastardie [35]
ICES	Dredges	5.47	Estimated by Hiddink, Jennings [37]
ScotMap	Nephrops trawls	2.44	No specific gear type stated, however most commonly used gear type is otter trawls.
ScotMap	Other trawls	2.44	No specific gear type stated, however most commonly used gear type is otter trawls.
ScotMap	Dredges	5.47	Estimated by Hiddink, Jennings [37]
CEFAS	Trawls	2.44	No specific gear type stated, however most commonly used gear type is otter trawls.
CEFAS	Dredges	5.47	Estimated by Hiddink, Jennings [37]

<https://doi.org/10.1371/journal.pclm.0000059.t001>

## Mobile bottom fishing landings value

Data on the annual value of landings from mobile bottom fishing in each pixel was calculated in a similar method to that described in the previous section. The ICES (2019) [31] and ICES (2021) [32] datasets contain estimated landings value in Euros from all mobile bottom fishing vessels combined to the same spatial and temporal extent as the fishing disturbance data. Value of landings reported in the two ICES datasets were combined in the same way as conducted for fishing disturbance and converted to £ (GBP) using a conversion of 0.835. For smaller vessels lacking VMS, ScotMap contains spatial estimated landings value in GBP for <15 m Scottish vessels [33]. For this dataset, values for the three mobile bottom fishing gear types (as described in previous section) were aggregated to produce an estimate of total landings value for Scottish vessels lacking VMS. Data of landings value from smaller vessels operating in England as Wales are not present within the dataset used for calculating fishing disturbance [34]. To approximate the landings value from these vessels, the mean annual landings value between 2015–2019 for all English and Welsh beam trawls, bottom-towed trawls/seines and dredges with vessel size of  $\leq 10$  m was calculated from the MMO 2019 UK Fisheries statistics (fleet landings by ICES rectangle dataset) [36]. As no data exist on the relationship between total landings value and SAR for these vessels, landings value per pixel was approximated by assuming a linear relationship between SAR and landings value, with the total value apportioned based on the proportion of total SAR within each pixel.

The three landings value datasets were converted to per unit area values ( $\text{£ km}^{-2} \text{y}^{-1}$ ) using the *area* function, and projected to align with organic carbon stock data using bilinear interpolation. The final annual total landings value in GBP per pixel was calculated by summing the combined ICES data layer with ScotMap and CEFAS/MMO estimates and multiplying by the pixel area.

## Annual organic carbon disturbance from mobile bottom fishing

As there is considerable uncertainty in the magnitude of organic carbon which is lost or remineralised following disturbance from mobile bottom fishing this was not estimated here [13]. Instead a value of annual cumulative disturbance of seabed organic carbon stocks was calculated by multiplying the organic carbon standing stock in each pixel by the SVR. This creates a quantitative value (measured in  $\text{t OC km}^{-2} \text{y}^{-1}$ ) which indicates the level of disturbance on organic carbon stocks but does not equate to carbon loss or  $\text{CO}_2$  produced.

## Selecting seabed organic carbon priority areas

Potential priority areas for protection from mobile bottom fishing were identified by selecting areas with aggregations of pixels with high organic carbon stocks or high carbon disturbance. To identify a range of potential outcomes, three sets of priority areas were created using different thresholds; these were the highest 1%, 5% and 10% of pixel values. Following the subsetting of pixels by threshold values, high carbon stock and disturbance datasets were combined and unfished pixels were removed from selection as these would show no direct additionality from protection. Spatial resolution of analysis was then reduced to 2 km x 2 km pixels to reduce processing time and to give coarser area selections. Neighbouring pixels were joined using an 8-way Queen's case method and raster data were then converted to individual polygons. A 2 km buffer was drawn around each polygon with overlapping polygons dissolved to form single areas; and finally any holes were removed from each area using the *remove.holes* command from the *spatialEco* package. As this is a semi-automated selection process, the resultant spatial datasets would contain areas where single pixels or very small aggregations of pixels were selected. To exclude these occurrences, areas were removed if they contained <0.1% of the total carbon stock and <0.1% of the total carbon disturbance across the study region. Overall,

this creates a set of coarse bounded area selections which contain the majority of high carbon stock and disturbance areas up to a given threshold.

### Modelling the effects of fisheries displacement

To estimate the net effect of excluding mobile bottom fishing from a given priority area, organic carbon disturbance was recalculated after modelled displacement of fishing activities. Displacement was modelled separately for each of the nine SVR data-layers and all fishing disturbance within a priority area was projected into new locations within the study region. The available locations for displaced fishing disturbance was determined by the following criteria: 1) maximum displaced distance from the edge of a priority area is 200 km for larger VMS vessels represented by the ICES data-layers, and 100 km for the smaller vessels represented by the ScotMap and CEFAS data-layers, as it is assumed that further distances would be logistically or financially inviable; 2) fishing disturbance cannot be displaced into other priority areas; 3) fishing disturbance cannot be displaced into areas that have no current fishing activity within that data-layer, as it was assumed if these areas have been completely avoided by these fishers they are likely to be inappropriate for the fishing activity.

The magnitude of displaced fishing disturbance in each available location was determined by taking the average of two displacement models—proportional redistribution and exponential redistribution (see Hoos, Buckel [38] for details). The proportional model predicts that disturbance is redistributed proportionally to baseline disturbance, i.e. areas with high disturbance receive a larger percentage of displaced effort. This assumes that the current distribution of fishing disturbance reflects the locations of productive and unproductive fishing grounds and is therefore likely to be targeted in the same proportions by displaced effort [39]. The exponential displacement model assumes that fishing disturbance from inside a closed area is spread inverse exponentially, with increasing disturbance as distance from the closed area decreases. This assumes fishers would aim to minimise displaced distance, due to financial/logistical costs, while gaining potential benefits from spill-over effects from the closed area [38, 40]. An exponent value of 0.75 was selected for the exponential model due to the larger areas under consideration when compared to Hoos, Buckel [38] and to better balance the two displacement models.

Following the calculation of modelled fisheries displacement, the sum of all nine SVR data-layers was taken and organic carbon disturbance recalculated as above. Finally, the difference in magnitude of organic carbon disturbance between the original baseline scenario and that following fisheries displacement was taken as the predicted net effect of excluding mobile bottom fishing from a given priority area.

