WORKSHOP ON ASSESSING THE IMPACT OF FISHING ON OCEANIC CARBON (WKFISHCARBON; outputs from 2023 meeting)

VOLUME 6 | ISSUE 12

ICES SCIENTIFIC REPORTS

RAPPORTS
SCIENTIFIQUES DU CIEM

ICES INTERNATIONAL COUNCIL FOR THE EXPLORATION OF THE SEA
CIEM CONSEIL INTERNATIONAL POUR L'EXPLORATION DE LA MER

International Council for the Exploration of the Sea
Conseil International pour l'Exploration de la Mer

H.C. Andersens Boulevard 44-46
DK-1553 Copenhagen V
Denmark
Telephone (+45) 33 38 67 00
Telefax (+45) 33 93 42 15
www.ices.dk
info@ices.dk

ISSN number: 2618-1371

ICES Scientific Reports

Volume 6 | Issue 12

WORKSHOP ON ASSESSING THE IMPACT OF FISHING ON OCEANIC CARBON (WKFISHCARBON; outputs from 2023 meeting)

Recommended format for purpose of citation:

ICES. 2024. Workshop on Assessing the Impact of Fishing on Oceanic Carbon (WKFISHCARBON; outputs from 2023 meeting). ICES Scientific Reports. 6:12. 63 pp. https://doi.org/10.17895/ices.pub.24949122

Editors

Emma Cavan • David Reid

Authors

François Bastardie • Alice Belin • Jacob Bentley • Fabio Berzaghi • Abdirahman Bore • Clare Bradshaw • Mattias Cape • Thibault Cariou • Natacha Carvalho • Emma Cavan • Villy Christensen • Peter Croot • Aderito de Miranda • Jenni Grossmann • Manuel Hidalgo • Simeon Hill • Rebecca Hubbard • William Hunter • Jannis Kuhlmann • Ola Kuznia • Kathy Lockhart • Christian Lønborg • Larissa Lörinczi • Cian Luck • Maija Marsh • Angela Martin • Ana Matias • Randa Mejri • Katherine Morris • Claudia Morys • Josiah Ogbuka • Michael Oke • Barry O'Neill • Miquel Ortega • Daniel Ottmann • Sarah Paradis • Ruth Parker • Pierre Petitgas • Luca Polimene • Pierre Polsenaere • Lucas Porz • Samuel Rastrick • David Reid • Ole Ritzau Eigaard • Sevrine Sailley • Antonello Sala • Pernille Schnoor • Sonia Seixas • Arielle Sutherland-Sherriff • Ant Türkmen • Sebastian Valanko • Berthe Vastenhoud • Andre Visser • Mike Walker • Mary Wisz • Kea Witting • Wenyan Zhang

ICES
CIEM
International Council for the Exploration of the Sea
Conseil International pour l'Exploration de la Mer

Contents

i Executive summary ii
ii Expert group information iii
1 Introduction 1
2 Fish in the biological Carbon Pump 3
  2.1 Background to the ToR 3
  2.2 Report from break-out group focusing on Fish carbon/biological pump/detritus (faeces)/ CO_2 migrant pump 4
  2.2.1 Key discussion points 5
  2.2.2 Statements and proposals 6
  2.2.3 Risk assessment by functional group 6
  2.2.4 Knowledge gaps relating to this ToR 8
3 Emissions of greenhouse gases from fishing vessels 10
  3.1 Background to the ToR 10
  3.2 Report from break-out group focusing on carbon emissions from fishing vessels 11
  3.2.1 Metrics needed for analysis of GHG emissions from fishing vessels 12
  3.2.2 Metrics impact and confidence evaluation around different possible approaches to reducing fishing vessel GHG emissions 12
  3.2.3 Knowledge gaps relating to this ToR 15
4 Benthic trawling impacts on carbon release 16
  4.1 Background to the ToR 16
  4.2 Report from break-out group focusing on impacts of fishing on seabed carbon 16
  4.2.1 Risk and confidence assessment of environmental factors governing seabed carbon remineralization and storage 18
  4.2.2 Knowledge gaps relating to this ToR 19
5 Implications of the findings from ToR a and b for inclusion in the Ecosystem and/or Fisheries Overviews 21
  5.1 Implications of the findings from ToR a and b for inclusion in the Ecosystem and/or Fisheries Overviews 21
6 Potential for translation to advice to inform EBFM, and proposals for a roadmap for what should be done next 23
  6.1 Synopsis of the current state of knowledge from WKFISHCARBON 23
  6.2 A proposed roadmap for ICES in the realm of fishing and carbon 24
7 Working documents given at the workshop, and summary of related discussion 27
  7.1 The role of fish in carbon fluxes in the open ocean 27
  7.2 On direct emissions from fishing fleets using different extraction methods 33
  7.3 On indirect emissions from disturbance of the seabed 35
Reference list 40
Annex 1: List of participants 45
Annex 2: Resolutions 50
Annex 3: Working Documents 52

i Executive summary

The Workshop on Assessing the Impact of Fishing on Oceanic Carbon (WKFISHCARBON) was set up to provide ICES and stakeholders with a summary of knowledge on the role of fishing in the process of carbon budgets, sequestration and footprint in the ocean. The workshop addressed the potential impact of fishing on the biological carbon pump (BCP), the possible impacts of bottom trawling on carbon stores in the seabed, as well as considering emissions from fishing vessels. The overall aim was to generate proposals on how to develop an ICES approach to fishing and its role in the ocean carbon budget, and to develop a roadmap for a way forward.

The main findings were that knowledge of the BCP in the open ocean was reasonably well developed, but that key gaps existed. In particular, information on the biomass of mesopelagic fish and other biota, and of some of the key processes e.g. fluxes and fish bioenergetics. Knowledge is much weaker for the BCP in shelf seas, where the bulk of fishing occurs. In particular, while biomass of fish was often well quantified, unlike the open ocean, the understanding of the important processes was lacking, particularly for the fate of faecal pellets and deadfall at the seabed.

There is extensive scientific knowledge of the impact of fishing on the seabed, but what is unclear is what it means for seabed carbon storage. There have been numbers of studies, which give a very divided view on this. There has also been open controversy about this in the literature. Physical disturbance to the seabed from fishing can affect sediment transport and has the potential to facilitate remineralization, but precise impacts will depend on habitat, fishing métier, and other environmental factors. From this, it is clear that more research is needed to resolve the controversy, and to quantify the impacts from different fishing gears and on different substrates or habitats in terms of carbon storage.

There has been much more research on minimizing fuel use by fishing vessels, and hence emissions, but this has mainly focused on fuel efficiency, fuel use per unit of landed catch, and less on the total emissions. Baselines for fuel use are available at the global level, but are lacking at the national and vessel level. There is a need for standardization of methodologies and protocols, and for improving the uptake of fuel conservation measures by industry, as well as for improving the uptake of existing and potential fuel conservation and efficiency measures by industry.

Finally, a roadmap was proposed to develop research and synthesis, on the understandings of the processes involved, the metrics and how to translate this into possible advice for policy-makers. To that end, a further workshop was proposed in 2024.

ii Expert group information

Expert group name	Workshop on Assessing the Impact of Fishing on Oceanic Carbon (WKFISHCARBON)
Expert group cycle	Annual
Year cycle started	2023
Reporting year in cycle	1/1
Chairs	Emma Cavan, UK
	Dave Reid, Ireland
Meeting venue and dates	25–27 April 2023, ICES HQ, Copenhagen, Denmark (98 participants)

1 Introduction

The role of fish and fishing in the marine carbon budget is an area of growing international scientific and policy interest. Fish in the context of the marine biological carbon pump (BCP) help regulate atmospheric CO_2 levels. Fish represent a component of the BCP, and fishing and fish removals are likely to perturb that contribution. Fishing may also lead to foodweb changes that in turn alter the carbon budget. Fishing also directly produces greenhouse gas emissions, through the burning of fossil fuels during fishing activities. In addition, fishing gear is known to have direct impacts on the seafloor, e.g. resuspending sediment, and hence carbon, and potentially altering the benthic community dynamics with further possible impacts on carbon sequestration.

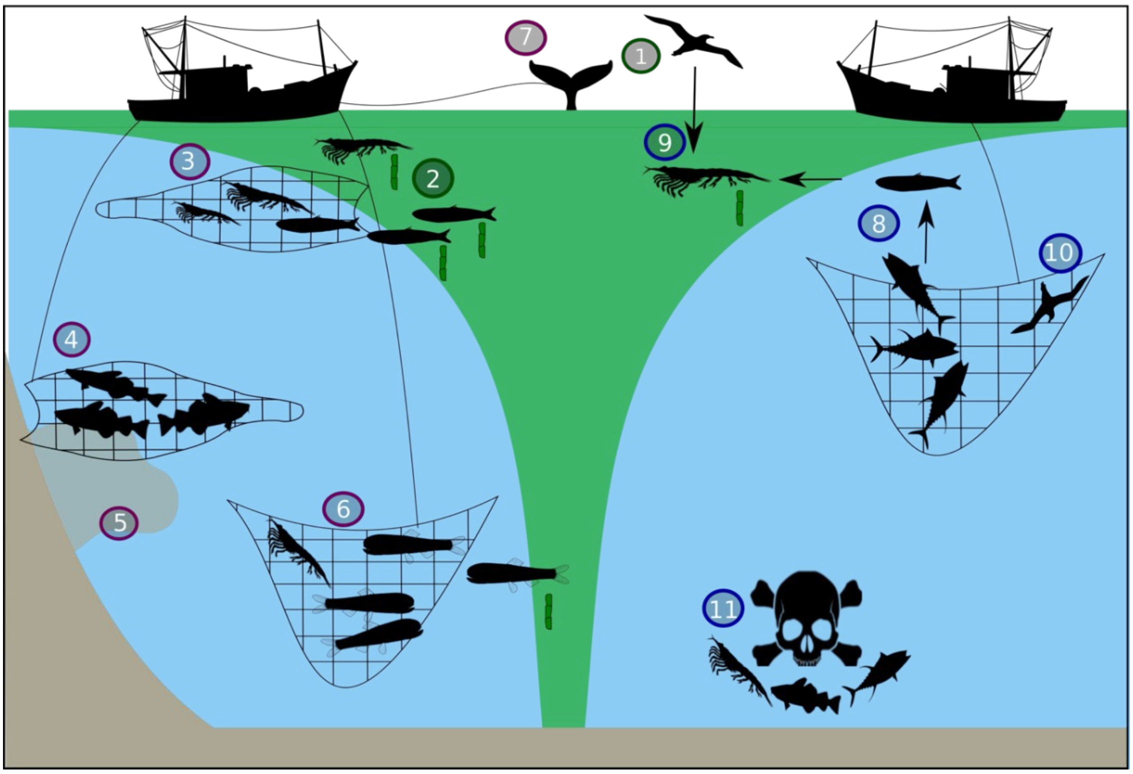


Figure 1.1 Influence of fishing on biological pump and sediment stores Cavan & Hill, 2021.

a) Fish in the biological Carbon Pump

The ocean's biological carbon pump (BCP) helps store carbon in the deep ocean and sediments for decades to millenia. Without this pump of carbon atmospheric CO2 levels would be 50% higher than they are today. Historically, dead plankton and their faeces have been the focus of the BCP research, however over the past 5 years the role of higher trophic levels such as fish in the BCP have been recognized (Figure 1.1). Some coastal fish (which are harvested) can sink large amounts of carbon to sediments through their faeces, whereas open-ocean mesopelagic fish (not yet currently harvested on a large-scale) are important in respiring surface-produced carbon at depth in the mesopelagic. Fishery removal of fish or higher trophic levels that are important in the BCP could be reducing the amount of carbon that can be stored through the BCP.

b) Emissions of Greenhouse Gas Emissions from fishing vessels

Fisheries are generally energy-intensive and heavily reliant on fossil fuels. The majority of fisheries greenhouse gas (GHG) emissions are produced during the 'at-sea' phase of fishing (e.g. steaming to and from fishing grounds, fishing itself, and onboard processing, refrigeration and freezing), with the greatest fuel consumption (and therefore emissions) related to vessel propulsion. At the global scale, assessments of CO2 emissions from fisheries have shown increases in both total emissions and emissions intensity (emissions per unit of catch landed) over time (Parker *et al*. 2018; Greer *et al*. 2019), although this has been contested by Ziegler *et al* (2019). Research and technological investment to date have largely focused on fuel use and efficiency, with more recent emphasis on how to reduce emissions in an effort for fisheries to reach net zero emissions. A wide array of measures exists for reducing fuel consumption – and thus reducing fisheries emissions including modifications to vessel design, fishing gears, and fishing behaviour; the use of green fuels; and the rebuilding of stocks.

WKFISHCARBON examined and summarized the latest research on GHG emissions of the fishery industry and new technological advances to 1) calculate fishery GHG emissions and 2) reduce fishery GHG emissions. GHG include carbon dioxide (CO_2), methane (CH_4), and Nitrous Oxide (N_2O).

c) Benthic trawling impacts on carbon release

Marine sediments store large amounts of carbon through the burial of detritus either sinking from above via the biological carbon pump or from river run-off to coastal sediments. Once the sediment has been buried and becomes anoxic, the carbon is stored for millennia, with very little or no degradation by microbes. Early studies by Duplisea *et al* (2021), and Kaiser *et al* (2002) highlighted the potential for trawling impacts to affect this process at a global scale. An influential study (Sala *et al* 2021) made the first global assessment of bottom trawling impacts to sediment carbon stores, suggesting resuspension of sediment from fishing gear could release as much CO_2 as the entire aviation industry each year. A further systematic review of empirical research (Epstein *et al*., 2021) found the evidence much more equivocal. This indicated no effect for 51% of 59 experimental studies, lower Organic Carbon (OC) for 41% of the studies and 8% reporting higher OC. These findings have stimulated considerable debate in the international scientific community to verify, or refute (Hiddink *et al* 2023; Atwood *et al* 2023; Hilborn *et al* 2023) this finding and resulted in a large amount of research on the impacts of bottom trawling.

2 Fish in the biological Carbon Pump

Tor a) Review and consolidate the existing knowledge, and identify knowledge gaps, on the functioning of the oceanic carbon pump in terms of the role of fish in carbon fluxes in the open ocean, including the extent of oceanic carbon released into the atmosphere due to the removal of fish; (Science Plan codes: 1.1, 2.1, 6.1);

2.1 Background to the ToR

Prior to the ICES WKFISHCARBON meeting an Ocean Carbon & Biogeochemistry (OCB) workshop on Fish, Fisheries, and Carbon was held online (6-9th March 2023). One of the main findings from this was that the mesopelagic biomass was still quite uncertain, with estimates ranging from about 1-16 billion metric tons (Kaartvedt *et al*., 2012; Irigoien *et al*., 2014; Proud *et al*., 2019). The carbon stored in fish is more important than just the biomass, and includes respiration and defaecation. Fish may contribute anything between 0.3% and 40% of total, biologically driven carbon flux out of the epipelagic zone (Saba *et al*., 2021; McMonagle *et al*., 2023; Pinti *et al*., 2023), again, with the key uncertainty being the biomass of mesopelagic fish. The impact of fishing on the contribution of fish to the BCP is another subject of uncertainty. Two recent studies suggested that this impact could be substantial (Bianchi *et al* 2021; Mariani *et al* 2020), but Saba *et al* (2021) also suggested that we need broadly accepted methodological standards, improved and more frequent measurements of biomass and passive and active fluxes of fishes, and stronger linkages between observations and models.

Defining what sequestration means is an important step for all carbon research and is often ambiguous in the literature. During the workshop we spent some time considering the correct definition, and this is summarized in the two definitions in the text box below, based loosely on Pinti *et al*., (2023):

Working Definitions agreed upon at WKFISHCARBON

- **Sequestered carbon**: all of the carbon in the Earth System that is not in the atmosphere.
- **Sequestration**: processes that cause these carbon stocks to expand

*Sequestration of carbon in the context of climate mitigation or ‘blue carbon’ needs to be on climatically relevant timescales, of at least 100 years.

The average residence time of carbon in the ocean is 130 years but we also need to think about total residence time, and the total carbon sequestered in the ocean at any one time.

One potentially useful idea from the OCB workshop would be to define species by their typology in terms of their role in the biological carbon pump and in the context of changes in carbon sequestration due to their biomass removal. Those types could be defined according to their contribution to the carbon cycle, e.g. mesopelagic fish or other mesopelagic biota.

The OCB workshop also considered the relative importance of passive carbon sink (urine, faecal pellets, respiration) and active flux (Diel Vertical Migration). The importance of faeces in the BCP was particularly emphasized. A further key issue was that the depth where faeces etc. sink to dictates retention time. 14 years for surface, 104 years for 400 m deep, 352 years for 1000 m (Turner, 2015). In turn, this raises the question what is meant by retention and how do we define it?

One key finding from the OCB workshop was that much of our knowledge of the biological carbon pump is based on an understanding of the biological, biogeochemical and physical processes in the open ocean, off the shelf. Far less is known about the shelf seas ecosystems where the processes are likely to be quite different. Importantly, coastal and shelf seas tend to be important for carbon export (Cavan & Hill, 2021), which are also areas of high fishing pressure and fish removals (Figure 2.1).

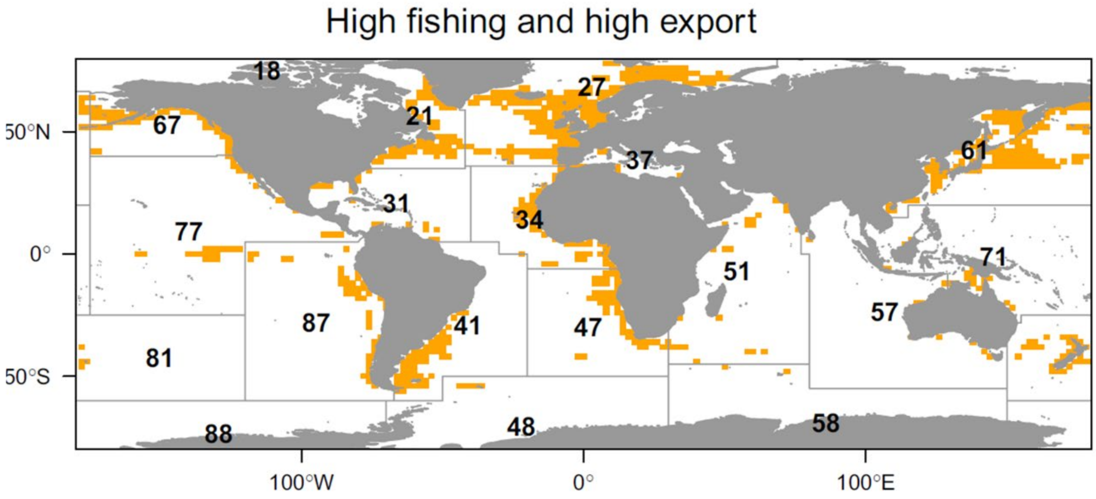


Figure 2.1 Shows where both organic carbon export and fishing intensity are in the upper quartile for both datasets (orange pixels), which is 9% of the surface ocean. Grey grid lines and black numbers indicate the FAO major fishing areas.