### Refining priority areas and calculating final net effects

Priority areas were excluded from a given set if they were calculated to cause a net increase in carbon disturbance following modelled fisheries displacement. After this refinement process, the net effect of establishing a mobile bottom gear closure within each final proposed priority area was recalculated following modelled fisheries displacement as described previously. Finally, fisheries displacement was modelled across all priority areas within a given set, and the net reduction of organic carbon disturbance across the entire study region was calculated.

## Results

### Organic carbon stock and spatial distribution

The study region covered  $\sim 722,723 \text{ km}^2$ , or 93.4% of the UK EEZ, with the northern-most section of the EEZ excluded due to lack of carbon stock data and the most south-westerly section

excluded due to lack of fishing activity data (Fig 1). By unifying four previously published spatial organic carbon datasets, the study region was estimated to hold 307.2 Mt of organic carbon in the top 10 cm of the seabed (Fig 1A).

Estimated stocks of organic carbon in the top 10 cm ranged from  $<100$ – $4,159$  t OC km<sup>-2</sup> with a mean of  $425 \pm 148$  (SD) t OC km<sup>-2</sup> (Fig 1A). Highest stocks of organic carbon were predicted in the fjords and lochs of Scotland and Northern Ireland, and nearshore areas of Tyne and Wear (Northeast England) (Fig 1A). High stocks were also found in coastal and inshore waters, particularly around Scotland, northeast and east England and the North Channel of the Irish Sea (Fig 1A). Offshore areas with high stocks of organic carbon were less extensive, predicted to occur in the Celtic Deeps, as well as small area of Haig Fras (southwest UK) and on the northwest shelf slope (Fig 1A).

### Mobile bottom fishing disturbance

Seabed disturbance from mobile bottom fishing vessels was quantified by combining nine spatial datasets of swept area ratios (SAR) i.e. the proportion of the seabed swept by towed gear per year (S1 Fig), along with gear penetration depths to calculate an annual swept volume ratio (SVR; S2 Fig). The vast majority of fishing disturbance was from otter trawling by larger vessels with VMS, contributing 81.6% to the total disturbance from mobile bottom fishing across the study region (S2 Fig). This was followed by beam trawling from VMS vessels, with a total of 6.5% of seabed disturbance (S2 Fig). Four vessel types contributed similar levels of remaining seabed disturbance—dredging by VMS vessels (2.5%), seining by VMS vessels (2.7%), *Nephrops* trawling by smaller Scottish vessels (3.7%), and bottom trawling by smaller vessels in English/Welsh inshore waters (2.4%) (S2 Fig). The remaining vessel types (dredging by smaller Scottish vessels, trawling by Scottish vessels for squid/flatfish and dredging in English/Welsh inshore waters) each contributed  $< 0.5\%$  (S2 Fig).

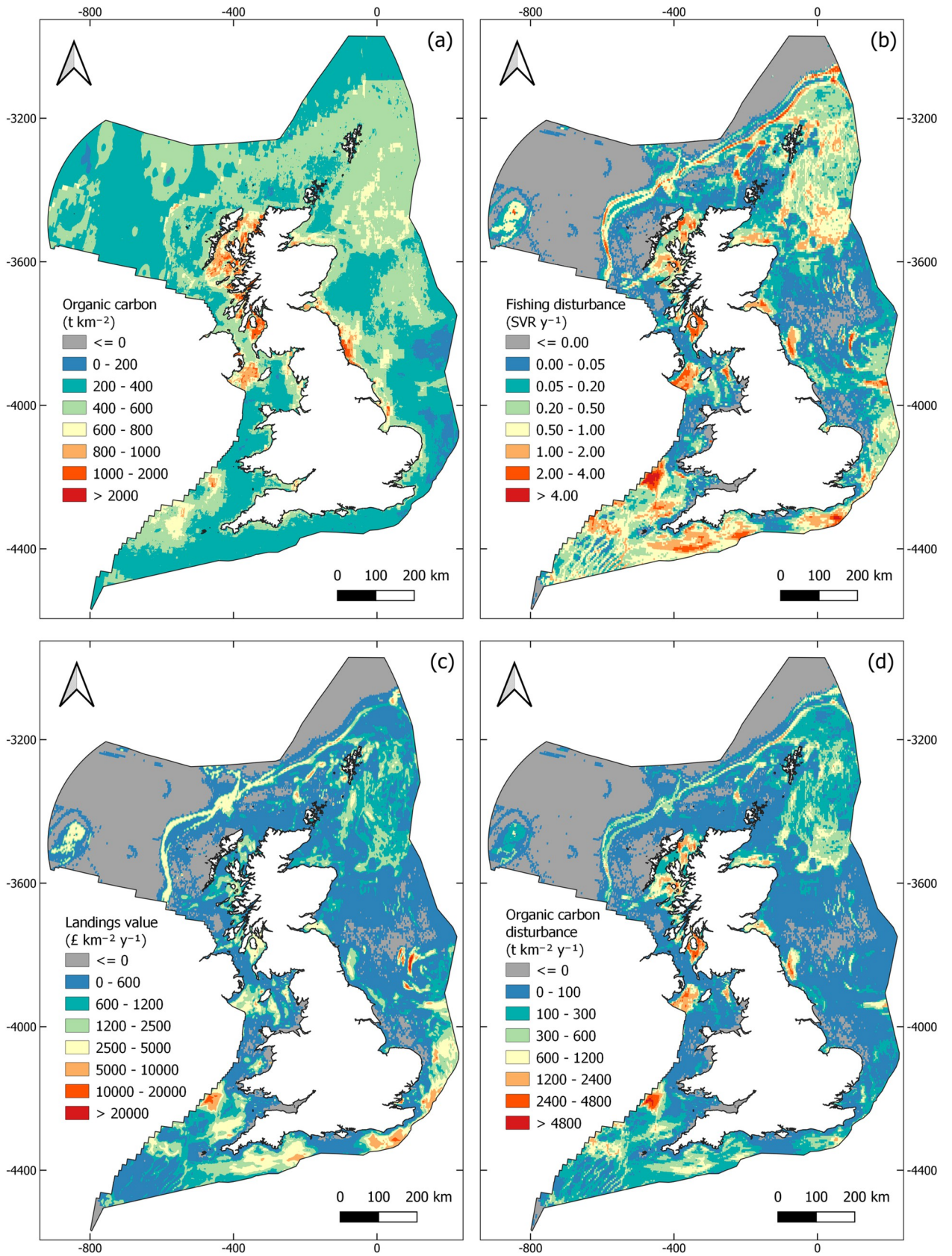
When combining these nine data-layers together, mean annual SVR across the study region was  $0.3 \pm 0.5$ , and ranged between  $<0.001$ – $8.5$  in fished areas (Fig 1B). There were a number of highly disturbed seabed areas across the UK continental shelf and slope, as well as within inshore waters (Fig 1B). The most highly impacted area was in the Celtic Deeps, with SVRs  $>5.5$  (Fig 1B). Mobile bottom fishing occurred across the majority of the study area, with only 26.2% of the seabed estimated to have been unaffected over the ~10 year period covered by the datasets (Fig 1B).

### Fisheries landing value

The total value of fish landed from mobile bottom fishing vessels operating in the study area was estimated as £494m yr<sup>-1</sup> (Fig 1C). The vast majority (95.5%) of this was predicted to be from larger vessels with VMS (S3 Fig). Both smaller mobile bottom fishing vessels lacking VMS in Scotland, as well as those in England and Wales were estimated to land fish with total value of £11m yr<sup>-1</sup>, each contributing ~2.2% to total landings value (S3 Fig). The estimated total landings value per unit area ranged from  $<£20$  - £29,317 km<sup>-2</sup> yr<sup>-1</sup> in fished areas, with a mean of  $£934 \pm £1,351$  km<sup>-2</sup> yr<sup>-1</sup> (Fig 1C). Highest value areas were predominantly located offshore, around east, south and southeast England, as well as on the Celtic Deeps and within the Greater Thames Estuary (Fig 1C).

### Organic carbon disturbance from mobile bottom fishing

To derive a value of annual cumulative disturbance to seabed organic carbon, the organic carbon standing stock in each pixel was multiplied by mean annual fishing disturbance from mobile bottom fishing (SVR). Total organic carbon disturbance across the study region was





**Fig 1. Modelled seabed variables across the UK.** (a) Stock of organic carbon in the top 10 cm of seabed sediments. (b) Disturbance from mobile bottom fishing vessels measured as mean annual swept volume ratio (SVR). (c) Mean annual landings value of fish caught by mobile bottom fishing vessels. (d) Annual cumulative disturbance of organic carbon from mobile bottom fishing. Basemap adapted from [MarineRegions.org](http://MarineRegions.org). Available online at [www.marineregions.org](http://www.marineregions.org).

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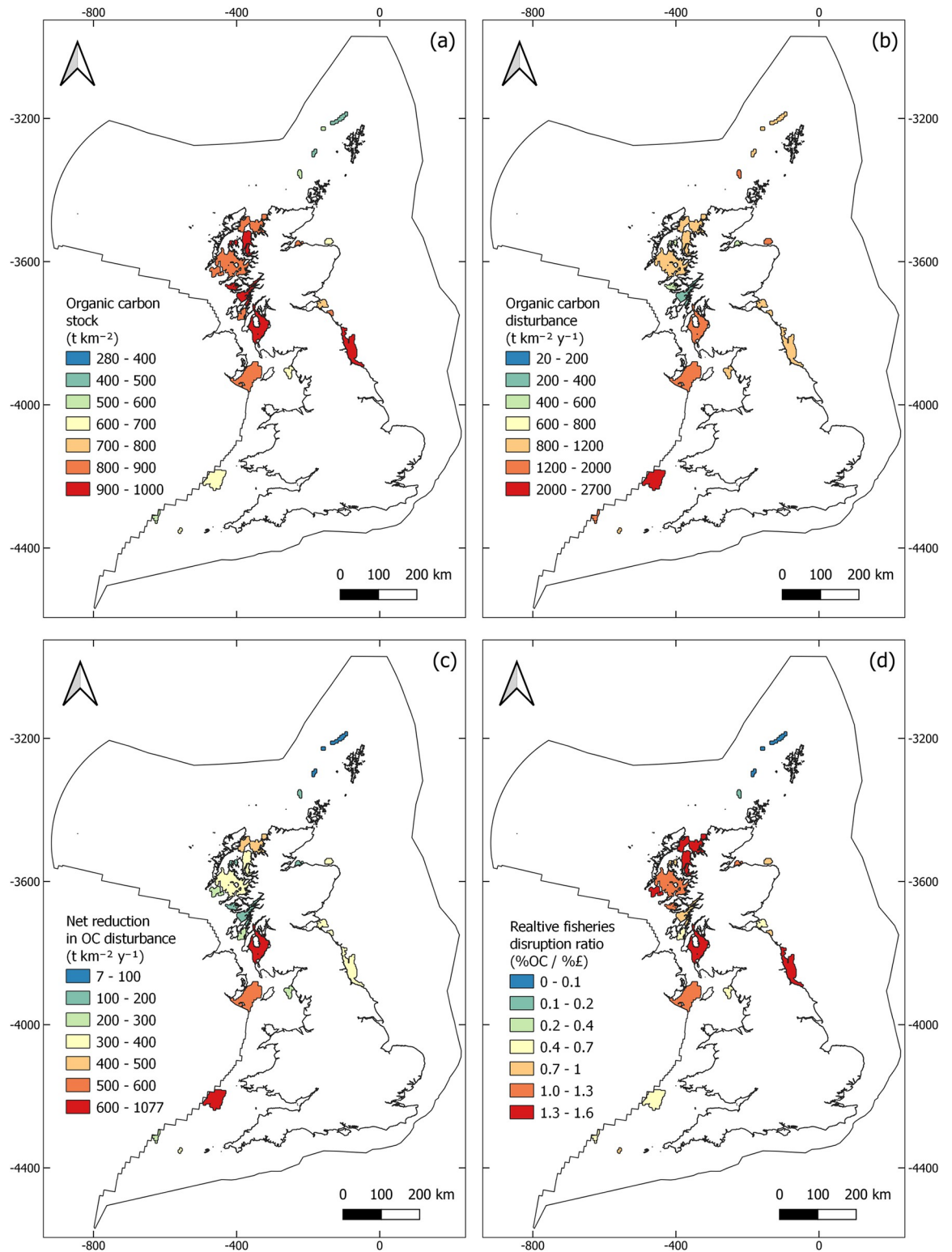
estimated as 109 Mt per year (Fig 1D). Organic carbon disturbance per unit area ranged from <1 to 6,918 t OC km<sup>-2</sup> yr<sup>-1</sup>, with a mean of 151 ± 332 t OC km<sup>-2</sup> yr<sup>-1</sup> (Fig 1D). High values of disturbance were spatially restricted across the study area (Fig 1D). Highest organic carbon disturbance occurred across the Celtic Deeps and in small parts of the Firth of Clyde (south-west Scotland) (Fig 1D). Other areas of high carbon disturbance were largely found in coastal/inland waters, particularly across western Scotland, the North Channel of the Irish Sea, near-shore areas of Tyne and Wear (northeast England) and Cumbria (northwest England), and in the outer parts of the eastern Scottish estuaries of the Moray and Forth (Fig 1D).