A second aspect to consider, which came up in the workshop, was the influence of fishing on the structure of foodwebs and, thus, on the BCP and sequestration. A number of studies have reported that removal of big fish, or top predators will have a negative impact on carbon flux (Stafford *et al*., 2021; Mariani *et al*., 2020). To quote Stafford *et al.*, **“Selective removal of predatory fish through extractive fishing alters the community structure of the ocean. This altered community results in increased biomass of more productive, low trophic level fish, higher overall fish respiration rates and lower carbon sequestration rates from fish, despite possible decreases in total fish biomass”.** The paper also suggests that more research on this is essential.

Given the potential importance of mesopelagic biota in the BCP, the workshop concluded that we should avoid any exploitation of the mesopelagic communities (including not only fish, but other important taxa part) in terms of carbon sequestration.

2.2 Report from break-out group focusing on Fish carbon/biological pump/detritus (faeces)/ CO_2 migrant pump

The group was asked to answer, as well as possible, a series of question relating to fish and the BCP, and then provide guidance on what should be done:

- Do we know enough about the system in ‘steady state’ and the impact of fisheries so far?

  - Probably YES in open ocean for the “steady state”, not for the impact of fisheries. Less so in shelf-sea fisheries
- If relevant, do we have baselines of carbon stores?
  - Generally, YES, not in seafloor.
- What do we have reasonable confidence in to advise policy? If none, what do we need to get there?
  - We know that qualitatively that fish are important in carbon products. We have quantitative values, but with large uncertainty, e.g. biomass of mesopelagic fish.
- What tools and methods are needed to get answers for policy? What data products are needed?
  - We have the models and tools, but need to be tied together around this question. Bind together all the available empirical data (acoustics, imaging, mesopelagic trawls, etc) of mesopelagic biomass and create a standardized database (EOV).
- What are the big unknowns? E.g. shelf advection vs. burial vs. recycling, gelatinous organisms and aquaculture impacts
  - Respiration, sinking rate, mortality rates, biomass, biomass distribution
- Do fish or other harvested species change the stocks/pools of carbon (inc. in atmosphere), does fishing change these pools?
  - YES, particularly in the mesopelagic system (mesopelagic fish, krill, squid, etc), as they play a proportionally large role in carbon sequestration. Our proposal is not to further develop fisheries.

2.2.1 Key discussion points

- We need to standardize approaches to fluxes of carbon of major marine communities. Start with the apparently most important ones - small pelagic and benthic communities – and then move towards other communities.
- There is a high uncertainty about mesopelagic communities (biomass distribution and fluxes) and how fisheries affect them. Project MEESO has put together 3 models at a regional scale. Currently focusing on biomass and biomass distribution.
- All flux parameters are as a function of biomass. Thus, abundance and distribution are the most important variables we need to find out.
- Assuming we know the biomass, what other parameters do we need to predict carbon fluxes? E.g. Depth distribution, other behavioural, metabolic traits, sinking speed of faecal pellets, etc.
  - We need to identify what the parameters of interests are, and what level of detail we need before focusing on finding them.
- The impact of fish communities in carbon sequestration is much more than the total biomass – organisms have a greater potential of sequestration due to their metabolic activities, which is orders of magnitude greater than their own biomass. It is the fish biomass + all the “carbon products” that they produce. Others disagree, because “carbon products” are already accounted as DOC, POC, DIC. The idea that X tons of biomass generate Y tons of sequestered carbon is intuitive and easy to explain to stakeholder: the carbon associated to this biomass is X+Y. However, this concept has risks. E.g. double counting or mixing up certain pools of carbon. E.g. DOC can be originated from fish or from other sources. A good way to approach this discrepancy is to write down these statements. Then validate these statements with numbers of the literature.
- We need to quantify the residence time of carbon in the ocean to be considered “sequestered”. The average residence time of a molecule of carbon in the ocean is 130 years. For

a climate crisis, some will consider it good enough. However, there is a risk of using flux as a synonym for sequestration because there is a high chance of misuse of this concept.

- Processes that transport carbon deeper into the ocean are a positive factor because this keeps it longer out of the atmosphere.
- Changing the standing stock of fish biomass will change the total pool of sequestered carbon in the ocean (fish biomass + carbonated carbon).
- Some species produce carbonated carbon with different residence time in the ocean depending on their traits like vertical migration (it depends on their contribution to the biological pump). For some species, we have these estimates, e.g. tuna, mesopelagic, forage fish. Changes in the biomass of some trophic levels can affect the biomass of other trophic levels with complex implication in total carbon sequestered in the oceans. This can be modelled. There are also empirical studies at community level in marine reserves.
- There are 9 global models and over 20 regional models where we can implement carbon flux to estimate carbon services of different functional groups. Some are coupled with biogeochemical models.

2.2.2 Statements and proposals

1. Management decisions need to consider impacts on carbon services to ecosystems, particularly in the context of any future mesopelagic fisheries, given the potentially substantial role mesopelagic fish play in the BCP.
2. We need to know the consequences that changing the foodweb structure have on carbon services.
3. Bind together all the available empirical data (acoustics, imaging, mesopelagic trawls, etc) of mesopelagic biomass and create a standardized database.
4. Fish communities contribute to 16% of ocean carbon flux.
5. 60% of all the carbon sequestered in the ocean has passed through a metazoan in the ocean.

All marine teleosts produce carbonate ($CaCO_3$) precipitates in the intestine as a product of the osmoregulatory requirements from drinking calcium- and magnesium-rich seawater, that is through calcification where calcium (Ca^{2+}) reacts with bicarbonate (HCO_3-) (Equation [1]).

$$Ca^{2+} + 2HCO_3^- \leftrightarrow CaCO_3 + CO_2 + H_2O \quad (1)$$

Wilson *et al* (2009) described this process for marine fish and calculated that marine fish contributed 3–15% of total oceanic carbonate production, which is predicted to rise with to future environmental CO_2 changes, thus becoming an increasingly important component of the inorganic carbon cycle.

2.2.3 Risk assessment by functional group

The subgroup was asked to carry out a risk assessment identifying where the primary risks lay in terms of the fishing impacts on the BCP (Table 2.1).

Table 2.1. Risk assessment for fishing and the BCP.

Confidence	Low	Medium	High
Impact *High*	Shelf fisheries in general	Oceanic krill	Oceanic mesopelagics Oceanic squid
	Seamount species?	Oceanic small pelagics Shelf edge species (like blue whiting)	-
Low	-	-	Oceanic large pelagics

Highlight statements

The biological pump is important for carbon sequestration in the ocean.

- We know that fish play an important role in the biological pump.
- Therefore, the removal of fish from the marine environment has a larger impact on carbon sequestration than the removal of their biomass alone.

***Takeaway*:** We know fishing has the potential to significantly impact on the biological pump

Roadmap to collecting information for carbon impact of *specific* fisheries is needed.

- There are other value systems (social ecological systems) aside from ours that we need to consider before employing management decisions.
- Our understanding is better developed in open ocean -> We need more studies and analysis.
- We know much less about the shelf in terms of carbon sequestration because there is a knowledge gap about what happens in the sediments. We are fairly confident about the open ocean because we can safely predict where that carbon ends up.
- It is unclear what the downstream effects are of changing the ecosystem, population, and community structure on carbon (this requires more trophic study and modelling of trophic relationships)
- *Big takeaway: No to developing mesopelagic fisheries*
    - Several trade-offs of development of such fisheries, *including* negative carbon impacts
- Rebuilding fish populations would transiently increase sequestration until reaching steady state, in which rate processes are most important
- There are potential trade-offs between carbon, economics, yield, and cultural value (local ecological knowledge), *so we should look at overlaps*. Together, we identify several values for healthy fish stocks: value as a provisioning service (*e.g.* food security) and a climate regulatory service (*e.g.* carbon sequestration)
- We should incorporate carbon removal by fish into ICES advice products
    - Goal to incorporate carbon into fishing assessments and management decisions

Possible Statement for concept communication to stakeholders:

This text provides a mockup of the sort of simple synopsis of the fishcarbon question. The numbers will come from further work intersessionally and at the propsed next workshop.

"There are X gigatons of living biomass in the global ocean and Y tons of carbon in the global ocean and its sediments. Most of this carbon results from biological processes. The biomass of fish in the global ocean is approximate X gigatons each year. This biomass delivers approximately X gigatons of carbon into the global ocean as a result of the following processes:

1. *Respiration, which produces X gigatons of DIC*
2. *Biological carbonate production produces X gigatons of carbonated carbon*
3. *Detrital material (from feeding) which produces X gigatons of carbonated carbon*

** All numbers are subject to uncertainties"*

2.2.4 Knowledge gaps relating to this ToR

Based on the above, and on the presentations and discussions (see below) a number of knowledge gaps can be identified:

1. Mesopelagic fish biomass: estimates of this biomass range from 1-10Gt (Irigoien *et al*., 2014; Proud *et al*., 2019). Combined with uncertainty about fish bioenergetics (McMonagle *et al*., 2023) this suggests that mesopelagic fish contribute between 0.3% and 40% of total, biologically driven carbon flux out of the epipelagic zone (Saba *et al*., 2021; McMonagle *et al*., 2023; Pinti *et al*., 2023). This range makes it difficult to advise on the sustainability of fishing the mesopelagic, and its importance in the BCP.
2. A lack of methodological standards was highlighted by Pinti *et al*. (2023) as also contributing to uncertainty in estimates of the importance of mesopelagics in the BCP.
3. Pinti *et al*. (2023) and McMonagle *et al*. (2023) also stressed the need for more empirical data on fluxes and fish bioenergetics
4. This workshop provided a working definition of sequestration and sequestered carbon, but a broader acceptance would be valuable. This would also include definitions of residence times rates and fluxes for common use.
5. The importance of faeces as a sequestration pathway was stressed (Cavan & Hill, 2021; Pinti *et al*., 2023) and there is a clear need for more knowledge of the role and fate of faeces in the BCP.
6. The need to establish baselines of carbon stores in the seafloor – which will require targetted field sampling
7. The need more empirical data on: respiration, sinking rate, mortality rates, biomass, and biomass distribution – again will require more targeted field sampling
8. We need to standardize approaches to fluxes of carbon of major marine communities. Starting with the most important ones – e.g. small pelagic and benthic communities – and then move towards other communities.
9. We need to identify what the parameters of interests are, and what level of detail we need before focusing on finding them, either through sampling or modelling.
10. Almost all of the research on the BCP has focused on the open ocean, and off the shelf. Knowledge of the role of fish (and hence fishing) in any on-shelf BCP is very weak. Both carbon export and fishing intensity are highest around coastlines (Cavan & Hill, 2021), making this knowledge gap critical. Estimates of global on-shelf fish biomass is in the order of 1Gt (Christensen *et al*., 2010) putting it within the possible range of mesopelagic fish biomass. Most fishing still takes place in this region, so the potential for disruption of a BCP is obvious. The processes for sequestration are likely very different on the shelf and this should be a priority for future research.
11. The changes caused by selective fishing on foodwebs may change the carbon flux and possibly then, carbon sequestration. This needs considerably more study to be established, and its scale, direction and implications determined.

A number of presentations were given at the meeting in relation to the fish carbon ToR. Short precis of these are provided in Section 7.

3 Emissions of greenhouse gases from fishing vessels

3.1 Background to the ToR

ToR b part 1) Review and consolidate the existing knowledge on direct emissions from fishing fleets using different extraction methods

Fisheries are generally energy-intensive and heavily reliant on fossil fuels. The majority of fisheries greenhouse gas (GHG) emissions are produced during the 'at-sea' phase of fishing (e.g. steaming to and from fishing grounds, fishing itself, and onboard processing, refrigeration and freezing), with the greatest fuel consumption (and therefore emissions) related to vessel propulsion. At the global scale, assessments of CO2 emissions from fisheries have shown increases in both total emissions and emissions intensity (emissions per unit of catch landed) over time (Parker *et al*. 2018; Greer *et al*. 2019), although this has been contested by Ziegler *et al* (2019) who "*demonstrated how the approach underestimates emissions of small-scale fisheries, while overestimating emissions of industrial fisheries*". Research and technological investment to date have largely focused on fuel use and efficiency, with more recent emphasis on how to reduce emissions in an effort for fisheries to reach net zero emissions. A wide array of measures exists for reducing fuel consumption – and thus reducing fisheries emissions including modifications to vessel design, fishing gears, and fishing behaviour; the use of green fuels; and the rebuilding of stocks.

WKFISHCARBON examined and summarized the latest research on GHG emissions of the fishery industry and new technological advances to 1) calculate fishery GHG emissions and 2) reduce fishery GHG emissions. GHG include carbon dioxide (CO_2), methane (CH_4), and Nitrous Oxide (N_2O).

Fuel use (and hence CO_2 equivalent emissions) has been a focus of fisheries research for some years (Gephart *et al* 2021; Parker *et al* 2018; Sala *et al*., 2011; 2022). The main driver of this research historically has been economic – reducing fuel to reduce costs (see review by Suuronen *et al*. (2012). Most of these studies also identified that such reductions could also lower emissions. This aspect has received more attention recently in light of efforts to mitigate the contribution of fisheries to greenhouse gas emissions.

Four elements of fishing practice could contribute to reduced emissions; fleet structure (Parker et al., 2018), gear adaptations (Caslake, 2021), fishing behaviour and stock management (Bastardie et al., 2022a). Vessels can be made more fuel-efficient, for example, through improvements to vessel hulls to reduce drag force, improvements to propulsion and auxiliary engines, changes to energy-consuming machinery onboard, and improvements that are directly related to fuel performance, such as the use of renewable energy for propulsion.

Fishing gears can be substituted with those that are less fuel-intensive e.g. switching from active gears to passive gears (Munoz *et al* 2023), or modified using designs that reduce the associated drag force. Much of the research to date has considered the impacts on the seabed by fishing gear in the context of seabed integrity, linking with the third aspect of WKFISHCARBON work on seabed impacts. Reducing gear contact with the seabed will also likely have the side effect of reducing drag, and hence fuel use, unless the new gear is heavier (see review by Sala *et al* 2023).

Beyond technological advances, fisheries-related GHG emissions can also be decreased through changes in fishing behaviour. More efficient fishing practices can be adopted that consider where and how fishing vessels operate, and what they aim to catch. Fuel use can be improved, for example, through route optimization measures such as slow steaming or speed optimization (Bastardie *et al* 2022a). Other examples can be found in Bastardie *et al.* (2010) which included some possible scenarios for spatial effort allocation, e.g. preferring nearby fishing grounds; shifting to other fisheries targeting resources located closer to the harbour; and allocating effort towards optimizing the expected area-specific profit per trip.

Another aspect that is related to fishing strategy or behaviour is the link between fuel efficiency and recovered or recovering stocks (Bastardie *et al*. 2022a and b; Martin *et al*. 2022). Both studies suggest that fuel efficiency can be improved when fishing is carried out on stocks that are in good condition, because fishers are not required to spend as much effort or fuel to obtain their catches. Similarly, a study of the factors influencing fisheries GHG emissions in Iceland identified the rebuilding and sustainable exploitation of fish stocks as the most efficient means of reducing emissions (Kristofersson *et al*. 2021). However, in at least one study (Martin *et al*. 2022), total emissions increased as a result of increased fishing of rebuilt stocks, emphasizing the need for fisheries management systems that prioritize minimizing fuel use and carbon emissions.

Regardless of the types of measures applied, reducing GHG emissions from fisheries depends on having standardized monitoring and reporting across countries, fleets and vessels. While global baseline estimates of fuel consumption and emissions are available, comparable data at finer scales are lacking. Such data are critical both for taking stock of present-day GHG emissions from fisheries, and for assessing the impacts of technological, strategic, or regulatory changes aimed at reducing them.

3.2 Report from break-out group focusing on carbon emissions from fishing vessels

The subgroup was asked to answer, as well as possible, a series of question relating to fishing vessel emissions, and then provide guidance on what should be done

- Do we know enough about the system in 'steady state' and the impact of fisheries so far?
    - Current knowledge of fuel use and fuel efficiency (at the high level) by fishing vessels is reasonably well developed but there is no clear framework for how to implement improvements which creates a barrier and lack of incentive for the fishing industry to implement these changes.
- If relevant, do we have baselines of carbon stores?
    - Not strictly relevant to this ToR, but, we do have global baselines for fuel use but lacking country-specific baselines and at the vessel level.
- What do we have reasonable confidence in to advise policy? If none, what do we need to get there?
    - Fishing gear modifications, fishing vessel design, fishing behaviour and fuel efficiency benefits of rebuilding stocks.
- What tools and methods are needed to get answers for policy? What data products are needed?
    - Need to develop framework/roadmap for how to implement improvements, especially at the vessel level. Data collection and reporting on fuel use needs to be more clearly standardized from different sources (member states).
- What are the big unknowns? (e.g. shelf advection *vs*. burial *vs*. recycling, role of gelatinous organisms, aquaculture impacts etc.)
    - Fuel consumption by inshore fisheries and bait fisheries. Standardized estimation and reporting of fuel use.
- Do fish or other harvested species change the stocks/pools of carbon (including in the atmosphere), does fishing change these pools?

  - Again, not strictly relevant but, fuel use and emissions vary by target species and stock status.
- What are the natural (biological and physical) controls on carbon store variability (e.g. temperature, hydrology) of system you're thinking about?
  - Again, not strictly relevant but, weather can affect fuel efficiency.
- As above, but what are the fishery controls on impact/policy on carbon/emissions (e.g. vessel length, gear type).
- Vessel design and gear type affect fuel efficiency. Relevant to Article 17 of the Common Fisheries Policy stating that Member States should endeavour to provide incentives to fishing vessels deploying selective fishing gear or using fishing techniques with reduced environmental impact, such as reduced energy consumption or habitat damage, and are also relevant for science-based target initiatives. Fuel efficiency and emissions should also factor in to allocation of fishing opportunities.

3.2.1 Metrics needed for analysis of GHG emissions from fishing vessels

- Vessel structure and gear modification
- Fishing strategy
- Standardized GHG reporting and estimation
- The effect of stock status on fuel efficiency
- Management and implementation with respect to fishing vessel emissions
- Relevant data on inshore small-scale fisheries

3.2.2 Metrics impact and confidence evaluation around different possible approaches to reducing fishing vessel GHG emissions

The subgroup carried out an impact and confidence evaluation around different possible approaches to reducing fishing vessel GHG emissions. This approach was different from the risk assessment by BCP and fishing subgroup.

Technical innovation with regards to vessel structure and gear modifications

- Justifications:
  - High confidence because of well-developed literature around fuel efficiency.
  - Not all modifications easily adopted at scale.
  - Some modifications can result in ~50% of fuel use but medium confidence because of wide range of estimated fuel use improvements.

An impact and confidence evaluation draft is provided in Table 3.1.