### Priority areas to protect seabed organic carbon

To identify where protection from mobile bottom fishing would achieve the largest potential carbon benefit, areas were selected if they contained aggregations of fished pixels with high densities of predicted organic carbon disturbance or organic carbon stock. To identify a range of potential outcomes, three sets of priority areas were created using different thresholds; these were based on prioritising the inclusion of highest 1%, 5% and 10% of organic carbon values from each of the two data layers. A semi-automated area selection process was undertaken to encapsulate the selected pixels in cohesive areas where possible, therefore the spatial coverage of a priority area scenario can be larger than the threshold proportion value. These three scenarios cover 3%, 12% and 21% of the area of the EEZ respectively, and encapsulate 7%, 18% and 29% of organic carbon stocks (Figs 2–4, S4–S6 Figs, Table 2). The total proportion of carbon disturbance that would be mitigated if all fishing disturbance within priority areas was eliminated is 27%, 51% and 67% respectively (Figs 2–4, S4–S6 Figs, Table 2). In contrast, if all fishing disturbance was displaced to other areas within the study region, the predicted net reduction in organic carbon disturbance following modelled fisheries displacement was 11%, 18% and 22% respectively, equivalent to 11.5, 20.1 and 24.4 Mt OC y<sup>-1</sup> (S7–S9 Figs, Table 2).

Priority areas with highest carbon stocks per unit area were those located in the insular water bodies west of Scotland (sealochs and inter-island spaces), the North Channel of the Irish Sea and coastal waters of northeast England (Figs 2–4, S2–S4 Tables). If all fishing effort within priority areas was eliminated those areas with the largest reductions in organic carbon disturbance per unit area were predominantly found in the Celtic Deeps, the Firth of Clyde and the North Channel of the Irish Sea (Figs 2–4, S2–S4 Tables). These were also the priority areas predicted to have the highest per unit area reduction of organic carbon disturbance following modelled fisheries displacement (Figs 2–4, S2–S4 Tables). Other priority areas with high per unit area reductions in carbon disturbance following fisheries displacement included the insular water bodies of northwest Scotland and coastal waters of northeast England (Figs 2–4, S2–S4 Tables).

To identify those priority areas likely to cause the least relative disruption to fisheries, a ratio was calculated by taking the estimated proportion of total organic carbon disturbance that would be mitigated following modelled fisheries displacement and dividing it by the proportion of total landings value within each priority area (Figs 2–4, S2–S4 Tables). This ratio varied among priority area scenarios, however the insular water bodies of northwest Scotland, the North Channel of the Irish Sea and the coastal waters of northeast England and the Firth of Forth were generally the areas with most carbon benefit compared to disruption to landings



**Fig 2. Top 1% proposed priority areas for managing mobile bottom fishing on seabed sediment carbon.** The location of priority areas is shown with colours indicating the following attributes: **(a)** Mean organic carbon stock in the top 10 cm of sediment; **(b)** Mean cumulative annual disturbance to this organic carbon from mobile bottom fishing; **(c)** Mean net reduction in disturbance if the priority area was closed to mobile fishing and all effort was displaced to locations outside priority areas; **(d)** A relative fisheries disruption ratio (the proportion of total carbon disturbance mitigated to the total proportion of fisheries value that would be disrupted). In all cases

colours closer to red would indicate a more preferential/beneficial priority area on a per unit area basis. See [S4 Fig](#) and [S2 Table](#) for total values, location descriptors and results as continuous data. Basemap adapted from [MarineRegions.org](#). Available online at [www.marineregions.org](#).

<https://doi.org/10.1371/journal.pclm.0000059.g002>

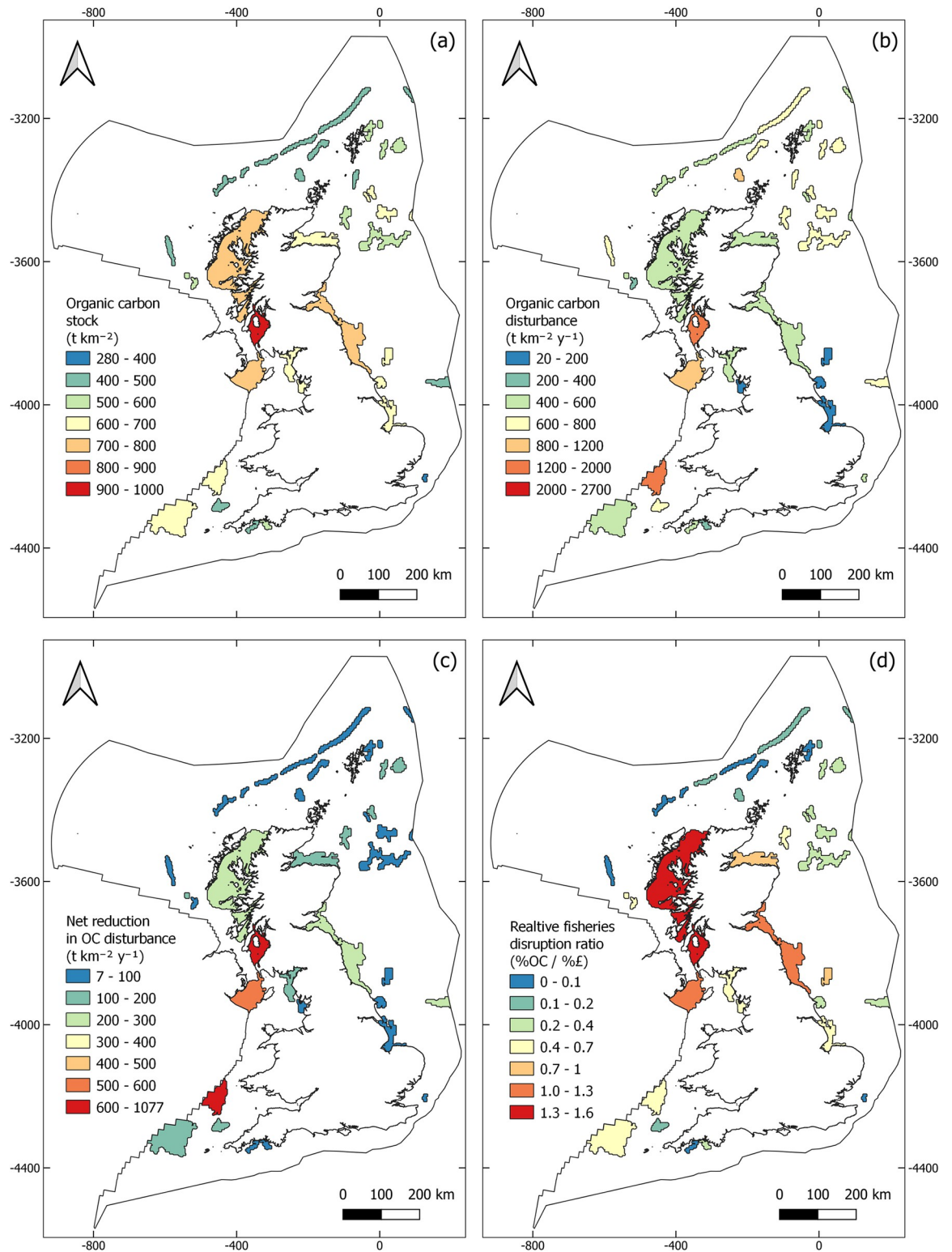
value (Figs 2–4, [S2–S4 Tables](#)). Areas around the shelf slope, Shetland and the English Channel generally had the most disruption compared to their net reduction in carbon disturbance (Figs 2–4, [S2–S4 Tables](#)).

## Discussion

The marine environment holds a large fraction of the UK organic carbon store. Seabed sediments across the UK EEZ are estimated to store 307 Mt of organic carbon in their top 10 cm ([Fig 1A](#)), which compares with an estimated 183 Mt stored in high carbon terrestrial and intertidal vegetation and soils (assuming even distribution across the top 30 cm of soils/sediments) [[41](#)]. Many of these habitats, such as peatland, forests, marsh, mudflats and heathland, are now recognised as important carbon stores with the potential to mitigate against climate change, which has led to widespread efforts to protect and restore them globally [[42](#)]. The contribution of seabed sediment habitats, by contrast, is under-appreciated, but due to the scale of their organic carbon stores, there is need to urgently reconsider their management and protection.

Across the UK EEZ the cumulative disturbance to organic carbon in seabed sediments from mobile bottom fishing was estimated as 109 Mt per year ([Fig 1C](#)). There is considerable uncertainty over the fate of organic carbon once it is disturbed by mobile fishing gears—being dependent on the abiotic and biotic settings as well as the chemical characteristics of the carbon itself [[13](#)]. Although some of the disturbed organic carbon is likely to be remineralised to CO<sub>2</sub>, some will simply remain in-situ, and some will be transported, either being consumed or relocated elsewhere [[11](#), [43](#)]. Even if organic carbon is remineralised to CO<sub>2</sub> it does not mean that it will be released to the atmosphere or even stay in the form of aqueous inorganic carbon; it is expected that a proportion would be re-fixed through photosynthesis of marine algae and aquatic plants [[18](#)]. Additionally, organic carbon in the top 10 cm of the seabed is still undergoing active processing with natural remineralisation occurring across differing sediment depths dependent on environmental settings [[44](#)]. The interaction between this natural processing and anthropogenic disturbance by mobile fishing gears adds further uncertainty. The oceanic carbon cycle is highly complex [[6](#)] and how disturbance of seabed sediment organic carbon will affect marine carbon cycling and the atmospheric concentration of CO<sub>2</sub> requires further research [[13](#), [18](#)]. Even so, the protection and restoration of organic carbon stores across land and sea is widely accepted as necessary for climate change mitigation [[42](#)]. Similar levels of uncertainty and complexity exist for the avoided loss of sediment/soil carbon in well-established blue carbon habitats [[45](#), [46](#)], yet there are numerous papers that quantify and value avoided emissions of CO<sub>2</sub> due to reduced anthropogenic disturbance in these wetland ecosystems [e.g. [47](#)]. This uncertainty does not diminish the validity of these studies, rather they each provide additional evidence to improve boundary setting and management approaches. Overall, fishing disturbance of seabed sediment carbon provides conditions conducive to remineralisation [[8](#), [13](#)], and recent modelling studies indicate that the level of loss and/or remineralisation may be significant [[11](#), [12](#), [19](#), [48](#)], therefore until the fate of carbon is better understood, protection of the most intensively disturbed carbon sinks represents sensible precautionary policy.