Table 3.1. Impact and confidence evaluation for vessel structure and gear modifications for reducing GHG emissions.

		Impact		
		Low	Medium	High
Confidence	Low			
	Medium			
	High		X	

Technical innovation with green fuels

- Justifications:
    - Low confidence because of the maturity of the technology and cost-effectiveness
    - Need more understanding of LCA of alternative fuels
    - Potential significant or total reduction of fuel emissions

An impact and confidence evaluation draft is provided in Table 3.2.

Table 3.2. Impact and confidence evaluation for green fuels for reducing GHG emissions.

		Impact		
		Low	**Medium**	**High**
Confidence	Low			X
	Medium			
	High			

Fishing strategy

- Justifications:
    - Medium confidence because of wide range of estimated fuel use improvements
    - Educating fishers and changing behaviour (e.g. vessel speed) has been shown to improve fuel efficiency between 10 and 50%
    - Consideration of route planning to optimize fuel consumption

An impact and confidence evaluation draft is provided in Table 3.3.

Table 3.3. Impact and confidence evaluation for fishing strategy for reducing GHG emissions.

		Impact		
		Low	**Medium**	**High**
Confidence	Low			
	Medium		X	
	High			

Standardized fuel use reporting and GHG estimation

- Justifications:
    - Medium confidence because there are an abundance of estimations of fuel use, but methodologies are not always comparable. **Need for standardized methodology**.
    - High impact because of importance for calculating baselines and setting meaningful reduction targets.

An impact and confidence evaluation draft is provided in Table 3.4.

Table 3.4. Impact and confidence evaluation for fuel use reporting and GHG estimation for reducing GHG emissions.

		Impact		
		Low	**Medium**	**High**
Confidence	Low			
	Medium			X
	High			

The effect of stock status

- Justifications:
    - Medium impact because examples from literature demonstrate correlation between stock status and fuel efficiency but does not speak to how this would apply to fisheries in general (see Ferrer *et al*. 2022; Martin *et al*. 2022; Bastardie *et al*. 2022b).

An impact and confidence evaluation draft is provided in Table 3.5.

Table 3.5. Impact and confidence evaluation for stock status for reducing GHG emissions.

		Impact		
		Low	**Medium**	**High**
Confidence	Low			
	Medium		X	
	High			

Management and implementation

- Justifications:
    - High impact because lack of policy and roadmaps prevents implementation of fuel efficiency improvements
    - Low confidence because general lack of roadmaps and related policy documents
    - Some exceptions like the "Energy Transition of Fisheries Aquaculture" communication which included suggested objectives and timeline for a roadmap.

An impact and confidence evaluation draft is provided in Table 3.6.

Table 3.6. Impact and confidence evaluation for management and implementation for reducing GHG emissions.

		Impact		
		Low	**Medium**	**High**
Confidence	Low			X
	Medium			
	High			

Inshore (Small-scale Fishery) fleet

- Justifications:

  - Data-limited with regards to emissions and catch and effort.
  - Potential high emissions-per-catch.
  - Also potential low hanging fruit for alternative fuels.

An impact and confidence evaluation draft is provided in Table 3.7.

Table 3.7. Impact and confidence evaluation for Small-scale Fisheries for reducing GHG emissions.

		Impact		
		Low	Medium	High
Confidence	Low			X
	Medium			
	High			

3.2.3 Knowledge gaps relating to this ToR

- Discussion focused on the current knowledge and the difficulty to translate to regional or vessel level.
- Tools and methods are available: emission calculators and gear modifications (with lots of ongoing research) but there is no apparent roadmap to make them cost-effective for fishers.
- More data is needed for fuel-use: might need different conversion factor (from living specimen caught to the final fisheries products) per country which render difficult the estimation of carbon/kg or carbon/value (monetary) of catch.
- How to account for fuel consumption (representing emissions for steaming and for fishing) where the emissions per litre of fuel used may not be the same for these different activities.
- More knowledge of rebuilding fish stocks to improve fuel efficiency. More direct measures are needed using fuel sensors.
- Need standardized methodology for monitoring and calculating fuel usage.
- Need more research on how vessel design and gear type affect fuel efficiency.
- How could fuel efficiency/emissions be factored into allocation of fishing opportunities (for example, as the Article 17 of the EU CFP allows).
- Need more information on fuel consumption by small-scale inshore fisheries and bait fisheries.
- Need to develop framework/roadmap for how to implement fuel efficiency improvements, especially at the vessel level. There is no clear framework for how to implement improvements which creates a barrier and lack of incentive for the fishing industry to implement these changes.
- Understanding how low fuel taxes may dis-incentivise fishers from adopting more fuel-efficient measures.

4 Benthic trawling impacts on carbon release

4.1 Background to the ToR

ToR b2) Indirect emissions from disturbance of the seabed, in terms of their contribution to climate change; (Science Plan codes: 1.1, 2.1, 6.1);

Marine sediments store large amounts of carbon through the burial of detritus either sinking from above via the biological carbon pump or from river run-offs to coastal sediments (Legge *et al*., 2020). Globally, marine sediments are estimated to store between 1 500 and 2 300 Pg C (Atwood *et al*., 2020; Hedges & Keil, 1995). Once the sediment has been buried and becomes anoxic, the carbon is potentially stored for millennia, with very little or no degradation by microbes. Early studies by Duplisea *et al*. (2021) and Kaiser *et al*. (2002) highlighted the potential for trawling impacts to affect this process at a global scale. An influential study (Sala *et al*., 2021) made the first global assessment of bottom trawling impacts to sediment carbon stores, suggesting resuspension of sediment from fishing gear could release as much CO_2 as the entire aviation industry each year. A further systematic review of empirical research (Epstein *et al*., 2021) found the evidence much more equivocal. This indicated no effect for 51% of 59 experimental studies, lower OC for 41% of the studies and 8% reporting higher OC. These findings have stimulated considerable debate in the international scientific community to verify, or refute (Atwood *et al*., 2023; Bradshaw *et al*., 2021; de Borger *et al*., 2021; Black *et al* 2022; Hiddink *et al*., 2023; Hilborn *et al*., 2023) this finding and resulted in a large amount of research on the impacts of bottom trawling.

4.2 Report from break-out group focusing on impacts of fishing on seabed carbon

The aim of the subgroup was to assess the evidence around potential impacts of fishing activities on seabed carbon burial and storage. Globally, marine sediments are estimated to store between 1500 and 2300 Pg C (Atwood *et al*., 2020; Hedges & Keil, 1995). As such, the sedimentation and burial of organic matter at the sea floor may represent an important pathway for carbon sequestration, providing a potential negative feedback against climate change. In marine sediments, oxygen availability is a key limiting factor on the degradation of organic matter (Hedges & Keil, 1995). Fishing activity, for example bottom trawling, disturbs the seafloor which then results in the resuspension of significant sediment plumes. As a consequence, fishing has the potential to enhance the degradation rates of sedimentary organic matter, resulting in higher remineralization of this carbon source to carbon dioxide. This has been identified as a significant barrier to global greenhouse gas emission reductions (Hiddink *et al*., 2023; Sala *et al*., 2021). The subgroup set out to review and consolidate the existing knowledge of indirect emissions from disturbance of the seabed, in terms of their contribution to climate change.

While there has been considerable controversy regarding global models of the impacts of fishing on seabed carbon (Hiddink *et al*., 2023; Sala *et al*., 2021), there is a clear recognition that these models need to be developed and parameterized with sufficient data to allow the potential impacts to be accurately assessed. The biogeochemical drivers of organic matter preservation and storage are well defined, with oxygen availability a key drivers of organic matter remineralization rates. As such, the resuspension of sediments by fishing has been postulated to be a significant control on seabed carbon storage. However, a comparison of the various fishing *métiers* found no clear influence of fishing activity on seabed carbon storage (Epstein *et al.*, 2021). Likewise, the potential supply of organic matter to the seafloor could present an important control on seabed carbon storage (Cavan & Hill, 2021; Saba *et al.*, 2021). While the seasonal fluxes of carbon from the sea surface to the seafloor are well understood at a qualitative level, the temporal and spatial variations in supply of carbon to the seafloor remain poorly constrained. While it is reasonable to infer that fisheries will have an influence on the movement of carbon through the water column to the seafloor, there is a lack of data on how these processes at spatial scales that are relevant for environmental management. What we do clearly understand about the impacts of fishing on seafloor carbon stocks can thus be summarized as follows:

- Direct impact on seabed biodiversity – effects on subduction of OM into deeper sediment layers and SCOC.
- Impacts are dependent on habitat and, fishing métier, and gear components. – Not all gear has an impact on the sediment, and not all fishing overlaps with areas of carbon accumulation.
- Possible to identify areas that are likely to be at risk of seabed carbon loss based upon fundamental sediment geochemistry and benthic ecology.
- Bioturbation and macrobenthos can have important impacts sediment carbon remineralization, but these impacts are context dependent and governed by community structure, temperature, DO and disturbance regime.

We sought to review the baseline carbon stocks of marine sediments, however, at present the spatial extent of data across the global seafloor is relatively sparse. As such, efforts need to be focused towards the curation and development of global databases of seabed carbon stocks to support a future assessment of carbon storage at the seabed and its sensitivity to fishing and other anthropogenic pressures. This will require International coordination needed to draw together available datasets within a single repository where the data are findable, accessible and reusable, to support the development of the assessment products which are useful in the marine spatial planning context.

At present, the current state of knowledge regarding seabed carbon storage is sufficient to advise policy-makers in broad terms regarding likely negative impacts of fishing. This is, however, little more than an evidence-informed approach to the precautionary principal. In essence, we can predict the likely areas of the seabed where carbon is likely to accumulate. However, we lack sufficient assessment tools for the potential sensitivity of seabed carbon to fishing disturbance. In addition, the economic valuation of carbon as a component of natural capital remains in its early stages, making a direct comparison with the values of fisheries challenging. We can however, provide advice based on our knowledge of the temporal dynamics of carbon inputs within shelf sea and deep sea ecosystems (Billett *et al.*, 1983; Lampitt *et al.*, 2001). This is based with our reasonable confidence that fishing activities will resuspend sediments (refs Black *et al.*, 2022; Epstein *et al.*, 2021; Mengual *et al.*, 2016; Yahel *et al.*, 2008), mean that we can suggest maximizing seabed carbon storage may be achievable by managing fishing effort around the end of seasonal plankton blooms to reduce resuspension of newly settled organic material at the seabed.

To effectively advise policy-makers and environmental managers on the potential for carbon storage in marine sediments we need to develop a range of new tools, methods and data products. In particular, standardized methods for quantifying sediment carbon content and estimating stocks are require urgently to support seabed carbon stock assessments. This includes a consensus on the definitions of lability and recalcitrance, and methods to determine carbon lability and reactivity within national monitoring programmes. These methods should be low-cost, rapid assessment tools to support effective mapping of carbon reactivity and provenance. While a growing number of studies highlight the potential power of modelling approaches for predicting the impacts of fishing on seabed carbon stocks (Black *et al.*, 2022; Epstein *et al.*, 2021; Hiddink *et al.*, 2023; Sala *et al.*, 2021). These models need to be developed and parameterized at a regional scale to allow them to be useful as a component in the marine spatial planning process. Ultimately, however, information on seabed carbon stocks and their sensitivity to disturbance should be provided in a useable format for decision-makers, perhaps using semi-quantitative scores for impact and confidence (Low/Medium/High) to allow seabed carbon stock assessments to be incorporated into existing advice products such as fisheries advice. Consequently, we provide in Table 4.1 an initial assessment of the environmental factors which govern seabed carbon storage, with an expert assessment of their potential to impact seabed carbon stocks and the degree of scientific confidence around their potential impacts. **The aim for any subsequent WKFISHCARBON workshops will be to develop this approach into a full risk assessment of the impacts of fishing on seabed carbon storage.**

The subgroup was asked to carry out a risk assessment identifying where the primary risks lay in terms of the fishing impacts on the BCP (Table 4.1).

4.2.1 Risk and confidence assessment of environmental factors governing seabed carbon remineralization and storage

The subgroup carried out a risk assessment identifying where the primary vulnerabilities lay for seabed carbon storage and remineralization, linking to fishing disturbance (Table 4.1)

Table 4.1 Vulnerabilities lay for seabed carbon storage and remineralization, for environmental factors, linking to fishing disturbance

Environmental Factor	Vulnerability	Severity of Impact	Confidence
Sea Temperatures	Rising near seabed will increase sediment community oxygen consumption, driving higher carbon remineralization rates.	Medium	High
Bottom water dissolved Oxygen	Bottom water oxygen concentrations are critical control on the remineralization of organic matter. Decreases in bottom water oxygen will restriction the potential for aerobic metabolism and restrict remineralization rates at the seabed.	High	High
Organic matter inputs	Changes to the input of organic matter from the overlying water column, or lateral transport from rivers estuaries will directly affect seabed carbon sequestration potential. At present, there is a lack of consensus regarding definitions of organic matter lability, which make assessment of the potential residence times of freshly deposited carbon at the seabed challenging.	Low	Low
Sedimentation rates and sediment transport processes.	We have a good understanding of the physical processes that govern sedimentation and sediment transport. Fundamental processes that are predicted by the hydrodynamic regime, particle size and volume of suspended particles.	Low	High
Grain Size and Sediment Type	Sediment grain size		
Sediment Organic Carbon Content and stocks.	High uncertainty about the spatial and temporal variability of seabed carbon stocks in European Shelf Seas.	High	Low
Sediment Carbon Lability	At present there is no consistent definition of sediment organic matter quality.	High	Low

	Method Development required to provide operational tools for rapid assessment of organic matter quality (low-cost, rapid assessment of lability).		
Sediment Oxygen Penetration	Recognized as critical driver of organic matter mineralization in marine sediments.	High	High
Organo-mineral associations	Poorly understood but with high potential to influence sediment organic matter lability.	Medium	Low
Sediment Community Structure and Ecology	Well established and regularly monitored aspect of marine sediments. Long time-series available through national monitoring programmes.	High	High
Biotrubation and Bioirrigation	Under seabed Good Environmental Status, Increased bioturbation and bioirrigation will support the subduction of organic matter deeper into the sediment for storage.	High	High
Physical Disturbance from Fishing	Potential for fishing pressure to impact seabed carbon storage is dependent on fishing métier. There is likely to be a gradient of effects from static gear, demersal seine netting, otter trawl, beam trawl and dredging. Currently, there is a lack of data on how sediment disturbance from fishing affects organic matter remineralization rates.	High	Low
Physical disturbance from storms or natural processes	Currently, there is a lack of data on how sediment disturbance from fishing affects organic matter remineralization rates.	High	Low

4.2.2 Knowledge gaps relating to this ToR

- We need more knowledge around carbon mineralization and what happens to carbon once it leaves the system.
- There is no baseline for carbon stored in the sediment because of the lack of data, but the issue is recognized and there is a lot of work in progress. This then needs the curation and development of global databases of seabed carbon stocks to support a future assessment of carbon storage at the seabed and its sensitivity to fishing and other anthropogenic pressures
- We need standardized methods for quantifying sediment carbon content and estimating stocks. This includes a consensus on the definitions of lability and recalcitrance, and methods to determine carbon lability and reactivity within national monitoring programmes
- We need to define lability and refractivity and lack data on this and on carbon residence times
- While the seasonal fluxes of carbon from the sea surface to the seafloor are reasonably well understood at least at a qualitative level, the temporal and spatial variations in supply of carbon to the seafloor remain poorly constrained.
- While it is reasonable to infer that fisheries will have an influence on the movement of carbon through the water column to the seafloor, there is a lack of data on how these processes act at spatial scales that are relevant for environmental management. We also lack sufficient assessment tools for the potential sensitivity of seabed carbon to fishing disturbance.
- The models of changes in carbon storage due to trawling need to be further developed and parameterized at a regional scale to allow them to be useful as a component in the marine spatial planning process.

- There is no point having very expensive sampling as we need quick assessment. We need data on seabed carbon stores and ultimately from that we can build a carbon sensitivity index.
- Should carbon assessment be incorporated at the same time as fishery advice?
- There is no real consensus on whether and by how much trawling actually does impact on carbon storage in the seabed. A dedicated programme of empirical research is almost certainly need here.

5 Implications of the findings from ToR a and b for inclusion in the Ecosystem and/or Fisheries Overviews

5.1 Implications of the findings from ToR a and b for inclusion in the Ecosystem and/or Fisheries Overviews

Tor c) Discuss how the existing approaches for assessing and prioritising the main ecosystem stressors can be adapted to enable the assessment of fishing impacts on the carbon sequestration processes. Report on the implications of the findings from ToR a and b for inclusion in the Ecosystem and/or Fisheries Overviews; (Science Plan codes: 2.5, 4.1);

The Workshop participants agreed there are still major knowledge gaps and uncertainties in the three major points discussed (ToRs a, b1 and b2), which would have limited our ability to assess or report on implications of ecosystem or fishery overviews for the time being. These knowledge gaps were detailed in chapters 2-4, and summarized here.

For the BCP, it was noted that most of the research to date had focused on the oceanic BCP, and little was known about the BCP in shelf seas, where most major fisheries are carried out. It should be noted that there was more certainty on the need to avoid harvesting resident or migrating mesopelagic species in the open-ocean due to their key role in the oceanic BCP. Otherwise, inclusion of consideration of the links between fishing and on-shelf BCP in either types of overviews would, therefore, be largely impossible based on current knowledge. Much more research would need to be done before such inclusion could be considered. WKFISHCARBON proposed that this should be a focus for a future meeting.

For GHG emissions from fishing vessels and potential reduction and mitigation, there was much more clarity. Research on seabed impacts of gears, and on fuel efficiency have been carried out for many years. These offer a number of routes to reduce GHG emissions through changes of gears or fishing practices. It is more difficult to identify how these measures could be included in the ecosystem or fisheries overviews. This is partially due to research focusing on fuel use intensity, i.e. fuel use (and, hence, GHG emissions) per kilogramme of fish landed. It is also made difficult by a lack of standardization in the metrics applied for fuel use, and critically the actual emissions that are generally inferred from fuel use rather than measured directly. The observation that exploitation of healthy stocks can have a lower fuel use intensity than fishing on depleted stocks is important, but it should be noted that this will probably not result in lower GHG emissions, and may increase them.

For trawling impacts on the seafloor and potential release and remineralization, the key issue is that research to date has been unable to confirm that any impacts would be negative, neutral or positive. All three possibilities have been identified, and would also depend on the habitats, and on the gear used. There is still an ongoing debate in the literature on this issue, making its inclusion in ecosystem and fisheries overviews problematic.

For GHG emissions from fishing vessels and their potential reduction and mitigation, there was much more clarity. Research on vessel fuel efficiency has been carried out for many years, and resulting findings and innovations offer a number of routes to reduce GHG emissions through changes to fishing vessels, gears or practices. It is more difficult to identify how these measures could best be included in the ecosystem or fisheries overviews. This is partially due to research focusing on fuel use intensity, i.e. fuel use (and hence GHG emissions) per kilogramme of fish landed. It is also made difficult by a lack of standardization in the metrics used for fuel use, and critically the actual total emissions that are generally inferred from fuel use rather than measured directly. The observation that exploitation of healthy stocks can have a lower intensity of GHG emissions than fishing on depleted stocks is important, and points to stock rebuilding as an important mitigation measures. However, it should be noted that without emissions-focused management measures, rebuilt stocks runs the risk of being subjected to higher total effort, which could in turn increase total emissions.