The priority areas identified in this study could act as sites for further investigation and potentially new management measures for the protection of seabed organic carbon. Dependent on the scale of management areas which were sought, they cover 7–29% of organic



**Fig 3. Top 5% proposed priority areas for managing mobile bottom fishing on seabed sediment carbon.** The location of priority areas is shown with colours indicating the following attributes: **(a)** Mean organic carbon stock in the top 10 cm of sediment; **(b)** Mean cumulative annual disturbance to this organic carbon from mobile bottom fishing; **(c)** Mean net reduction in disturbance if the priority area was closed to mobile fishing and all effort was displaced to locations outside priority areas; **(d)** A relative fisheries disruption ratio (the proportion of total carbon disturbance mitigated to the total proportion of fisheries value that would be disrupted). In all cases

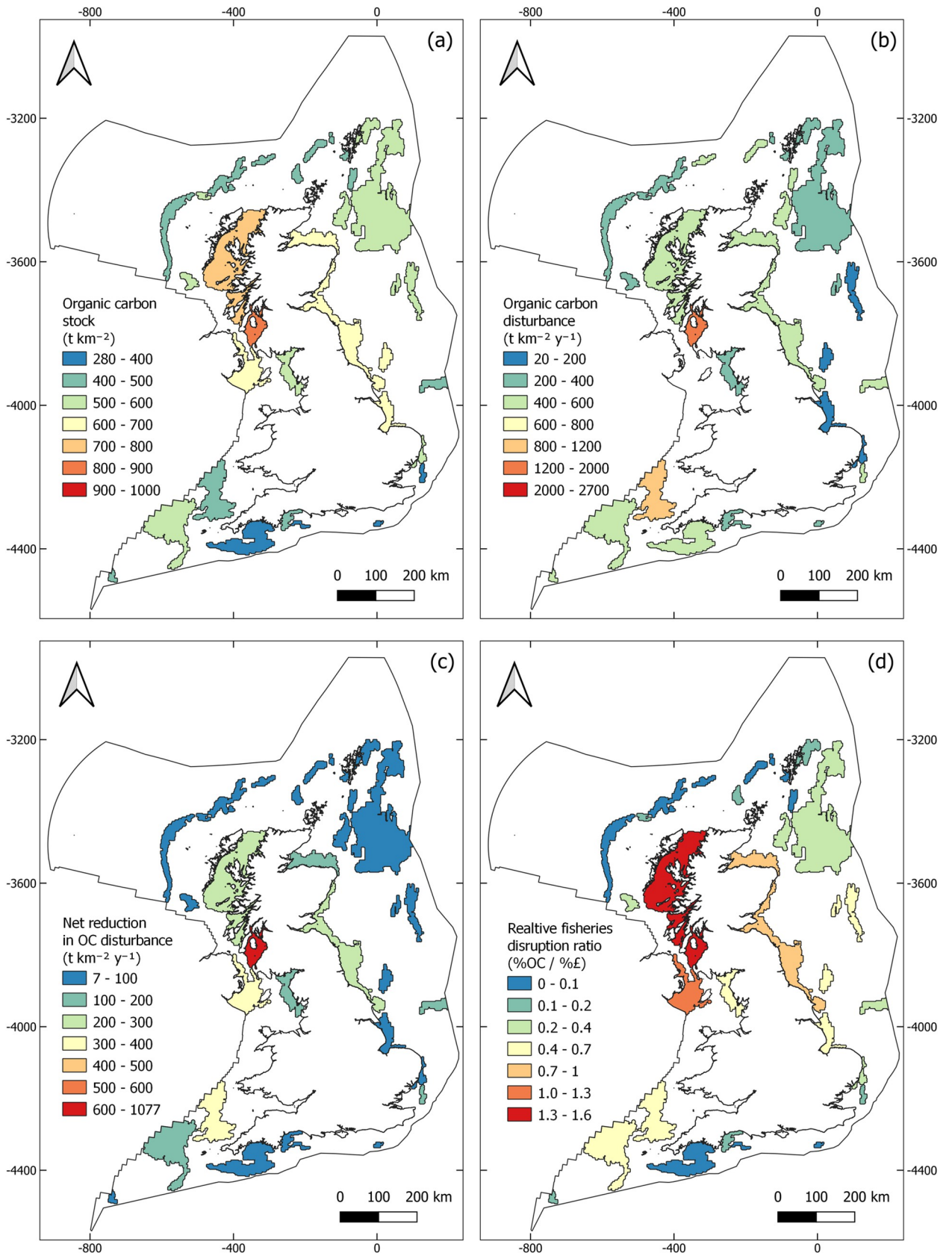
colours closer to red would indicate a more preferential/beneficial priority area on a per unit area basis. See [S5 Fig](#) and [S3 Table](#) for location descriptors, total values and results as continuous data. Basemap adapted from [MarineRegions.org](#). Available online at [www.marineregions.org](#).

<https://doi.org/10.1371/journal.pclm.0000059.g003>

carbon stocks, 27–67% of carbon disturbance but only 3–21% of the area of the EEZ (Figs 2–4, S4–S6 Figs, Table 2). If all mobile bottom fishing effort occurring within priority areas was retired, this would therefore mitigate up to 67% of carbon disturbance. However, if fishing disturbance was displaced elsewhere within the study region we predict a net reduction in carbon disturbance between 11–22% (S7–S9 Figs, Table 2). After accounting for fisheries displacement, the majority of the carbon benefit was predicted to come from the west of the UK, along the majority of Scotland's insular waters (sealochs and inter-island spaces), as well as in the North Channel of the Irish Sea, and offshore areas of the Celtic Deep (S4–S6 Figs, S2–S4 Tables). To the east of the UK the largest potential reductions in carbon disturbance derived from priority areas in coastal areas of northeast England and the Firth of Forth, as well as offshore at the Fladen Grounds (S4–S6 Figs, S2–S4 Tables). Although protecting some of these areas would disproportionately affect fisheries landing value compared to the proportion of carbon disturbance mitigated—particularly those on the Fladen Grounds, mobile bottom fishing closures in insular water bodies of western Scotland and in the North Channel of the Irish Sea are predicted to provide some of the largest potential carbon benefits while also having lower levels of fisheries disruption (Figs 2–4, S4–S6 Figs, S2–S4 Tables).

Establishing mobile bottom fishing closures in priority areas would displace a significant proportion of mobile fisheries, with an estimated total landings value between £55m and £212m per year (11–43% of landings value from mobile bottom fishing across the EEZ). However, at least some of this value could be recovered from the areas that the fishing is displaced to. Additionally, only certain types of fishing gear would need to be excluded from priority areas to safeguard carbon. The target species sought by mobile bottom fisheries, such as flatfish and shellfish, could still be targeted in carbon protection areas by fishing methods which cause little-to-no disruption to the seafloor such as static nets, lines and traps, offsetting some further economic loss. Against possible fisheries losses, it is important to consider the societal carbon value of any climate change mitigation actions [49]. Detailed calculations are currently not feasible due to the uncertain link between seabed carbon disturbance and atmospheric CO<sub>2</sub> concentrations [11, 13, 48]. But the economic costs of protection could be outweighed by the value of carbon savings [50].

The net reduction in carbon disturbance estimated in this study relies on predicting and modelling how fishers will redistribute following spatial management measures. Displaced effort is likely to move to areas both in proportion to current effort, following the present distribution of productive fishing grounds, and inverse exponentially with distance from new closed areas, which would minimise displaced distance and reflect possible gains from spillover effects from protected areas [38–40, 51]. Maximum displaced distance is also likely to depend on the size of the vessel [38, 40, 52]. It is for these reasons the mean effect of multiple simulated fisheries displacement scenarios was used to best net organic carbon disturbance. Even so, other factors will influence fishing displacement [51, 53], which are outside the scope of this study due to lack of sufficient data. They include the distribution and behaviour of fish and shellfish stocks [54–56], distance to port [40, 54, 57], fuel costs [54], water depth [40], habitat type [58], physical obstacles or barriers [54], tradition [57, 59], competition among fishers [56, 60] and potential landings value [56, 59]. To refine estimates of net carbon disturbance after fisheries displacement, some of these additional factors could be considered and modelled on a site-by-site basis where data are available.



**Fig 4. Top 10% proposed priority areas for managing mobile bottom fishing on seabed sediment carbon.** The location of priority areas is shown with colours indicating the following attributes: (a) Mean organic carbon stock in the top 10 cm of sediment; (b) Mean cumulative annual disturbance to this organic carbon from mobile bottom fishing; (c) Mean net reduction in disturbance if the priority area was closed to mobile fishing and all effort was displaced to locations outside priority areas; (d) A relative fisheries disruption ratio (the proportion of total carbon disturbance mitigated to the total proportion of fisheries value that would be disrupted). In all cases colours closer to red would indicate a more preferential/beneficial priority area on a per unit area basis. See S6 Fig and S4 Table for location descriptors, total values and results as continuous data. Basemap adapted from [MarineRegions.org](http://MarineRegions.org). Available online at [www.marineregions.org](http://www.marineregions.org).

<https://doi.org/10.1371/journal.pclm.0000059.g004>

The estimated net reduction in carbon disturbance if all fishing effort was displaced from priority areas into other parts of the study region ranged from 11–22% by closing between 3–37% of the EEZ to mobile fishing gears (S7–S9 Figs). Short of closing all of the sea to mobile gears, additional non-spatial management measures that reduce overall seabed disturbance could protect more of the carbon present [61, 62]. For example gear modifications to reduce seabed disturbance, overall effort reductions through total effort quotas, and incentives to switch to alternative fishing methods [62], could produce further reductions in organic carbon disturbance. In this study, modelled fisheries displacement from priority areas assumes that all effort from closed areas moves to new locations. However, it is expected that after the establishment of new closed areas, some fishing effort will be eliminated as fishers move to alternative methods or industries, especially if the logistical or financial costs of relocation are too high [51]. This is particularly applicable to the smaller <15 m vessels who are generally less likely to be able to relocate to new fishing grounds. Overall, if less effort is displaced and more disturbance is eliminated by the establishment of mobile gear restrictions within priority areas, then the net reduction in carbon disturbance could be significantly higher than estimated here.

Mobile bottom fishing is by far the most widespread human activity affecting the seabed and therefore likely dominates cumulative human impacts on marine organic carbon stores [14, 15]. However, other activities also impact the seabed, including marine energy developments, mineral extraction, shipping and coastal development and should be considered for their potential to impact seabed organic carbon stores [8, 16]. The scale of impact will be site specific and activity dependent, but any human activity which increases the distribution or frequency of seabed sediment disturbance may limit surface organic carbon concentrations and subsequent storage [8, 43].

There is an urgent need to decarbonise our industries, requiring a step change in how we extract and use resources [63]. We must concurrently carbonise our environment by protecting organic carbon stores and promoting natural carbon sequestration on both land and at sea

**Table 2. Summary statistics for different seabed carbon priority area scenarios.** Information is given for each seabed carbon priority area scenario on the overall spatial coverage, organic carbon (OC) stock, mobile bottom fishing landings value, cumulative OC disturbance due to mobile bottom fishing, and the estimated net reduction in OC disturbance after modelled fisheries displacement if priority areas were closed to mobile bottom fishing; each value is also shown as a proportion of the total across the UK EEZ (%). Three sets of priority areas were created using different thresholds in estimated OC stock and predicted OC disturbance due to mobile bottom fishing; these were based on targeting the highest 1%, 5% and 10% of values. See Figs 2–4 for location of priority areas.

Priority area scenario	Area		OC stock		Landings value from mobile bottom fishing		Cumulative disturbance of OC due to mobile fishing		Net reduction in OC disturbance after fisheries displacement	
	(km <sup>2</sup> )	(%)	(Mt)	(%)	(£m)	(%)	(Mt yr <sup>-1</sup> )	(%)	(Mt yr <sup>-1</sup> )	(%)
1%	25,268	3.4	21.41	7.0	55.42	11.2	29.47	27.0	11.51	10.6
5%	84,397	11.7	56.01	18.2	135.36	27.4	55.55	51.0	20.09	18.4
10%	152,607	21.1	90.02	29.3	212.10	42.9	72.27	66.7	24.36	22.4

<https://doi.org/10.1371/journal.pclm.0000059.t002>

[20]. The UK fishing industry is estimated to emit ~914.4 kt of CO<sub>2</sub> per year from the burning of fossil fuels [64], but its potential emissions from disturbance to sediment organic carbon stores could greatly outweigh these direct emissions [11]. If the uncertainty in magnitudes of CO<sub>2</sub> production from this disturbance can be reduced, there may be potential for carbon financing to offset the economic costs of protection to both the fishing industry and environmental managers [47]. Our study shows that targeted area-based management of mobile bottom fishing has the potential to significantly reduce disturbance to organic carbon in seabed sediments. We must re-evaluate current seabed management measures and incorporate new evidence-based carbon considerations.