6 Potential for translation to advice to inform EBFM, and proposals for a roadmap for what should be done next

ToR d. Identify how the knowledge on the role of fishing (by fish removals, seabed abrasion and emissions) could be translated to advice to inform ecosystem-based (fisheries) management (EBFM/EBM), and to develop a roadmap for what needs to be done next and whether further workshops would useful (Science Plan codes: 6.4)

6.1 Synopsis of the current state of knowledge from WKFISHCARBON

WKFISHCARBON identified and synthesized a wide range of knowledge on the role of fishing in the context of carbon sequestration and GHG emissions. The main potential for translating into advice would lie in the impacts on the BCP and carbon sequestration of fishing in terms of fish removals, and in the impact of trawling on carbon storage and retention.

In terms of the BCP and carbon sequestration, it was clear from the workshop that most of the knowledge and studies are in the oceanic realm (i.e. off the continental shelves). Most fishing in this region is for pelagic fish (e.g. mackerel. horse mackerel, blue whiting, tunas and capelin – in the NE Atlantic). Given the reasonable understanding of the oceanic BCP and of the biomass of these stocks, it should be possible to determine their contribution to the overall BCP. From there, it should be possible to include this into the EBFM advice. The effect of the removals from these stocks and then the impact on the foodweb dynamics could be investigated using foodweb models, including Ecopath with Ecosim (EwE), SEAPODYM and FEISTY. This work is currently being carried out within the Horizon Europe project OceanICU.

However, most managed fisheries are conducted in shelf seas. In these regions, knowledge of the BCP is much less., and probably more complicated. Transit times of faeces and carcasses will be much shorter. But recycling of these and remineralization is probably quite substantial and more rapid in shelf seas. Again, investigations are underway in OceanICU and via Natural England and DEFRA, but it is still early days.

In both the shelf and off-shelf ecosystems, it may be possible to determine the scale of impact of fishing on the BCP through biomass removal, and its consequences. For this to be useful in EBFM, we would still need to determine whether the scale also required management to reduce that impact. What that means in terms of needing to manage, i.e. reduce removals, depends on the relative global importance of the impact on the BCP and sequestration from these fisheries.

Managing the impact of trawling on carbon storage and retention is also mainly a shelf seas issue, as this is mainly where bottom trawling occurs. Currently, the evidence of negative impacts on the carbon stored in shelf sediments is conflicting and controversial, and there is even some evidence of it having a positive effect. There is also evidence that this is strongly dependent on the fishing gear used, and on the substrate it is used on. There may be a scope for management advice on areas and/or gears to avoid using, but again, there is a need for more work and for determining the relative importance of these impacts on a global scale. Goods and services from fishing are important globally, and there will need to be studies of the trade-offs involved if we aim to manage fisheries in a carbon-based context. In addition, our knowledge of any BCP process in shelf seas is very minimal. We need much more empirical data on what happens to biological material at the seafloor in shelf seas. Water movement is much more active in these areas (tides and currents), there is likely a high level of detritivory, and of bioturbation, and we know little about sedimentation rates and, hence, burial rates. In addition, some of the biological material will be transported off the shelves into deeper waters where sequestration will more likely follow the pattern in oceanic waters.

From this perspective there is a major need for more research that critically includes the quantification of the various process described above. This is unlikely to be solved by modelling alone, as there are too many uncertainties, and a concerted field programme will also be required before any fisheries management proposals would be robust.

Finally, there is the issue of GHG emissions from fishing vessel operations. Much attention has been given to fuel use intensity, i.e. the amount of fuel (and hence) GHG emissions linked to fishing yields – the carbon footprint of a kilogramme of fish - than the absolute amount of GHG emissions produced. Both are important and, thus, both should be considered relative to the footprint of other food production, and of the total GHG emissions from the sector. There are, however, a range of technical measures which can be adopted to reduce fuel use intensity, and these have been described in this report. Such measures also often entail reductions in the seafloor contact e.g. pelagic otter boards, lighter groundgear etc. These could also, potentially, reduce the seafloor impacts and the release of carbon from the seabed. Aiming to travel shorter distances to and from fishing grounds could also reduce overall emissions. Finally, there is evidence that fishing on healthier (larger/recovered) stocks reduces fuel use intensity although probably not the overall GHG emissions. Alternative fuel sources or power plants may also contribute to a certain degree, but this is beyond the scope of this report.

Finally, there is the issue of GHG emissions from fishing vessel operations. Much attention has been given to fuel use intensity, i.e. the carbon footprint of a kilogramme of fish landed, rather than the absolute amount of GHG emissions produced. Both are important, and both should be considered relative to the footprint of other types of food production, and of the total GHG emissions from the sector. There are, however, a range of technological, behavioural and management changes which can be adopted to reduce direct emissions from fishing, and these have been described in this report. Such measures include modifications to vessels, the use of renewable energy for propulsion, and changes in gear type or design. Some such gear modifications also entail reductions in seafloor contact which, could also, potentially, reduce seafloor impacts and the release of carbon from the seabed. Changes in fishing practices, such as travelling shorter distances or steaming at slower speeds, to and from fishing grounds could also reduce overall emissions. Finally, there is evidence that fishing on healthier (i.e. larger or recovered) stocks reduces emissions intensity, because less fishing effort is needed to obtain catches. However, there is also a risk that rebuilt stocks can be subjected to higher total effort, and hence higher total emissions, if fisheries management does not explicitly prioritize emissions reductions.

6.2 A proposed roadmap for ICES in the realm of fishing and carbon

On the basis of section 6.1, there is a clear need for further research and analyses in this area, and a role for further involvement by ICES. The links between fishing and both carbon sequestration and direct and indirect emissions (through seabed impacts), are clear, but largely uncertain to date. Therefore, we propose a continuation of the work of WKFISHCARBON, using the following roadmap:

By April 2024

- Develop a Policy brief – and seek funding for this.
  - UK DEFRA have agreed to provide funding support.
  - Small-scale desk study to model likely implication of a small number of commercial species (i.e. herring and cod) to scope out the likely scale of carbon into the sediment via deadfall and faecal pellets. The plan is to use the Irish Sea EwE model and simple biogeochemical equations to simulate possible pathways from fish to sequestered carbon and would likely include sensitivity analysis to guide future empirical field studies.
  - Emma Cavan, Paula Alvarez, Jacob Bentley, Simeon Hill and Dave Reid
  - May provide a SWOT analysis for the approach.
  - Possible ICES viewpoint publication.
- Villy Christensen to explore with the Ecopath Research and Development Consortium the possibility for add-ons to EwE to explicitly model carbon flows in the model. Other members of WKFISHCARBON will also help provide parameters to support the World Bank project on functional group contribution to carbon sequestration, with cod and herring as start
- Set up three Discussion subgroups to carry out intersessional work online on the three main aspects of WKFISHCARBON. Emissions, chaired by Arielle Sutherland-Sherriff, trawling impacts chaired by Samuel Rastrick, and the BCP chaired by Simeon Hill. The aim of the subgroups will be to prepare proposed actions to be discussed at a proposed second meeting of WKFISHCARBON in autumn 2024 online. If appropriate, the groups will meet together online in April 2024

By end of 2024:

- The participants agreed that there was a considerable amount of work that needed to be carried out and that another meeting in Autumn 2024 should be organized, with particular emphasis on the shelf seas regions. This upcoming meeting should focus on:
  - How to pool data and modelling efforts with a particular focus on:
    - Sourcing data and/or studies that could provide support to shelf carbon sequestration modelling and simulation. At the minimum, it should provide a list of parameters such as sinking rates, sedimentation rates, sediment organics composition, natural rates of resuspension and remineralization, and possible proxies for these.
  - Defining terms for carbon sequestration, lability, refractivity, remineralization, timescales.
  - Understanding the on-shelf contribution of fish and fished organisms to shelf/off-shelf C sequestration. And consider blue carbon stored by benthic species (i.e. *Nephrops*, corals, bivalves, scallops, etc.).
  - Standardizing operational metrics and procedures for determining vessel GHG emissions
  - Benthic trawling, observations on physical impact to seafloor and carbon remineralization and sediment carbon maps
- The importance of identifying who are the people who would want and need advice on this topic, and what advice products would be useful given the current state of knowledge.
- Linking in with other ICES Expert Groups - e.g. Working group (WG) on climate, biodiversity, ecosystem services, ecological effects of fishing activities (Working Group on Ecosystem Effects of Fishing Activities (WGECO)). Invite appropriate additional experts to the next workshop (WK) meeting/s.

- Maintaining the valuable collaboration with the eNGOs that characterized the present workshop. This could include sharing data products and policy knowledge to understand fishery impacts to carbon sequestration. For example, the ongoing Global Fishing Watch on quantifying fishing effort and potentially GHG on global emissions.
- Continuing to review and synthesize the latest research across all the aspects: fish removals, seabed impacts and reducing emissions in the fishing sector.

7 Working documents given at the workshop, and summary of related discussion

It should be noted that the material presented here represents the perspective of the authors. It does not necessarily represent that of the whole WKFISHCARBON nor of ICES

7.1 The role of fish in carbon fluxes in the open ocean

Fish and carbon: from biogeochemical models to fish models - The need for dynamic linking between these.

Sevrine Sailley - Plymouth Marine Laboratory, UK.

Marine biogeochemical models excel at tracking carbon through the lower trophic levels of the foodweb and any non-biological compartment, similarly fish models excel at tracking fish populations whether it be through size spectrum or species approach. Unfortunately, these models need a lot of work to be used in conjunction (i.e. units are different with biogeochemical models using moles of carbon or nitrate while fish models deal in grammes of wet weight; spatio-temporal time-scale discrepancies) and are often used with what is referred to as an offline or one-way coupling meaning that information goes from the biogeochemical model to the fish model but there is no feedback (i.e. removal of biomass from the lower trophic level, consumption of oxygen and production of faecal matter by fish are not taken into account). In order to progress projections of fish and their impact on the carbon cycle it would be necessary to develop a coupler so that the feedback of the fish model can be included in the biogeochemical model, a review of parameters in either model and data for validation of the coupled models.

Assessing carbon sequestration with the JRC Marine Modelling Network.

Luca Polimene - Joint Research Centre (JRC) of the European Commission.

Carbon sequestration strongly increases the capacity of the ocean to absorb atmospheric CO2, in this way regulating the Earth's climate and counteracting global warming. As such, carbon sequestration provides a fundamental ecosystem service to humans. However, the capacity of the ocean to store carbon is not unlimited since factors such as increasing temperature and thermal stratification might down regulate this service. Biogeochemical models are useful tools to understand and predict how anthropogenic pressures (including climate change) are affecting ocean carbon sequestration. In my presentation, I briefly described the main processes underpinning ocean carbon sequestration and the JRC capability to model them. Two examples were provided showing how global (increased atmospheric CO2) and regional (increased discharge of terrestrial organic matter) factors might downregulate ocean carbon uptake. The presentation was based on a published work (Polimene *et al.*, 2022) and preliminary results generated by the JRC marine modelling group.

Discussion points

- Theoretically, we may reach a point where the ocean can't take up carbon anymore. Keeping the surface DIC lower than the atmosphere is the only way to keep the ocean carbon uptake positive. As we have a more acidic ocean, the increase of carbon *per se* should not affect the primary production.

- A distinction should be made between carbon sequestration and sequestering carbon. The latter is removing the carbon present in the atmosphere. The former is the process of retaining carbon in the ocean. Sequestering carbon should not be a purpose. The global scale model showed residence time that gives the amount of carbon sequestrated. Now we need to reassess how the processes (and the fish activity) contribute to that. Fish biomass is one thing, but faeces and fish removal can be calculated in terms of carbon sequestration.
- Production is different from sequestration. We still don't know how much particles are degraded along the way by bacteria or on reaching the bottom? Models tend to use one attenuation rate but we need to do better.

Characterizing Pathways of the Biological Carbon Pump in two Fjords with Contrasting Pelagic Foodweb Structures.

Kea Witting - GEOMAR, Germany.

To implement the role of mesopelagic fish into biogeochemical carbon model simulations and further enhance state-of-the-art processes to investigate current mesopelagic processes, CO2Meso is aimed to combine ecological observations with modelling approaches, socio-economics and international law. Within the framework of the HE570 research cruise, the mesopelagic ecosystem structures of two fjords (Masfjord and Lurefjord) close to Bergen (Norway) were studied and the pathways of the respective biological carbon pumps were compared. Both fjords served as "natural mesocosms" as they are topographically very similar but host entirely different ecosystems. Key players in the Masfjord are the two mesopelagic fish species *Maurolicus muelleri* and *Benthosema glaciale*, whereas the Lurefjord is mainly shaped by mass occurrences of the deep-sea medusa *Periphylla periphylla*. This study aimed at identifying and characterizing different pathways of the mesopelagic biological carbon pump and additionally compared a multitude of catching devices (MultiNets) and imaging instruments (UVP5, PELAGIOS). We also hypothesized that the presence of mesopelagic fish species can be detected in the seabed sediment of the fjord by using the relatively new approach of using sedimentary environmental DNA (eDNA).

Results indicate major differences between the fjord ecosystems that can be seen across all the different instruments used. High appendicularian abundances in one fjord were found mainly by the data collected with the UVP5, which was validated by video material gathered with the PELAGIOS. Copepods could mainly be detected using the MultiNets and UVP5 as they were too small to identify exactly using the PELAGIOS. Additionally, this study provides records of *P. periphylla* occurring in the Masfjord, which is typically used to represent a classical fjord ecosystem structure. All findings suggest a lower carbon sequestration rate in the *P. periphylla* dominated Lurefjord, due to BCP pathway alterations.

Discussion points

- Because of the limited exchange between fjords, fishing would likely change the whole ecosystem; thus, is not encouraged, although fisheries on *Nephrops* do exist.
- For now, transferring information collected in fjords to the open ocean is a huge task and would probably require a lot of modelling. However, showing that fishing has an impact in one ecosystem would reinforce the fact that caution would be required in others.

Metazoans, vertical migrations and carbon sequestration.

Andre Visser, DTU-Aqua, Denmark

Professor Visser gave an impromptu presentation on broad concepts around the BCP, and the global carbon inventory, following from the current state-of-the-art as presented in the 2021 IPCC report. This work is being prepared for publication.

The definitions of blue carbon and sequestered carbon in Figure 7.1 were developed by Professor Visser, but are well in line with others that have tried to pin down a precise meaning (e.g. Hain *et al*., 2014; Lovelock & Reef, 2020). The aim was to make this mathematically sound by defining B as the size of the reservoir (PgC), and relate this to the Influx (PgC/year) and residence time (T) as B=QT (see text box below). This is a somewhat different way of approaching sequestration; the usual approach is to concentrate on Q only. The point is, Q is not the sequestration rate, rather its dB/dt.

Blue Carbon = all carbon sequestered in ocean reservoirs (coastal regions, pelagic ocean, benthic communities and marine sediments) that derive from biological production. This includes organic carbon (living and dead), respired carbon and mineral carbonates.

By sequestration we mean stored within a reservoir out of contact with the atmosphere. Broadly seen, this is controlled by two metrics: Q [PgC year^{-1}] the flux of carbon into the reservoir and T [years] the mean residence time of carbon within the reservoir.

At steady state, B [PgC], the blue carbon content of the reservoir is given by B = Q T.

Changes in B over time ultimately reflect changes in the balance between Q and T and any expansion of the physical extent of the reservoir.

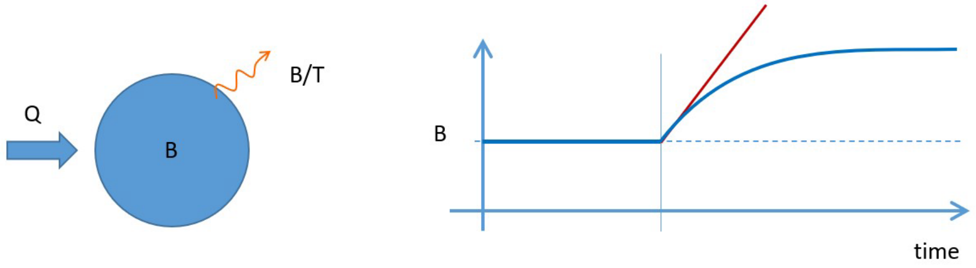


Figure 7.1 A summary of the size of the various carbon reservoirs in the ocean (i.e. blue carbon).

The ocean stores a huge amount of carbon, mainly in the form of dissolved inorganic carbon. The partitioning of this carbon is summarized in Figure 7.2.