## Supporting information

### **S1 Table. List of input data sources required to run analyses.**

(XLSX)

**S2 Table. Top 1% priority area scenario.** Details of priority areas for protecting seabed sediment carbon from mobile bottom fishing in the UK EEZ, when prioritising the top 1% of concentrations in seabed sediment organic carbon stock and top 1% in predicted rates of disturbance from mobile fishing.

(XLSX)

**S3 Table. Top 5% priority area scenario.** Details of priority areas for protecting seabed sediment carbon from mobile bottom fishing in the UK EEZ, when prioritising the top 5% of concentrations in seabed sediment organic carbon stock and top 5% in predicted rates of disturbance from mobile fishing.

(XLSX)

**S4 Table. Top 10% priority area scenario.** Details of priority areas for protecting seabed sediment carbon from mobile bottom fishing in the UK EEZ, when prioritising the top 10% of concentrations in seabed sediment organic carbon stock and top 10% in predicted rates of disturbance from mobile fishing.

(XLSX)

**S1 Fig. Mean annual swept area ratio from mobile bottom fishing vessels.** The average annual swept area ratio (SAR) is shown for mobile bottom fishing vessels under the following categories: (a) Dredging by vessels with VMS; (b) Otter trawling by vessels with VMS; (c) Seining by vessels with VMS; (d) Beam trawling by vessels with VMS; (e) Dredging by < 15 m Scottish vessels; (f) Trawling for *Nephrops* by < 15 m Scottish vessels; (g) Trawling for other species by < 15 m Scottish vessels; (h) Dredging by < 15 m vessels in England & Wales; (i) Trawling by < 15 m vessels in England & Wales.

(TIF)

**S2 Fig. Mean annual swept volume ratio from mobile bottom fishing vessels.** The average annual swept area ratio (SAR) for mobile bottom fishing vessels was multiplied by the average gear penetration depth to derive a value of swept volume ratio (SVR) and is shown under the following categories: (a) Dredging by vessels with VMS; (b) Otter trawling by vessels with VMS; (c) Seining by vessels with VMS; (d) Beam trawling by vessels with VMS; (e) Dredging by < 15 m Scottish vessels; (f) Trawling for *Nephrops* by < 15 m Scottish vessels; (g) Trawling for other species by < 15 m Scottish vessels; (h) Dredging by < 15 m vessels in England & Wales; (i) Trawling by < 15 m vessels in England & Wales.

(TIF)



**S3 Fig. Mean annual landings value from mobile bottom fishing vessels.** The average annual value of fish landed from mobile bottom fishing in each area is shown for (a) All vessels with VMS; (b) < 15 m Scottish vessels; (c) < 15 m vessels in England & Wales.

(TIF)

**S4 Fig. Total values for the 1% priority area scenario.** The location of priority areas is shown with colours indicating the following attributes: (a) Total organic carbon stock in the top 10 cm of sediment; (b) Total cumulative annual disturbance to this organic carbon from mobile bottom fishing; (c) Total net reduction in disturbance if the priority area was closed to mobile fishing and all effort was displaced to locations outside priority areas; (d) Total annual landing value of fish caught within priority areas. Basemap adapted from [MarineRegions.org](https://www.marineregions.org). Available online at [www.marineregions.org](https://www.marineregions.org).

(TIF)

**S5 Fig. Total values for the 5% priority area scenario.** The location of priority areas is shown with colours indicating the following attributes: (a) Total organic carbon stock in the top 10 cm of sediment; (b) Total cumulative annual disturbance to this organic carbon from mobile bottom fishing; (c) Total net reduction in disturbance if the priority area was closed to mobile fishing and all effort was displaced to locations outside priority areas; (d) Total annual landing value of fish caught within priority areas. Basemap adapted from [MarineRegions.org](https://www.marineregions.org). Available online at [www.marineregions.org](https://www.marineregions.org).

(TIF)

**S6 Fig. Total values for the 10% priority area scenario.** The location of priority areas is shown with colours indicating the following attributes: (a) Total organic carbon stock in the top 10 cm of sediment; (b) Total cumulative annual disturbance to this organic carbon from mobile bottom fishing; (c) Total net reduction in disturbance if the priority area was closed to mobile fishing and all effort was displaced to locations outside priority areas; (d) Total annual landing value of fish caught within priority areas. Basemap adapted from [MarineRegions.org](https://www.marineregions.org). Available online at [www.marineregions.org](https://www.marineregions.org).

(TIF)

**S7 Fig. Modelled fisheries displacement for the 1% priority area scenario.** Results of modelled fisheries displacement from proposed priority areas. (a) Fisheries disturbance (measured as swept volume ratio; SVR) after modelling for a scenario where priority areas were closed to mobile bottom fishing and all fishing disturbance is displaced in other locations within the study region. (b) Annual cumulative disturbance of organic carbon from this new mobile bottom fishing disturbance scenario.

(TIF)

**S8 Fig. Modelled fisheries displacement for the 5% priority area scenario.** Results of modelled fisheries displacement from proposed priority areas. (a) Fisheries disturbance (measured as swept volume ratio; SVR) after modelling for a scenario where priority areas were closed to mobile bottom fishing and all fishing disturbance is displaced in other locations within the study region. (b) Annual cumulative disturbance of organic carbon from this new mobile bottom fishing disturbance scenario.

(TIF)

**S9 Fig. Modelled fisheries displacement for the 10% priority area scenario.** Results of modelled fisheries displacement from proposed priority areas. (a) Fisheries disturbance (measured as swept volume ratio; SVR) after modelling for a scenario where priority areas were closed to mobile bottom fishing and all fishing disturbance is displaced in other locations within the

study region. (b) Annual cumulative disturbance of organic carbon from this new mobile bottom fishing disturbance scenario. (TIF)

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**Conceptualization:** Graham Epstein, Callum M. Roberts.

**Data curation:** Graham Epstein.

**Formal analysis:** Graham Epstein.

**Funding acquisition:** Callum M. Roberts.

**Investigation:** Graham Epstein.

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**Supervision:** Callum M. Roberts.

**Validation:** Graham Epstein.

**Visualization:** Graham Epstein.

**Writing – original draft:** Graham Epstein.

**Writing – review & editing:** Graham Epstein, Callum M. Roberts.

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