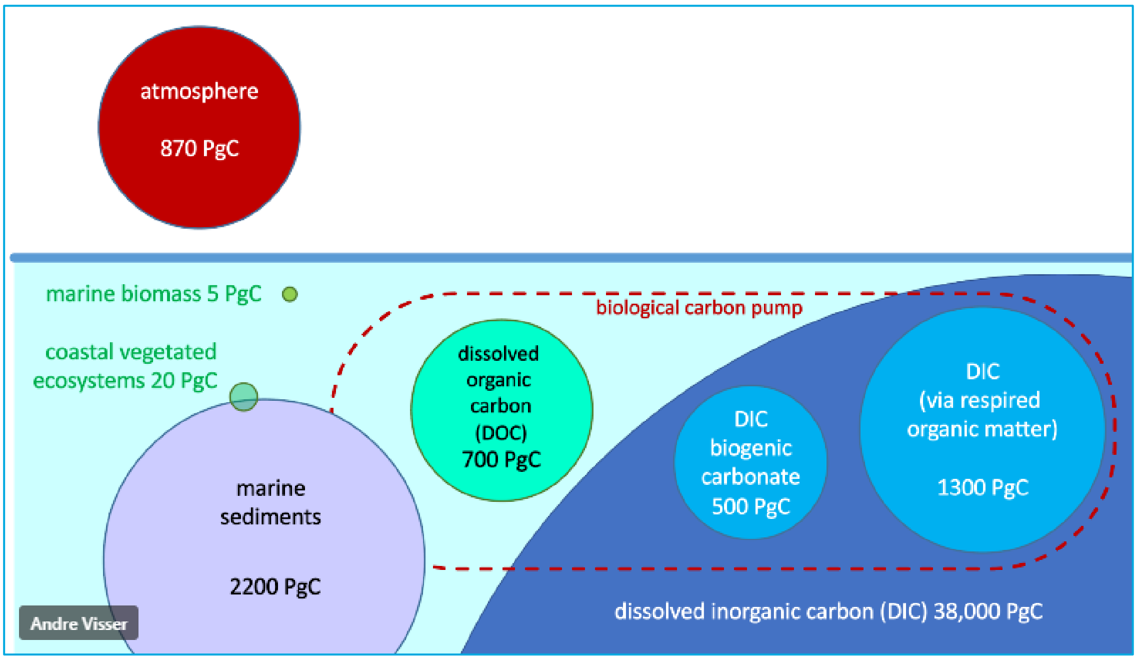
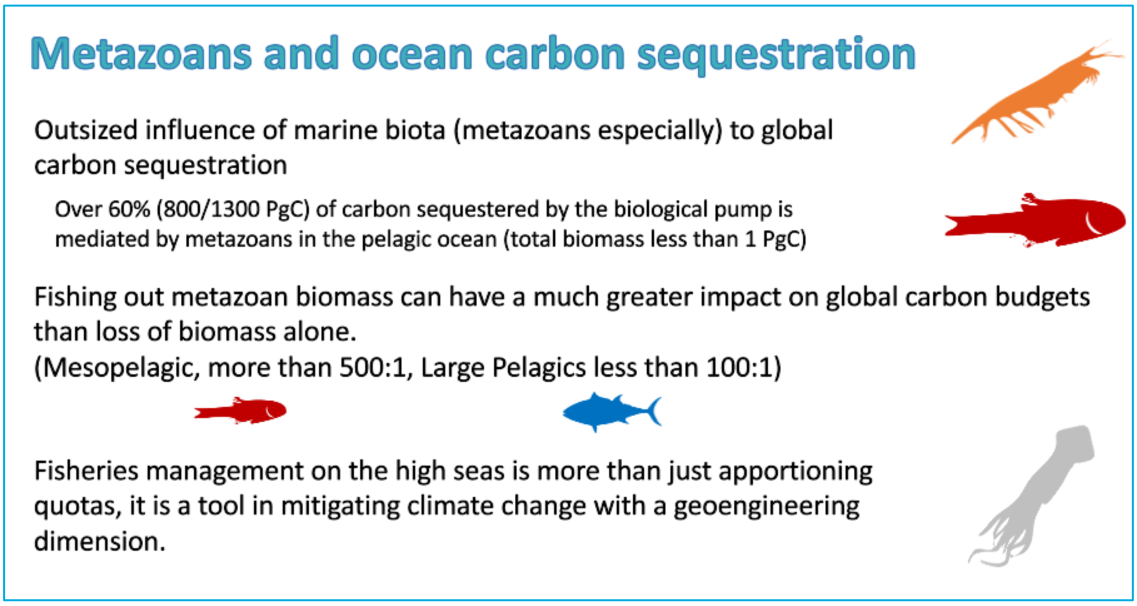


Figure 7.2 A summary of the size of the various carbon reservoirs in the ocean (i.e. blue carbon).

To date coastal vegetated ecosystems have been seen as the main focus of the blue carbon concept, but this does not encompass all of what should be considered. Sequestrated carbon can be seen as all of the carbon in the Earth System that is not in the atmosphere; and sequestration is then any process that cause these carbon stocks to expand. The key question is then: what is it about fish and fisheries that affect the pool sizes?

Metazoan responsible for 800 PgC with meso fish (35%) krill (30%) and copepods (15%)

Faecal pellets are the major player as pathways, particularly for zooplankton pellets (Cavan *et al.*, 2015, Bisson *et al.*, 2020), followed by the deadfall. This is expressed in the Figure 7.3.



Metazoans and ocean carbon sequestration

Outsized influence of marine biota (metazoans especially) to global carbon sequestration

Over 60% (800/1300 PgC) of carbon sequestered by the biological pump is mediated by metazoans in the pelagic ocean (total biomass less than 1 PgC)

Fishing out metazoan biomass can have a much greater impact on global carbon budgets than loss of biomass alone.
(Mesopelagic, more than 500:1, Large Pelagics less than 100:1)

Fisheries management on the high seas is more than just apportioning quotas, it is a tool in mitigating climate change with a geoengineering dimension.

Figure 7.3 The importance of metazoans in carbon sequestration

Discussion points

- The global scale in this presentation is made to give a context where we can go into regional or local effects. Starting to ask those questions and putting numbers on those contributions will enable management to start to measure impacts. The biogenic carbon estimates are not definitive, as there is a 10% error margin but we are fairly confident in the estimate. The ratios between biomass and carbon budget are also not definitive. We don't know enough about the system to say how they would change with biomass removal. However, they are here to start giving an indication.
- What is sequestration. Is it the same as accumulation and/or burial? The general statement is that carbon has to be kept for a thousand year to call it sequestration. But we can and should do better. With such a broad definition, we could include the changes in biomass, and pellet production for instance. The definition of sequestration is contestable but the question here is can we sequestrate more or not. One important point is that for the most part we are not fishing the open ocean to the same scale as we fish the shelf, arguably apart from for small and large pelagics (e.g. mackerel or tunas). So in the open ocean it may be more possible to infer from less disturbed populations.
- The main focus here was on diel-vertical migration, which is limited on the shelf.

Evaluation of carbon sequestration impacts of marine projects, a study for the World Bank Group

Villy Christensen, Miquel Ortega Cerdà, Jeroen Steenbeek and Marta Coll. University of British Columbia

The conclusion from this study is that there is clear consensus in the scientific literature and in scientific community that the marine biological pump plays a major role in the regulation of climate change, and there's a broad understanding of the main pathways by which the carbon is exported from the upper oceanic layer to the deeper ocean.

There is also an agreement that qualitatively, fish are important for carbon storage and flow, but quantitative values come with large uncertainty. In these areas, there are still significant knowledge gaps, especially for coastal and shelf areas, and the scientific community is actively striving to establish a comprehensive consensus on essential elements required for accurately evaluating the effects of fishing activities and policies on marine carbon sequestration. These gaps include the need to better characterize how different fish species contribute to the various carbon flows.

There are also relevant uncertainties on the biochemical transformations of the various carbon flows identified in the marine realm – that depend in complex ways on the environmental variables such as oxygen and temperature, and the POM characteristics that condition remineralization processes and sinking speeds. These processes are better understood in open ocean, while in coastal and shelf areas their characterization is more complex and require better data availability.

Specific difficulties have been identified arising from the fact that most fishing activities take place on the coast and marine shelf, where finer modelling resolutions are needed and key complex physico-chemical and biological processes take place, leading to a high level of complexity in evaluating carbon sequestration and as a consequence the role of fisheries in carbon sequestration. There is also a clear need to better characterize the interrelation between trawling activities and sedimentary ecosystems where there is a high degree of uncertainty.

There is considerable research starting up aimed at quantifying fish sequestration and fisheries interactions as part of policy initiatives to ensure that the impact of the marine biological pump is considered in the decision-making processes. While with the current state of knowledge it does not seems feasible in the short term to integrate new marine-fishing biological pump processes in the international carbon market schemes, the presence of habitats considered to be of importance to the long-term storage of carbon are starting to be taken into consideration for both fishing and conservation policies. These policies will benefit from the scientific focus that is emerging, especially in improving the understanding of carbon sequestration times of the different carbon pathways.

Given that the World Bank Group is a provider of financial products and technical assistance to development projects around the globe, and with its mandate to facilitate the sharing and applying innovative knowledge, the Group is in a prime position to support the global development of scientific understanding of fish and fisheries carbon sequestration at the global level, in particular with funding scientific capacity and knowledge building through the establishment of standard methodologies and databases.

Discussion points

- Coastal biogeochemical models may also have a part of the information but that information may also be spatially different. The time dedicated to build those pathways will dictate the level of uncertainty. In this case, it is better to deal with uncertainty rather than nothing at all. DOM and POM carbon pools are starting points. Once again, sequestration is part of the focus and needs to be properly defined. Their perspective is that decades are a short time-scale for the ocean, but at a human scale it might be what is needed to fix other issues. Using the decades as emergency measure is a new concept for carbon sequestration as earlier, it was said that thousands of years was the time-scale considered.
- In terms of uncertainty, if the results obtained from this WK are such as: the carbon sequestration for some fish groups is 5% of intake with a range between 1-20%, then it is acceptable. The project wants to know what the pathways are while the model wants to simulate management changes.
- On time-scale, a question was raised on historical changes in fish stocks and in carbon chemistry. Should we consider a pre-fishing baseline? The deep sea environment provides a lot of examples to illustrate carbon sequestration. However, we know less about this process in anoxic muds, shelf or coastal areas. If carbon sequestration is what we want to achieve, does that mean that we want to consider degraded ecosystems (such as oxygen minimum zones) if they show better properties?
- The World Bank is interested in fish carbon in the context of climate finance and carbon sequestration. We have a few models ready for use. There should be a rating of carbon sequestration. Planting a tree is different from whale sinking or fish faecal pellets. At some point ecosystems can become carbon sources instead of sinks.

  Yes. however, currently we need to develop ways of financial accounting - should we sell carbon sequestrated for decades or hundreds of years? As far as economics is concerned, we need to define that:
  - The bottom line is if the World Bank is involved, it will be interested in economics. Climate finance is essential to global south adaptation. For the ProBLue project we have to be pragmatic and skip principles. This brings people working on carbon sequestration and flows with modelers together to find solutions. Fish-MIP has been looking for baselines, and has been doing that a bit. The interactions/trade-offs potentially between biodiversity and carbon cycling though is a key consideration to keep in mind. Perhaps we can't always have both. Where and how can we manage activities to optimize both services?

7.2 On direct emissions from fishing fleets using different extraction methods

Carbon footprint and contribution of marine capture fisheries to global energy use. Antonello Sala- CNR-IRBIM, Italy

The rise in fuel prices, stock decline and the possibility of finding a different future for new generations are some of the factors that have made fishing arrive at its ‘survival limits’, in many parts of the world. A FAO background study (in press) provides an overview of the current state of research into energy use and greenhouse gas (GHG) emissions in fisheries with a focus on industrial fleets. Fuel use intensity, or litres of fuel consumed per tonne of landings, resulted typically much higher in low volume fisheries than for many other fishing techniques. There are two widely acknowledged main approaches to estimate the contribution of marine capture fisheries to global fuel use and GHG emissions. One approach uses catch-based fuel use intensity for well-studied fisheries, the second uses fishing effort data to estimate fuel use-based on vessel size and fishing times. In our opinion, the two approaches are found to be complementary to each other, not contradictory, and global estimates of fuel use and GHG emissions from marine fishing should be based on their combination, depending on the data available. However, both approaches have several limitations and rely in many cases on strong assumptions when it comes to “catch or effort reconstruction”. The advantages and disadvantages of each method regarding the limits of the nominal effort available for both coastal and industrial fisheries but also of the current algorithms have been largely discussed. Coherent monitoring of the energy profile of fishing vessels may efficiently highlight inefficiency sources, enabling the deployment of informed and economical corrective measures. We conducted energy audits on three major trawl fisheries in the Mediterranean: the midwater pair trawl, the bottom otter trawl, and the Rapido beam trawl. This contribution seeks to provide ship owners and researchers with experience undertaking energy audits in order to lower fishing vessel fuel costs. On average, these fisheries use 2.9 litres of fuel per kilogramme of fish landed, however the rate of fuel use varies greatly depending on the type of gear and vessel size. This amount of fuel burned from capture to landing generates approximately 7.6 kg·CO_2/kg fish on average. Another crucial component to lowering fishing's environmental costs may be minimizing effects and energy use along the whole supply chain. Now is an opportune time for commercial fishers to invest in fuel saving technologies in anticipation of future price increases. Energy audits not only decrease reliance on limited fossil fuels, but also contribute to reduce GHG emissions and help fishers retain profitability during periods of high fuel prices and/or low landings value. Our results provided a set of recognized benchmarks that can be used for monitoring progress in this field and contribute to quantify fuel inputs and GHG emissions for the global fishing fleet. This work has been published (Sala *et al.*, 2022).

Discussion points

- Few studies use fuel use intensity. The increase of fuel efficiency would not decrease the footprint and disturbance of the seafloor but would reduce the drag. These changes might lead to reduction in herding in midwater. The catch profile could then be different but the total will be same. Hence, GHG/kg stays the same. This calls for a better insight for the economic results as landings prices are species dependent.

Better Use of Public Money: The End of Fuel Subsidies for the EU Fleet[1]

Laura Elsler (Independent Consultant) and Maartje Oostdijk University of Iceland Report for ClientEarth and OurFish

The EU fishing fleet has enjoyed a significant exemption from fuel taxes, in an estimated range from €0.8 to €15.7 billion between 2010 and 2020. Presently, the European Green Deal and Fit-for55 initiatives are imposing demands on various industries to curtail emissions and reduce the provision of subsidies for fossil fuels. Within the framework of the revised Energy Taxation Directive (ETD) proposal, a remarkably modest tax rate is suggested for fuel used in the fishing sector—merely €0.036 per litre. This rate stands in stark contrast to the average tax rates employed for road transportation, which is around €0.67 per litre.

Harmful subsidies, such as fuel tax exemptions, have led to increased CO_2 emissions and overfishing. The elimination of fuel subsidies does not have to lead to a reduction in overall support for the fishing sector. Our analysis illustrates that 17 alternative subsidies outperform fuel subsidies across environmental, social and economic dimensions. On average, these alternative measures yield an impact score that surpasses fuel subsidies by 188%.

A scenario of a €0.33 per litre tax, which is the minimum level mandated by the EU Council Regulation on energy product taxation for motor fuels in 2019, could have fully covered the twenty thousand full-time fishers' salaries for a year or paid for six thousand energy reduction and decarbonization projects.

A tax rate as low as €0.036 per litre fails to account for the environmental cost of carbon emissions accurately and consequently falls short of providing adequate support for the crucial transition toward green and low-carbon EU fisheries.

The removal of fuel subsidies should be recognized as an essential initial stride towards achieving a just and equitable transition to fisheries that have a minimal ecological impact and operate on low-carbon principles.

Discussion points

- Labelling (such as MSC) are moving towards considering the carbon impact in their certification. There are distinctions to be made between large-scale and small-scale or demersal and pelagic fleets as they have different contribution to greenhouse gas emissions. The resilience observed in small-scale fisheries comes from data of vessels <12 m which use passive gear (source: STECF).

Integrative surface-to-bottom carbon footprint of fisheries: economic benefits and sustainable fishing of contrasting Mediterranean fisheries[2]

Manuel Hidalgo (IEO, CSIC), Spain.

Ensuring economically viable, sustainable and low CO_2 emissions of extractive fisheries is critical worldwide, and particularly important in the most overexploited region of the world, e.g. Mediterranean Sea. We here presented an integrative assessment of the CO_2 emissions combining different gears, vessel size classes as well as a wide range estimation of low spatial resolution carbon release from the seafloor by bottom trawling of the Western Mediterranean commercial fisheries (Alboran Sea, Northern Spain and the Balearic Islands). We also consider detailed socio-economic and ecosystem indices of the trophic structure of extractive fishery.

---

[1] For a more comprehensive information and presentation see Elser and Oostdjik (2023).

[2] For a fuller and comprehensive presentation see Munoz *et al.* (2023).

While sea surface CO_2 footprint of purse-seine and bottom trawling is among the lowest of animal protein production, our results evidence that considering sweeping released CO_2 from the seafloor the bottom trawling footprint becomes the animal protein production with the highest CO_2 footprint. Moreover, the lowest bottom released CO_2 estimation overrides 3-10 times the CO_2 buried in the seafloor through the biological pump in trawled areas. Net profit per fuel derived of CO_2 emission for all fleets is lower than 1 € $kgCO_2^{-1}$, being the lowest for large trawlers (0.025 € $kgCO_2^{-1}$). We evidence spatial variation of the carbon footprint, with the Alboran Sea requiring a reduction in purse-seine fishery and Northern Spain a reduction in trawling. Our results provide the scientific basis for urgent mitigation and adaptation measures needed to obtain sustainable fishery in terms of net profit, and sustainable seafood extraction and CO_2 emission reduction through an integrative assessment of different sources of CO_2 emissions and spatial variation of fleets.

Discussion points

- The last figure of the presentation showed the CO_2 footprint of carbon production by fisheries. Numbers for other food production types have been taken from other papers, it was not a unified framework. Very large numbers in CO_2 released from the bottom were surprising as the Mediterranean hasn't much to release in the first place. But that number was taking into account resuspension. The type of sediment was taken into account in the study and a point has been made the importance of doing it. The sediment should not be treated as homogenous data as trawling is not a homogenous activity. Papers on trawling in the UK show different level of disturbance. Combined with that the diversity of sediment and carbon stocks lead to a variability of impacts.

7.3 On indirect emissions from disturbance of the seabed

Effects of bottom trawling in Norway: sediments and carbon remineralization[3].

Samuel Rastrick, IMR Bergen

In a meta-analysis of 49 different studies 29% reported a decrease in sediment organic carbon (OC), 10% reported an increase in sediment OC and 61% reported no significant effect on sediment OC associated with trawling (Epstein *et al.*, 2021).

In Norway, bottom trawls and seines are widespread. Beam trawling and dredging rare or banned. Trawls doors make tracks from 0.2 to 30cm (median= 5.5cm). Most of sediment returns to the seabed within hours but some particles stay suspended for much longer. However, Norway has little information on OC stored and disturbed by trawling. Most trawling activity does not take place on high OC storage area, but there is overlap from shrimp trawls.

Discussion points

- One of the reasons for remineralization is the presence of certain groups of marine bacteria. It is then important to look at their genomics as they are often forgotten and not present in the models. Some metals also have a role. OC remineralization may also increase when refractory organic matter in the sediment is mixed with more labile organic matter in a process known as priming (e.g. Bianchi, 2011), but there is no straightforward process for addressing priming.

---

[3] This text is a short abstract of the presentation, for which a fuller version is attached as an appendix (Annex 3).

Impacts of bottom trawling on long-term carbon sequestration in shelf sea sediments

Wenyan Zhang, Lucas Porz Institute of Coastal Systems, Helmholtz-Zentrum Hereon, Max-Planck-Str. 1, 21502 Geesthacht, Germany

Bottom trawling represents the most widespread anthropogenic physical disturbance to surface sediments and benthic habitats (Halpern *et al.*, 2008; Sala *et al.*, 2021). A recent estimate suggests that ~22 Gt of sediment are resuspended by bottom trawling every year on the world's continental shelves, comparable to the total annual sediment supply through rivers (Oberle *et al.*, 2016). Bottom trawling significantly restructures the top layers of seafloor sediments and thereby alters benthic faunal communities (Hiddink *et al.*, 2017; Tiano *et al.*, 2022), biogeochemical processes and element fluxes across the sediment-water interface (De Borger *et al.*, 2021). A recent global estimate by Sala *et al.* (2021) highlighted the impact of bottom trawling on the storage of organic carbon (OC) in seafloor sediments. They suggested that trawling causes remineralization of 0.16–0.4 Gt of sedimentary OC globally every year, resulting in an emission of 0.58–1.47 Gt of CO2. However, this estimate was subsequently questioned by several authors (Epstein *et al.*, 2022; Hiddink *et al.*, 2023), who pointed out large uncertainties in several assumptions made by Sala *et al.* (2021). Epstein *et al.* (2021) emphasized that there is no consensus in existing literature on whether or to what extent trawling would lead to reduced OC storage

The blurred picture of the net effect of bottom trawling on OC sequestration in sediments originates from several counteracting mechanisms. On the one hand, trawling-induced resuspension and physical mixing of sediments may enhance remineralization of OC by increasing oxygen exposure time and limit OC sequestration by inhibiting deposition and burial of fine-grained sediments (Hartnett *et al.*, 1998; Zonneveld *et al.*, 2010; Keil, 2017; Freitas *et al.*, 2021; Paradis *et al.*, 2021). On the other hand, intensified lateral transport towards offshore depocenters and increase in primary production from the resuspension of nutrients may offset the loss of OC to varying extents (Dounas *et al.*, 2007; Martín *et al.*, 2008; Paradis *et al.*, 2018). The complexity of OC sequestration is further increased by benthic fauna, which do not only contribute OC but also play a vital role in mediating OC fluxes across the sediment-water interface (Middelburg, 2018; Zhang *et al.*, 2021). The overall effect of trawling on macrobenthos is a depletion of biomass and a change of the community from sessile to mobile and opportunistic species (Kaiser *et al.*, 2006; Sciberras *et al.*, 2018; Tillin *et al.*, 2006). However, for quantitative assessments of how trawling-induced impacts on benthic fauna would affect OC sequestration, the current evidence base is incomplete and often contested (Epstein *et al.*, 2021; LaRowe *et al.*, 2020).

As a heavily fished region, the North Sea has been subject to trawling for more than one century (Thurstan *et al.*, 2010). Bottom trawling is performed in ~90% of the North Sea area (ICES, 2021), with a particularly high intensity in shallow waters (water depth < 300 m) of the Skagerrak, where the swept-area ratio (SAR) reaches ≥10 yr-1. Bottom trawling intensity shows a positive correlation ($r = 0.18$, $p < 0.001$) with OC contents in near-surface sediments, implying a disproportionately high trawling impact in areas of natural OC burial. Existing estimates of the total stock of OC in the uppermost 10 cm of North Sea sediments range between 96 and 476 Mt (Bockelmann *et al.*, 2018; Wilson *et al.*, 2018; Diesing *et al.*, 2021), with a major part (~75%) being stored in mud depocenters which represent ~20% of the North Sea.

To identify the linkage between carbon storage in surface sediments and bottom trawling, we first combined independent datasets of sediment (Bockelmann *et al.*, 2018) and bottom trawling intensity (Kroodsma *et al.*, 2018) for the North Sea. A pattern emerges when comparing the surface sediment OC-to-mud ratio (OC/mud) and the trawling intensity represented by the annual swept-area ratio (SAR). OC/mud is relatively scattered where SAR < 1, but becomes increasingly confined to a narrower and lower range as SAR increases. The constraint of bottom trawling on OC/mud can be described by a power function. To understand the driving mechanisms of the relationship between OC/mud and trawling, a coupled numerical ocean-carbon-macrobenthos model (Zhang *et al.*, 2017; 2019) was utilized to quantify the effects of bottom trawling on the distributions of macrobenthos and sedimentary organic carbon in the North Sea (Zhang *et al.*, 2023). The model resolves the mechanistic feedbacks between macrobenthos growth and decline, bioturbation, organic carbon fluxes across the sediment-water interface, sediment transport and bottom trawling. Daily bottom trawling activity is modelled through sediment resuspension, macrobenthos depletion and mechanical mixing of the upper sediment layers taking into account gear types, penetration depth, vessel size, trawling speed and sediment properties. Short-term simulations show a 20% reduction of remineralizable organic carbon from the sediment com-pared to a non-trawled scenario after one year, roughly equivalent to emission of 0.6 Mt CO_2. Long-term simulations using reconstructed fishing effort data from 1950-2020 show an accumu-lative trawling-induced reduction of total macrobenthos biomass by 10-17% and an associated loss of carbon sequestration capacity in North Sea sediments by 21-67% when compared to the no-trawling scenario. The highest trawling-induced carbon and biomass losses occur in muddy, depositional areas with high trawling intensities: the slope of the Norwegian Trench, Skagerrak, Fladen Ground, Oyster Ground and parts of UK's east coast. It is noteworthy that the North Sea still acts as a net carbon sink, albeit with strongly reduced capacity by trawling. According to our simulations, the spatially averaged reduction of OC storage capacity over the entire North Sea amounts to ~1 t C km-2yr^{-1}, equivalent to emission of 3.67 t CO2 km-2yr^{-1}. Our estimate is smaller than the original global estimate (21.5 t CO2 km-2yr^{-1} or 0.58 Pg CO2 yr^{-1} in total) of Sala *et al.* (2021) but comparable to their later estimate (1.6 Mg CO2 km-2yr^{-1} or 0.043 Pg CO2 yr^{-1} in total) using a lower remineralization rate (Atwood *et al.*, 2023). Our study points out a central role of benthic ecosystem functioning in long-term carbon sequestration in shelf seas.

Open data and scientific collaboration for a sustainable ocean

Cian Luck, Fisheries Analyst, Global Fishing Watch

Global Fishing Watch is an international non-profit organization dedicated to advancing ocean governance through increased transparency of human activity at sea, presented an overview of existing data products produced by Global Fishing Watch that could be applied to research ques-tions on the carbon impact of fishing. This included an explanation of how machine-learning algorithms are used to identify apparent fishing activity from fishing vessels transmitting their locations using the Automatic Identification System (AIS), the Global Fishing Watch database of vessel identity information, how ports and port visits are identified as well as potential trans-shipment activity at sea, and a high level overview of how technologies can be combined to iden-tify activity by non-AIS transmitting vessels. Information was included on how to access and download the publicly available datasets through the Global Fishing Watch map, data download portal, and application programming interfaces.

In addition to the currently available datasets, Joanna Turner (Machine Learning Engineer) ex-plained the current research that Global Fishing Watch are undertaking in partnership with Woods Hole Oceanographic Institution to construct a machine learning algorithm to detect ap-parent trawling activity, and differentiate likely bottom trawling and likely midwater trawling activity. This will allow users to more reliably map the potential impact of bottom trawling on the seafloor.

Discussion points

- The distinction between demersal and pelagic trawling can be difficult to evaluate, just looking at fishing behaviour might not be enough. The first release on the research should be by the end of the year, although preliminary results could be shared beforehand. GlobalFishingWatch also works with management organizations to help send patrols, US coastguards as well, and vessel viewers for ports inspectors. The data collected through R is not different from the downloadable products on the website, just the queries are more customable. A library in Python is also in the work. An applied research team is looking at the rates of AIS disabling.

Comparison of fishing effort obtained through AIS and VMS data

Sarah Paradis, Joan Sala, Ruth Durán, Pere Puig, Joan Batista Company, José Antonio García del Arco. Geological Institute, Department of Earth Sciences. Zurich,

Demersal fishing may be one of the most harmful anthropogenic activities occurring in marine environments due to its widespread extension and intensity. This fishing activity causes a myriad of effects in marine ecosystem: it leads to stock overexploitation, habitat destruction, depletion of benthic communities, alteration of sedimentary dynamics and may be impairing marine sediments' capacity to sequester carbon. In order to properly quantify the threats of this anthropogenic activity, a proper delimitation of fishing grounds and its spatio-temporal fishing intensity is required. With the advancement of geographical information systems, the positioning of fishing vessels can now be tracked using Vessel Monitoring System (VMS) and Automatic Identification Systems (AIS), each of which comes with its unique challenges. In this study, we compare the spatial resolution of fishing effort as swept-area ratio (SAR) from VMS and AIS data of bottom trawlers in the NW Mediterranean margin. While AIS data provide fine resolution output of fishing effort, certain fishing grounds were not captured since vessels intentionally turned off their AIS transponders. In contrast, since VMS transponders cannot be tampered with, VMS data can identify fishing effort in these hidden fishing grounds. However, the low frequency of VMS data emission along with its low geographical resolution hinders a fine-scale analysis of fishing effort using this method. We conclude that both VMS and AIS come with their respective trade-offs, and a proper understanding of fishing behaviour along with the desired resolution of fishing effort should be established to properly map the spatio-temporal distribution of demersal fisheries.

Discussion points

- AIS is a combination of terrestrial and satellite data. There are gaps that can be in the EEZ when terrestrial data are lost. Also satellite receivers can be overloaded, leading to low data in high vessel densities areas. GlobalFishingWatch could also adapt product to the needs of scientists. The role of small-scale fisheries (vessels < 12 bm) is unclear but there are 2 WKs at ICES dealing with those issues and WKFISHCARBON could collaborate with these groups.

Burying Treasure: Carbon sequestration and storage in Northern Irish Waters

Billy Hunter, AFBI, Northern Ireland, UK.

In shelf seas up to 50% of the phytoplanktonic primary production can reach the seabed through direct deposition of senescent phytoplankton and the faecal pellets of zooplankton and fish. As such, shelf sea sediments may represent a key site for carbon sequestration and storage. This sedimentary carbon has the potential to be disturbed by fishing activities such as bottom trawling, which can resuspend sediment and thus facilitate the aerobic remineralization of sedimentary organic matter. The global extent of this is, however, poorly constrained because of a lack of empirical data on seabed carbon stocks in shelf seas.

Northern Ireland's sea floor area represents a tiny 0.1% of the United Kingdom's Exclusive Economic Area. It consists of 6 000 km^2 of coastal and shelf seas, 518 km^2 of sea lough habitat and 1 670 km^2 of deep, offshore muds in the Irish Sea. The deep muddy sediments occur primarily underlie the western Irish Sea Gyre and support a substantial proportion of the UK's *Nephrops* *norvegicus* fishery. Northern Ireland, thus provides a useful case study to investigate the spatial and temporal distribution of carbon within shelf sea sediments, and the impacts of trawling on these carbon stocks. Mapping of the carbon stocks across Northern Ireland's coastal and shelf seas is ongoing. VMS data from the western Irish Sea reveals intense fishing pressure across the deep muddy sediments, and weak correlations between fishing pressure and sediment organic carbon content. In terms of management of the carbon, the strongest environmental predictors of sediment carbon content were increasing distance to land, and increasing water depth. As such, the preliminary evidence suggests that actions to maximize seabed carbon storage should be targeted and the deepest offshore sediments within the Irish Sea. However, a full stock take of the sediment carbon storage potential requires an understanding of the flux of carbon entering the system from the overlying water column, the relative reactivity of the organic carbon entering the system and the respiratory demands of the sediment community. For effective carbon sequestration the incoming flux of organic matter needs to exceed the energetic demands of the resident faunal and microbial communities and be able to resist further remineralization following disturbance events. As such, a full carbon mass balance is required for regional seas to ascertain the relative importance to global efforts to mitigate anthropogenic climate change.

The gradient observed (distance to land) is also stably moving in very coastal water. At the moment in Northern Ireland nothing is approved but the impact of offshore renewable energy on carbon stocks is something to look at. For windfarm, evidence from Belgian North Sea show that it enhanced the biological carbon pump, leading to a greater carbon accumulation on the seabed. Is it something we want? The MPA-Europe project is building datasets on carbon storage, deposition and sequestration as it aims at finding the optimal locations for MPA. Residence time have not been estimated yet in Northern Ireland.

Discussion points

- The gradient observed (distance to land) is also stably moving into very coastal water. At the moment in Northern Ireland nothing is approved but the impact of offshore renewable energy on carbon stocks is something to look at. For windfarms, evidence from Belgian-North Sea installations show that it enhanced the biological carbon pump, leading to a greater carbon accumulation on the seabed. Is it something we want? The MPA-Europe project is building datasets on carbon storage, deposition and sequestration as it aims at finding the optimal locations for MPAs. Residence time has not been estimated yet in the Northern Ireland.

Reference list

Amoroso, R.O., Pitcher, C.R., Rijnsdorp, A.D., McConnaughey, R.A., Parma, A.M., Sbuhl-Mortesen, L., Campbell, A.B., Catarino, R., Collie, J., Cowan Jr., J.H., Durholtz, D., Engstrom, N., Fairweather, T.P., Fock, H.O., Ford, R., Gálvez, P.A., Gerritsen, H., Góngora, M.E., González, J.A., Hiddink, J.G., Hughes, K.M., Intelmann, S.S., Jenkins, C., Jonsson, P., Kainge, P., Kangas, M. Kathena, J.N., Kavadas, S., Leslie, R.W., Lewis, S.G., Lundy, M., Makin, D., Martin, J., Mazor, T., Gonzalez-Mirelis, G., Newman, S.J., Papadopoulou, N., Posen, P.E., Rochester, W., Russo, T., Sala, A., Semmens, J.M., Silva, C., Tsolos, A., Vanelslander, B., Wkaefield, C.B., Wood, B.A., Hilborn, R., Kaiser, M.J., Jennings, S. 2018. Bottom trawl fishing footprints on the world's continental shelves. Proc Natl Acad Sci U S A 115(43), E10275– E10282.

Atwood, T.B., Sala, E., Mayorga, J., Bradley, D., Cabral, R.B.n, Auber, A., Cheung, W., Ferretti, F., Friedlander, A.M., Gaines, S.D., Garilao, C., Goodell, W., Halpern, B.S., Hinson, A., Kaschner, K., Kesner-Reyes, K., Leprieur, F., McGowan, J., Morgan, L.E., Mouillot, D., Palacios-Abrantes, J., Possingham, H.P., Rechberger, KD., Worm, B., Lubchenco, J. 2023. Reply to: Quantifying the carbon benefits of ending bottom trawling. Nature 617(7960): E3-E5. https://doi.org/10.1038/s41586-023-06015-6.

Atwood, T.B., Witt, A., Mayorga, J., Hammill, E., Sala, E. 2020. Global Patterns in Marine Sediment Carbon Stocks. Front. Mar. Sci. 7, 165.

Bastardie, F., Nielsen, J.R., Andersen, B.S., Eigaard, O.R. 2010. Effects of fishing effort allocation scenarios on energy efficiency and profitability: An individual-based model applied to Danish fisheries. Fisheries Research 106(3): 501-516.

Bastardie, F., Hornborg, S., Ziegler, F., Gislason, H., Eigaard, O.R. 2022a. Reducing the Fuel Use Intensity of Fisheries: Through Efficient Fishing Techniques and Recovered Fish Stocks. Frontiers in Marine Science 9. https://www.frontiersin.org/article/10.3389/fmars.2022.817335.

Bastardie, F., Feary, D.A., Brunel, T., Kell, L.T., Döring, R., Metz, S., Eigaard, O.R., Basurko, O.C., Bartolino, V., Bentley, J., Berges, B., Bossier, S., Brooks, M.E., Caballero, A., Citores, L., Daskalov, G., Depestele, J., Gabiña, G., Aranda, M., Van Vlasselaer, J. 2022b. Ten lessons on the resilience of the EU common fisheries policy towards climate change and fuel efficiency - A call for adaptive, flexible and well-informed fisheries management. Frontiers in Marine Science, 9, 947150. https://doi.org/10.3389/fmars.2022.947150.

Bianchi, T.S. 2011. The role of terrestrially derived organic carbon in the coastal ocean: A changing paradigm and the priming effect. Proceedings of the National Academy of Sciences, 108(49), 19473–19481. https://doi.org/10.1073/pnas.1017982108

Bianchi, D., Carozza, D.A., Galbralth, E.D., Gulet, J., DeVries, T. 2021. Estimating global biomass and biogeochemical cycling of marine fish with and without fishing. Science Advances 7(41). https://doi.org/10.1126/sciadv.abd7554

Billett, D.S.M., Lampitt, R.S., Rice, A.L., Mantoura, R.F.C. 1983. Seasonal sedimentation of phytoplankton to the deep-sea benthos. Nature, 302 (5908): 520-522. Retrieved from https://doi.org/10.1038/302520a0

Black, K.E., Smeaton, C., Turrell, B., Austin, W.E.N. 2022. Assessing the potential vulnerability of sedimentary carbon stores to bottom trawling disturbance within the UK EEZ. Frontiers in Marine Science 9. https://www.frontiersin.org/articles/10.3389/fmars.2022.892892

Bradshaw, C., Jakobsson, M., Brüchert, V., Bonaglia, S., Mörth, C.-M., Muchowski, J. Stranne, C., Sköld, M. 2021. Physical Disturbance by Bottom Trawling Suspends Particulate Matter and Alters Biogeochemical Processes on and Near the Seafloor. Frontiers in Marine Science 8 (1127).

Cavan, E.L., Hill, S.L. 2021. Commercial fishery disturbance of the global ocean biological carbon sink. Global Change Biology 28(4): 1212-1221.

Christensen, V., Walters, C.J., Ahrens, R., Alder, J., Buszowski, J., Christensen, L.B., Cheung, W.W.L., Dunne, J., Fröese, R., Karpouzi, V., Kaschner, K., Kearney, K., Lai, S., Lam, V., Palomares, M.L.D., Peters-Mason, A., Piroddi, C., Sarmiento, J.L., Steenbeeek, J., Sumaila, R. Pauly, D. 2009. Database-driven models of the world's Large Marine Ecosystems. Ecological Modelling 220(17): 1984-1996.

De Borger, E., Tiano, J., Braeckman, U., Rijnsdorp, A.D., Soetaert, K. 2021. Impact of bottom trawling on sediment biogeochemistry: A modelling approach. Biogeosciences 18, 2539– 2557.

Diesing, M., Thorsnes, T., Bjarnadóttir, L.R. 2021. Organic carbon densities and accumulation rates in surface sediments of the North Sea and Skagerrak, Biogeosciences 18, 2139–2160.

Dounas, C., Davies, I., Triantafyllou, G., Koulouri, P., Petihakis, G., Arvanitidis, C., Sourlatzis, G., Eleftheriou, A. 2007. Large-scale impacts of bottom trawling on shelf primary productivity. Cont. Shelf Res. 27(17), 2198–2210.

Duplisea, D.E., Jennings, S., Malcolm, S.J., Parker, R., Sivyer, D. 2001. Modelling potential impacts of bottom trawl fisheries on soft sediment biogeochemistry in the North Sea. Geochemical Transactions 2(1): 112-117.

Eigaard, O.R., Bastardie, F., Hintzen, N.T., Buhl-Mortesen, L., Buhl-Mortesen, P., Catarino, R., Dinesen, G.E., Egekvist, J., Fock, H.O., Geitner, K., Gerritsen, H., González, M.M., Jonsson, P., Kavadas, S., Laffargue, P., Lundy, M., Gonzalez-Mirelis, G., Nielsen, J.R., Papadopoulou, N., Posen, P.E., Pulcinella, J., Russo, T., Sala, A., Silva, C., Smith, C.J., Vanelslander, B., Rijnsdorp, A.D. 2017. The footprint of bottom trawling in European waters: distribution, intensity, and seabed integrity. ICES J Mar Sci 74, 847–865.

Elsler, L., Oostdijk, M. Better Use of Public Money: The End of Fuel Subsidies for the EU Fleet. A report for Our Fish and Client Earth Available from: https://www.researchgate.net/publication/370580659_Better_Use_of_Public_Money_The_End_of_Fuel_Subsidies_for_the_EU_Fleet

Epstein, G., Middelburg, J.J., Hawkins, J.P., Norris, C.R., Roberts, C.M. 2021. The impact of mobile demersal fishing on carbon storage in seabed sediments. Global Change Biology, 28, 2875–2894. https://doi.org/10.1111/gcb.16105

Ferrer, E.M., Giron-Nava, A., Aburto-Oropeza, O. 2022. Overfishing Increases the Carbon Footprint of Seafood Production From Small-Scale Fisheries. Frontiers in Marine Science 9. https://www.frontiersin.org/articles/10.3389/fmars.2022.768784

Freitas, F.S., Pika, P.A., Kasten, S., Jørgensen, B.B., Rassmann, J., Rabouille, C., Thomas, S., Sass, H., Pancost, R.D., Arndt, S. 2021. New insights into large-scale trends of apparent organic matter reactivity in marine sediments and patterns of benthic carbon transformation, Biogeosciences 18, 4651–4679.

Greer, K., Zeller, D., Woroniak, J., Coulter, A., Winchester, M., Palomares, M.L.D., Pauly, D. 2019. Global trends in carbon dioxide (CO_2) emissions from fuel combustion in marine fisheries from 1950 to 2016. Marine Policy 107. https://doi.org/10.1016/j.marpol.2018.12.001

Hain, M.P., Sigman, D.M., Haug, G.H. 2014. The biological Pump in the Past. Reference Module in Earth Systems and Environmental Sciences, Treatise on Geochemistry (Second Edition), The Oceans and Marine Geochemistry 8: 485-517. https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=f7ec1afedd2ec4a6005891749f296796023754c7

Halpern, B.S., Walbridge, S., Selkoe, K.A., Kappel, C.V., Micheli, F., D'Agrosa, C., Bruno, J.F., Casey, K.S., Ebert, C., Fox, H.E., Fujita, R., Heinemann, D., Lenihan, H.S., Madin, E.M.P., Perry, M.T., Selig, E.R., Spalding, M., Steneck, R., Watson, R. 2008. A global map of human impact on marine ecosystems. Science 319, 948– 953.

Hartnett, H., Keil, R., Hedges, J., Devol, A.H. 1998. Influence of oxygen exposure time on organic carbon preservation in continental margin sediments. Nature 391, 572–575.

Hedges, J.I., Keil, R.G. 1995. Sedimentary organic matter preservation: an assessment and speculative synthesis. Marine Chemistry, 49(2), 81-115. https://www.sciencedirect.com/science/article/pii/030442039500008F

Hiddink, J.G., van de Velde, S.J., McConnaughey, R.A., De Borger, E., Tiano, J., Kaiser, M.J., Sweetman, A.K., Sciberras, M. 2023. Quantifying the carbon benefits of ending bottom trawling. Nature 617(7960): E1-E2. https://doi.org/10.1038/s41586-023-06014-7

Hiddink, J.G., Jennings, S., Sciberras, M., Szostek, C.L., Hughes, H.M., Ellis, N., Rijnsdorp, A.D., McConnaughey, R.A., Mazor, T., Hilborn, R., Collie, J.S., Pitcher, C.R., Amoroso, R.O, Parma, A.M., Suuronen, P., Kaiser, M.J. 2017. Global analysis of depletion and recovery of seabed biota after bottom trawling disturbance. Proc Natl Acad Sci USA 114 (31), 8301-8306.

Hilborn, R., Amoroso, R., Collie, J., Hiddink, J.G., Kaiser, M.J., Mazor, T., McConnaughey, R.A., Parma, A.M., Pitcher, C.R., Sciberras, M., Suuronen, P. 2023. Evaluating the sustainability and environmental impacts of trawling compared to other food production systems. ICES Journal of Marine Science 80(6): 1567–1579.

Irigoien, X., Klevjer, T.A., Røstad, A., Martinez, U., Boyra, G., Acuña, J.L., Bode, A., Echevarria, F., Gonzalez-Gordillo, J.I., Hernandez-Leon, S., Agusti, S., Aksnes, D.L., Duarte, C.M., and Kaartvedt, S. 2014. Large mesopelagic fishes biomass and trophic efficiency in the open ocean. Nat Commun 5(1): 3271.

Kaartvedt, S., Staby, A., Aksnes, D. 2012. Efficient trawl avoidance by mesopelagic fishes causes large underestimation of their biomass. Mar. Ecol. Prog. Ser. 456: 1–6. https://doi:10.3354/meps09785

Kaiser, M. J., Collie, J.S., Hall, S.J., Jennings, S., Poiner, I.R. 2002. Modification of marine habitats by trawling activities: prognosis and solutions. Fish and Fisheries 3(2): 114-136.

Kaiser, M.J., Clarke, K.R., Hinz, H., Austen, M.C.V., Somerfield, P., Karakassis, I. 2006. Global analysis of response and recovery of benthic biota to fishing. Mar. Ecol. Prog. Ser. 311, 1–14.

Keil, R. 2017. Anthropogenic forcing of carbonate and organic carbon preservation in marine sediments. Annu. Rev. Mar. Sci. 9(1), 151– 172.

Kristofersson, D., Gunnlaugsson, S., Valtysson, H. 2021. Factors affecting greenhouse gas emissions in fisheries: evidence from Iceland's demersal fisheries. ICES Journal of Marine Science 78(7): 2385-2394.

Kroodsma, D.A., Mayorga, J., Hochberg, T., Miller, N.A., Boerder, K., Ferretti, F., Wilson, A., Bergman, B., White, T.D., Block, B.A., Woods, P., Sullivan, B., Costello, C., Worm, B. 2018. Tracking the global footprint of fisheries. Science 359, 904–908.

Lampitt, R.S., Bett, B.J., Kiriakoulakis, K., Popova, E.E., Ragueneau, O., Vangriesheim, A., Wolff, G.A. 2001. Material supply to the abyssal seafloor in the Northeast Atlantic. Progress in Oceanography, 50 (1), 27-63. https://www.sciencedirect.com/science/article/pii/S0079661101000477

Lee, T.R., Wood, W.T., Phrampus, B.J. 2019. A machine learning (kNN) approach to predicting global seafloor total organic carbon. Global Biogeochem. Cycles 33, 37–46.

LaRowe, D.E., Arndt, S., Bradley, J.A., Estes, E.R., Hoarfrost, A., Lang, S.Q., Lloyd, K.G., Mahmoudi, N., Orsi, W.D., Shah Walter, S.R., Steen, A.D., Zhao, R. 2020. The fate of organic carbon in marine sediments—New insights from recent data and analysis. Earth-Sci. Rev. 204, 103146.

Legge, O., Johnson, M., Hicks, N., Jickells, T., Diesing, M., Aldridge, J., Andrews, J., Artioli, Y., Bakker, D.C.E., Burrows, M.T., Carr, N., Cripps, G., Felgate, S.L., Fernand, L., Greenwood, N., Hartman, S., Kröger, S., Lessin, G., Mahaffey, C., Mayor, D.J., Parker, R., Queirós, A.M., Shutler, J.D., Silva, T., Stahl, H., Tinker, J., Underwood, G.J.C., Van Der Molen, J., Wakelin, S., Wetson, K., Williamson, P. 2020. Carbon on the Northwest European Shelf: Contemporary Budget and Future Influences. Frontiers in Marine Science 7. https://www.frontiersin.org/articles/10.3389/fmars.2020.00143

Lovelock, C.E., Reef, R. 2020. Variable impacts of climate change on blue carbon. One Earth 3(2): 195-211. https://www.cell.com/one-earth/pdf/S2590-3322(20)30354-7.pdf

Mariani, G.l., Cheung, W.W.L., Sala, E., Mayorga, J., Velez, L., Gaines, S.D., Dejean, T., Troussellier, M., Mouillot, D. 2020. Let more big fish sink: Fisheries prevent blue carbon sequestration - half in unprofitable areas. Science Advances 6(44). https://doi.org/10.1126/sciadv.abb4848

Martín, J., Puig, P., Palanques, A., Masqué, P., García-Orellana, J. 2008. Effect of commercial trawling on the deep sedimentation in a Mediterranean submarine canyon. Mar. Geol. 252(3–4), 150–155.

Martin, A.H., Ferrer, E.M.,Hunt, C., Bleeker, K., Villasante, S. 2022. Exploring Changes in Fishery Emissions and Organic Carbon Impacts Associated with a Recovering Stock. Frontiers in Marine Science 9. https://www.frontiersin.org/article/10.3389/fmars.2022.788339

McMonagle, H., Llopiz, J.K., Hilborn, R., Essington T.E. 2023. High uncertainty in fish bioenergetics impedes precision of fish-mediated carbon transport estimates into the ocean's twilight zone. Progress in Oceanography: 103078. https://doi.org/10.1016/j.pocean.2023.103078

Mengual, B., Cayocca, F., Le Hir, P., Draye, R., Laffarge, P., Vincent, B., Garlan, T. 2016. Influence of bottom trawling on sediment resuspension in the "Grande-Vasière" area (Bay of Biscay, France). Ocean Dyn 66:1181–1207. doi:10.1007/s10236-016-0974-7

Middelburg, J.J. 2018. Reviews and syntheses: To the bottom of carbon processing at the seafloor. Biogeosciences 15(2), 413–427.

Muñoz, M., Reul, A., Guijarro, B., Hidalgo, M. 2023. Carbon footprint, economic benefits and sustainable fishing: Lessons for the future from the Western Mediterranean. Science of The Total Environment 865: 160783.

Oberle, F.K.J., Storlazzi, C.D., Hanebuth, T.J.J. 2016. What a drag: Quantifying the global impact of chronic bottom trawling on continental shelf sediment. J. Mar. Syst. 159, 109–119.

Paradis, S., Puig, P., Sanchez-Vidal, A., Masqué, P., Garcia-Orellana, J., Calafat, A., Canals, M. 2008. Spatial distribution of sedimentation rate increases in Blanes Canyon caused by technification of bottom trawling fleet. Prog. Oceanogr. 169, 241–252.

Pinti, J., DeVries, T., Norin, T., Serra-Pompei, C. Proud, R., Siegel, D.A., Kiørboe, T., Petrik, C.M., Andersen, K.H., Brierley, A.S., Visser, A.W. 2023. Model estimates of metazoans' contributions to the biological carbon pump. Biogeosciences 20(5): 997-1009. https://bg.copernicus.org/articles/20/997/2023/bg-20-997-2023.pdf

Pitcher, C.R., Hiddink, J.G., Jennings, S., Collie, J., Parma, A.M., Amoroso, R., Mazor, T., Sciberras, M., McConnaughey, R.A., Rijnsdorp, A.D., Kaiser, M.J., Suuronen, P., Hilborn, R. 2022. Trawl impacts on the relative status of biotic communities of seabed sedimentary habitats in 24 regions worldwide. Proc Natl Acad Sci U S A 119(2), e2109449119. https://doi.org/10.1073/pnas.2109449119

Polimene, L., Torres R., Powley, H.R., Bedington, M., Juhls, B., Palmtag, J., Strauss, J., Mann, P.J. 2022. Biological lability of terrestrial DOM increases CO2 outgassing across Arctic shelves. Biogeochemistry. 160 (3): 289-300.

Proud, R., Handegard, N.O., Kloser, R.J., Cox, M.J., Brierley, A.S. 2019. From siphonophores to deep scattering layers: uncertainty ranges for the estimation of global mesopelagic fish biomass. ICES Journal of Marine Science 76 (3): 718–733. https://doi:10.1093/icesjms/fsy037

Saba, G.K., Burd, A.B., Dunne, J.P., Hernández-León, S., Martin, A.H., Rose, K.A., Salisbury, J., Steinberg, D.K., Trueman, C.N., Wilson, R.W., Wilson, S.E. 2021. Toward a better understanding of fish-based contribution to ocean carbon flux. Limnol Oceanogr: lno.11709. https://doi:10.1002/lno.11709

Sala, A., Depestele, J., Gümüş, A., Laffargue, P., Nielsen, J.R., Polet, H., Smith, C.J., Zengin, M., Bastardie, F., Eigaard, O.R., Haman, K.G., Jensen, F., Lucchetti, A., Méhault, S. Notti, E., Papadopoulou, N., Petetta, A., Sköld, M., Vincent, B., Rijnsdorp, A.D. 2023. Technological innovations to reduce the impact of bottom gears on the seabed. Marine Policy 157: 105861. https://www.sciencedirect.com/science/article/pii/S0308597X23003949

Sala, A., Damalas, D., Labanchi, L., Martinsohn, J., Moro, F., Sabatella, R., Notti, E. 2022. Energy audit and carbon footprint in trawl fisheries. Scientific Data, 9, 428: 1-12. https://doi.org/10.1038/s41597-022-01478-0

Sala, A., De Carlo, F., Buglioni, G., Lucchetti, A. 2011. Energy performance evaluation of fishing vessels by fuel mass flow measuring system. Ocean Engineering 38: 804-809. https://doi.org/10.1016/j.oceaneng.2011.02.004

Sala, E., Mayorga, J., Bradley, D., Cabral, R.B., Atwood, T.B., Auber, A., Cheung, W., Costello, C., Ferretti, F., Friedlander, A.M., Gaines, S.D., Garilao, C., Goodell, W., Halpern, B.S., Hinson, A., Kaschner, K., Kesner-Reyes, K., Leprieur, F., McGowan, J., Morgan, L.E., Mouillot, D., Palacios-Abrantes, J., Pssingham, H.P., Rechberger, K.D., Worm, B., Lubchenco, J. 2021. Protecting the global ocean for biodiversity, food and climate. Nature 592: 397–402. https://doi.org/10.1038/s41586-021-03371-z

Sciberras, M., Hiddink, J.G., Jennings, S., Szostek, C.L., Hughes, K.M., Kneafsey, B., Clarke, L.J., Ellis, N., Rijnsdorp, A.D., McConnaughey, R.A., Hilborn, R., Collie, J.S., Pitcher, C.R., Amoroso, R.O., Parma, A.M., Suuronen, P., Kaiser, M.J. 2018. Response of benthic fauna to experimental bottom fishing: A global meta-analysis. Fish Fish. 19(4), 698–715.

Stafford, R., Boakes, Z., Hall, A.E., Jones, G.C.A. 2021. The Role of Predator Removal by Fishing on Ocean Carbon Dynamics. Anthropocene Science 1: 204–210.

Suuronen, P., Chopin, F., Glass, C., Løkkeborg, S., Matsushita, Y., Queirolo, D., Rihan, D. 2012. Low impact and fuel efficient fishing: Looking beyond the horizon. Fisheries Research 119/120 (0): 135-146.

Thurstan, R., Brockington, S., Roberts, C. 2010. The effects of 118 years of industrial fishing on UK bottom trawl fisheries. Nat. Commun. 1, 15.

Tiano, J.C., Depestele, J., Van Hoey; G., Fernandes, J., van Rijswijk, P., Soetaert, K. 2022. Trawling effects on biogeochemical processes are mediated by fauna in high-energy biogenic-reef-inhabited coastal sediments. Biogeosciences 19, 2583–2598.

Tillin, H.M., Hiddink, J.G., Jennings, S., Kaiser, M.J. 2006. Chronic bottom trawling alters the functional composition of benthic invertebrate communities on a sea-basin scale. Mar. Ecol. Prog. Ser. 318, 31–45.

Turner, J.T. 2015. Zooplankton fecal pellets, marine snow, phytodetritus and the ocean's biological pump. Progress in Oceanography, 130, 205–248. https://doi.org/10.1016/j.pocean.2014.08.005

Wilson, R.J., Speirs, D.C., Sabatino, A., Heath, M.R. 2018. A synthetic map of the north-west European Shelf sedimentary environment for applications in marine science. Earth Syst. Sci. Data 10, 109–130.

Yahel, G., Yahel, R., Katz, T., Lazar, B., Herut, B., Tunnicliffe, V. 2008. Fish activity: a major mechanism for sediment resuspension and organic matter reminiralization in coastal marine sediments. Marine Ecology Progress Series 372: 195-209.

Zhang, W., Wirtz, K. 2017. Mutual dependence between sedimentary organic carbon and infaunal macrobenthos resolved by mechanistic modeling. J. Geophys. Res. Biogeosci. 122, 2509–2526.

Zhang, W., Wirtz, K., Daewel, U., Wrede, A., Kröncke, I., Kuhn, G., Neumann, A., Meyer, J., Ma, M., Schrum, C. 2019. The budget of macrobenthic reworked organic carbon — A modelling case study of the North Sea. J. Geophys. Res. Biogeosci. 124(6), 1446– 1471.

Zhang, W., Porz, L., Yilmaz, R., Kuhlmann, J., Neumann, A., Liu, B., Müller, D., Spiegel, T., Holtappels, M., Ziebarth, N., Taylor, B., Wallmann, K., Kasten, S., Daewel, U., Schrum, C. 2023. Impact of bottom trawling on long-term carbon sequestration in shelf sea sediments. Authorea. February 07, https://doi.org/10.22541/essoar.167578408.84551876/v1.

Zonneveld, K.A.F., Versteegh, G.J.M., Kasten, S., Eglington, T.I., Emeis, K.-C., Huguet, C., Koch, B.P., de Lange, G.J., de Leeuw, J.W., Middelburg, J.J., Mollenhauer, G., Prahl, F.G., Rethemeyer, J., Wakeham, S.G. 2010. Selective preservation of organic matter in marine environments; processes and impact on the sedimentary record. Biogeosciences 7, 483–511.

Annex 1: List of participants

Name	Institute	Country (of institute)	E-mail
Abdirahman Bore	Lukenya University	Kenya	babafadhil115@gmail.com
Abdirasakh Hassan	City University of Mogadishu	Somalia	abdirasakhhaasa914@gmail.com
Aderito de Miranda	National Institute of Sea and Boundaries	Mozambique	aderytomiranda@hotmail.com
Aida Sartimbul	Brawijaya University	Indonesia	aida@ub.ac.id
Akansha Tiwari	Tangled Seas	India	akansha13.work@gmail.com
Alice Belin	European Commission Directorate-General for Environment A4	International	alice.belin@ec.europa.eu
Ana Matias	Marine Conservation and Cooperation Association	Portugal	amatias@sciaena.org
Andre Visser	DTU Aqua, National Institute of Aquatic Resources	Denmark	awv@aqua.dtu.dk
Angela Martin	University of Agder	Norway	angela.martin@uia.no
Ant Türkmen	Ecological Research Society	Turkey	turkmen@me.com
Antonello Sala	National Research Council (CNR)	Italy	antonello.sala@cnr.it
Arielle Sutherland-Sherriff	Oceana Belgium	Belgium	asutherland@oceana.org
Augustin Lafond	Bloom Association France	France	augustinlafond@bloomassociation.org
Barry O'Neill	DTU Aqua - Hirtshals	Denmark	barone@aqua.dtu.dk
Berthe Maria Johanna Vastenhoud	DTU Aqua, National Institute of Aquatic Resources	Denmark	bmjv@aqua.dtu.dk
Bill Turrell	Marine Laboratory	United Kingdom	Bill.Turrell@gov.scot
Christian Lønborg	Department of Ecoscience	Denmark	c.lonborg@ecos.au.dk
Cian Luck	Global Fishing Watch	United States	cian@globalfishingwatch.org
Clare Bradshaw	Department of Ecology, Environment and Plant Sciences	Sweden	clare.bradshaw@su.se
Claudia Morys	Federal Agency for Nature Conservation	Germany	Claudia.Morys@BfN.de
Daniel Ottmann	Coastal Ocean Observing and Forecast System Balearic Islands	Spain	daniel.ottmann.riera@gmail.com

David Reid	Marine Institute	Ireland	david.reid@marine.ie
Edward Farrell	Killybegs Fishermen's Organisation Ltd.	Ireland	edward@kfo.ie
Emma Cavan	Imperial College London	United Kingdom	e.cavan@imperial.ac.uk
Fabio Berzaghi	World Maritime University	Sweden	fab@wmu.se
François Bastardie	DTU Aqua, National Institute of Aquatic Resources	Denmark	fba@aqua.dtu.dk
Ganesh Nakhawa	BluCatch Seafood	India	ganeshnakhawa@gmail.com
Gemma Rayner	Oceans North	Canada	grayner@oceansnorth.ca
Gennadi Lessin	Plymouth Marine Laboratory	United Kingdom	gle@pml.ac.uk
Gonçalo Ferreira de Carvalho	Marine Conservation and Cooperation Association	Portugal	gcarvalho@sciaena.org
Gwilym Rowlands	University of Oxford	United Kingdom	gwilym.rowlands@biology.ox.ac.uk
Henrik Svedäng	University of Gothenburg	Sweden	henrik.svedang@gu.se
Henrike Le Semmler	WWF Denmark	Denmark	henrike.semmler@wwf.dk
Jacob Bentley	Natural England	United Kingdom	Jacob.Bentley@naturalengland.org.uk
Jannis Kuhlmann	German Federation for the Environment and Nature Conservation	Germany	jannis.kuhlmann@bund.net
Jean-Pierre Gattuso	Villefranche Oceanographic Laboratory	France	jean-pierre.gattuso@imev-mer.fr
Jemimah Kassah	Department of Biology Education	Ghana	jemimahkassah@gmail.com
Jenni Grossmann	ClientEarth	United Kingdom	jgrossmann@clientearth.org
Jeroen Steenbeek	Ecopath International Initiative	Spain	jeroen.steenbeek@gmail.com
Joachim Claudet	French National Centre for Scientific Research	France	joachim.claudet@cnrs.fr
Joanna Turner	Global Fishing Watch	United States	joanna.turner@globalfishingwatch.org
Jonathan Falciani	DTU Aqua, National Institute of Aquatic Resources	Denmark	joeri@aqua.dtu.dk
Jonathan Kwesi Arthur	Kwame Nkrumah University of Science and Technology	Ghana	yadisonj17@gmail.com
Josiah Ogbuka	University of Nigeria	Nigeria	josiah.ogbuka@unn.edu.ng
Juliana Quevedo	Institute of Marine Science	Spain	jquevedoz@icloud.com
Katherine Morris	Heriot-Watt University	United Kingdom	kjm2001@hw.ac.uk

Kathy Lockhart	Fisheries and Marine Resources Management	Turks and Caicos Islands	klockhart@gov.tc
Kea Witting	GEOMAR Helmholtz Centre for Ocean Research KIel	Germany	kwitting@geomar.de
Larissa Lörinczi	European Commission	International	Larisa.LORINCZI@ec.europa.eu
Luca Polimene	Joint Research Centre	International	Luca.Polimene@ec.europa.eu
Lucas Porz	Helmholtz-Zentrum Heroen Institute of Coastal Research	Germany	Lucas.Porz@hereon.de
Maija Marsh	Natural England	United Kingdom	Maija.Marsh@naturalengland.org.uk
Maike Scheffold	University of Hamburg	Germany	Maike.scheffold@uni-hamburg.de
Manuel Hidalgo	Spanish Institute of Oceanography	Spain	jm.hidalgo@ieo.csic.es
Maria Ching Villanueva	Ifremer Centre de Bretagne	France	Ching.Villanueva@ifremer.fr
María Morales Camacho	International Institute of Social Studies	Netherlands	moralescamacho@iss.nl
Marija Sciberras	Heriot-Watt University	United Kingdom	M.Sciberras@hw.ac.uk
Marta Coll	Institute of Marine Science	Spain	mcoll@icm.csic.es
Mary Wisz	World Maritime University	Sweden	msw@wmu.se
Mathieu Doray	Centre Atlantique	France	Mathieu.Doray@ifremer.fr
Mattias Cape	Environmental Defense Fund	United States	mcape@bigelow.org
Michael Oke	Talent Upgrade Global Concepts	Nigeria	talentupgradeglobalconcept@gmail.com
Mike Walker	Our Fish	Netherlands	mike@odcommunications.com
Miquel Ortega	Institute of Marine Science	Spain	m.ortegac@icm.csic.es
Mireia Valle	AZTI Sukarrieta	Spain	mvalle@azti.es
Mohammed Mofizur Rahman	Potsdam Institute for Climate Impact Research	Germany	mofizur.rahman@pik-potsdam.de
Natacha Carvalho	European Environment Agency	International	Natacha.Carvalho@eea.europa.eu
Nayrah Shaltout	National Institute of Oceanography and Fisheries	Egypt	nshaltout@gmail.com
Nazli Demirel	Istanbul University	Turkey	ndemirel@istanbul.edu.tr
Ola Kuznia	Our Fish	Netherlands	ola@our.fish
Ole Ritzau Eigaard	DTU Aqua, National Institute of Aquatic Resources	Denmark	ore@aqua.dtu.dk

Peng Lian	Institute of Oceanology, Chinese Academy of Sciences	China	fisheries@foxmail.com
Pere Masque	IAEA Marine Environment Laboratory	Monaco	p.masque@ecu.edu.au
Pernille Schnoor	World Maritime University	Sweden	schnoorpernille@wmu.se
Peter Croot	National University of Ireland Galway	Ireland	peter.croot@universityofgalway.ie
Pierre Petitgas	Ifremer Centre Atlantique	France	pierre.petitgas@ifremer.fr
Pierre Polsenaere	Ifremer, National Institute for Ocean Science	France	pierre.polsenaere@ifremer.fr
Randa Mejri	University of Sfax	Tunisia	randa.mejri@fss.usf.tn
Rebecca Hubbard	Our Fish	Netherlands	rebecca@our.fish
Rodrigo Ataíde Dias	European Commission	International	rodrigo.ataide-dias@ec.europa.eu
Rufus Danby	University of Aberdeen	United Kingdom	r.danby.19@abdn.ac.uk
Rui Vieira	Cefas Lowestoft Laboratory	United Kingdom	rui.vieira@cefas.gov.uk
Ruth Parker	Centre for Environment, Fisheries and Aquaculture Science	United Kingdom	ruth.parker@cefas.gov.uk
Samuel Rastrick	Institute of Marine Research	Norway	samuel.rastrick@hi.no
Sarah Paradis	ETH Zurich	Switzerland	sarah.paradis@erdw.ethz.ch
Sebastian Valanko	International Council for the Exploration of the Sea	International	sebastian.valanko@ices.dk
Sevrine Sailley	Plymouth Marine Laboratory	United Kingdom	sesa@pml.ac.uk
Simeon Hill	British Antarctic Survey	United Kingdom	sih@bas.ac.uk
Sonia Seixas	University Aberta	Portugal	Sonia.Seixas@uab.pt
Sulemani Masoud	University of Dar es Salaam	Tanzania, United Republic Of	sulemanimasoud8@gmail.com
Suzannah Walmsley	ABPMer	United Kingdom	swalmsley@abpmer.co.uk
Svenja Halfter	National Institute of Water and Atmospheric Research	New Zealand	Svenja.Halfter@niwa.co.nz
Terry Pedersen	Institute for Marine and Antarctic Studies	Australia	top@utas.edu.au
Thibault Cariou	Marine Institute	Ireland	Thibault.Cariou@Marine.ie
Tom Collinson	Blue Ventures	United Kingdom	tom@blueventures.org
Villy Christensen	Institute for the Oceans and Fisheries	Canada	v.christensen@oceans.ubc.ca

Wenyan Zhang	Helmholtz-Zentrum Heroen Institute of Coastal Research	Germany	Wenyan.Zhang@hereon.de
William Hunter	AFBI Fisheries and Aquatic Ecosystems Branch	United Kingdom	Billy.Hunter@afbini.gov.uk

Annex 2: Resolutions

2022/WK/IEASG06 The **Workshop on Assessing the Impact of Fishing on Oceanic Carbon (WKFISHCARBON)**, chaired by Dave Reid, Ireland, and Emma Cavan, UK, will meet in person at ICES Secretariat, Copenhagen, and be open to online participation, from 25-28th April 2023 to:

a) Review and consolidate the existing knowledge, and identify knowledge gaps, on the functioning of the oceanic carbon pump in terms of the role of fish in carbon fluxes in the open ocean, including the extent of oceanic carbon released into the atmosphere due to the removal of fish; (Science Plan codes: 1.1, 2.1, 6.1);

b) Review and consolidate the existing knowledge on direct emissions from fishing fleets using different extraction methods, and indirect emissions from disturbance of the seabed, in terms of their contribution to climate change; (Science Plan codes: 1.1, 2.1, 6.1);

c) Discuss how the existing approaches for assessing and prioritising the main ecosystem stressors can be adapted to enable the assessment of fishing impacts on the carbon sequestration processes. Report on the implications of the findings from ToR a and b for inclusion in the Ecosystem and/or Fisheries Overviews; (Science Plan codes: 2.5, 4.1);

d) Identify how the knowledge on the role of fishing (by fish removals, seabed abrasion and emissions) could be translated to advice to inform ecosystem-based (fisheries) management (EBFM/EBM), and to develop a roadmap for what needs to be done next and whether further workshops would useful (Science Plan codes: 6.4);

WKFISHCARBON will report by June 2023 for the attention of the SCICOM.

Supporting information

Priority	The workshop is a targeted response to the role of fisheries in blue carbon sequestration, as was listed as an emerging issue in WGECO ICES. 2021. Working Group on Ecosystem Effects of Fishing Activities (WGECO).ICES Scientific Reports. 3:83. 33 pp. http://doi.org/10.17895/ices.pub.8279. The impact of climate change on marine ecosystems is a key issue that ICES builds into its work. The activities of this workshop will contribute to knowledge related to the carbon impacts of fisheries, as well as the climate implications of fish extraction, thus contributing to EBM development. Since ocean carbon sequestration is highly important from the climate change mitigation and adaptation point of view, these activities are considered to have a very high priority.

Scientific justification	In recent years, the scientific body of evidence describing the role of marine ecosystems in climate adaptation and mitigation has considerably grown. As a consequence, there is a noticeable interest in the scientific community and among fisheries managers and policy-makers in exploring the unwanted side effects of fishing and the extent to which fishing activities reduce carbon sequestration and/or increase emissions from the ocean. Assessing and measuring this impact may allow redirecting fishing pressure to the right places, identification of fishing methods which minimise the negative ecosystem and climate impacts. This is consistent with the ICES approach to support EBFM and the need to expand the evidence base for EBM. *Term of Reference a)* Several ICES working groups focus on the functioning of ecosystem components, including the fish species. WGECO activities are centred on the ecosystem impacts of fishing, but these do not directly consider the role of marine life in the ocean carbon pump. Fish and other marine organisms sequester and mediate carbon fluxes to the deep sea, but this contribution has not yet been accounted for. WKFISHCARBON will explore current and report on knowledge and gaps for future research. *Term of Reference b)* The cumulative impacts of human activities on marine ecosystems and their services, such as the disturbance of benthic habitats or changes in foodweb structures, are already assessed by ICES working groups. However these assessments do not currently consider the carbon emission (climate mitigation) impact of fishing, either through the burning of fossil fuel or the disturbance of carbon stored in the seabed. The WKFISHCARBON will discuss these considerations. *Term of Reference c)* This ToR will investifate how knowledge from ToRs A & B (and future developments) could be integrated into the existing EO and or FO advice products to ensure inclusion of the full suite of impacts of fishing, and the scale of the climate services provided by the biological carbon pump. *Terms of Reference d)* The aim of this ToR is to evaluate the ecosystem knowledge to support the progression of ecosystem-based fisheries advice more widely, and identify additional pathways to advice for the idenfified knowledge.
Resource requirements	ICES Secretariat support and meeting facilkities. Participants will be expected to prepare input in advance of the meeting, and participate during the meeting dates.
Participants	The workshop is expected to attract about 25-30 participants, members of WGECO, IEASG, WGFBIT, WGBIODIV, the authors of the Frontiers in Marine Science Research Topic, NGO representatives and European Commission staff including from DG MARE research unit and DG ENV marine unit.
Secretariat facilities	ICES Secretariat support and meeting facilkities
Financial	No financial implications.
Linkages to advisory committees	Workshop outputs are expected to be of interest to ACOM
Linkages to other committees or groups	WGECO, WGFBIT, WGBIODIV, IEASG
Linkages to other organizations	OSPAR, HELCOM

Annex 3: Working Documents

ICES Fish carbon report – Norway

Samuel P.S. Rastrick

The conversion of organic carbon (OC) stored in the seabed to inorganic carbon dissolved in the water column can be affected by bottom fishing. However, some effects of bottom fishing will tend to increase OC remineralization, while others will have the opposite effect. In a meta-analysis of 49 different studies 29% reported a decrease in sediment OC, 10% reported an increase in sediment OC and 61% reported no significant effect on sediment OC associated with trawling (Epstein *et al*., 2022). Published estimates of OC remineralization associated with bottom fishing also vary widely. Reflecting the great uncertainty and the many assumptions and simplifications associated with such calculations. Sala *et al* estimated (2021) that between 0.58 and 1.47 billion tonnes of CO_2 is released globally each year due to bottom trawling. However, this is considered and overestimation as the effect of bottom trawling on carbon storage in bottom sediments is more complex (Epstein *et al*., 2022; Hilborn and Kaiser, 2022), and organic carbon is less vulnerable to physical disturbances than assumed (Smeaton and Austin, 2022).

Fishing gear/disturbance:

In Norwegian waters, bottom trawls and seines are widespread. Beam trawls and dredging affect bottom habitats to a greater extent than bottom trawls (e.g. Hiddink *et al.* ,2017) and in Norway dredging is almost non-existent and there is a total ban on fishing with beam trawls.

In Norwegian waters demersal seining is less common than bottom trawling. There is a general ban on using rock jumps and it is forbidden to use bobbin lines north of 62° N. In the area within 4 nautical miles of the baselines, it is prohibited to use seine nets that have a ball line or ground line longer than 123 m, a circumference of the opening greater than 156 m or more than 2 000 m rope length. It is also forbidden to use seines within fjords, with some exceptions for vessels under 11 m. The rope, which can be 2 600 m long, affects a much larger area of the bottom sediment than the gear. It is assumed that demersal seining has less impact that bottom trawling. However, no studies have investigated how these components affect the bottom sediments in Norwegian waters (Løkkeborg, *et al*., 2023).

In Norway bottom trawling is used mostly for fish and shrimp. The largest impact on sediments comes from the barn doors, groundgear and centre blocks (used in double or triple trawls). For shrimp trawls doors vary in weight from 500 to 2 000 kg and centre blocks can be 2.5 tonnes. Trawling is regulated to protect vulnerable habitats which can be important areas for carbon sequestration (e.g. cold water coral reefs). Trawling is prohibited in less than 60 m from the Swedish border to Jæren's reef, shallower than 100 m from Jæren's reef up to and including Trøndelag county and shallower than 170 m north of Trøndelag. It is permitted to fish with shrimp trawl (small-mesh bottom trawl) within 12 n.mil of the baselines, but it is forbidden to use rock-hopper gears (Løkkeborg, *et al*., 2023). Trawl doors make tracks that vary in depth from 0.2 to 30 cm (median value = 5.5 cm), with the deepest tracks observed on mud bottoms (Review of 18 studies, Hiddink *et al*. (2017) (Figure A1.1).

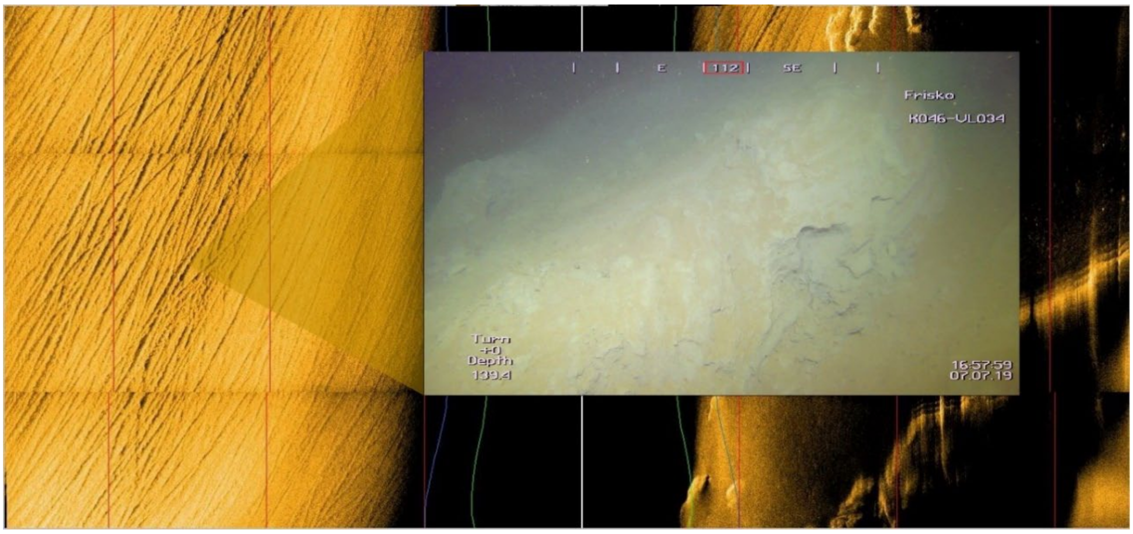


Figure A1.1 Trawl tracks on soft sediment bottom (silt) in outer Oslofjord/inner Skagerrak recorded with side-scanning HISAS sonar and tracks observed with video/ROV (from, Løkkeborg, *et al.*, 2023).

Few studies have been carried out in Norwegian waters. In Eidangerfjord (Greenland), however, a 1.8 km long trawl created a sediment cloud of 3-5 million m 3 containing 9 tonnes of silt. The sediment clouds had a width of 120–150 m and a height of 15–18 m above the bottom (Bradshaw *et al.*, 2012). Most resuspended sediments will sink back to the bottom within hours, while light particles can remain in the water masses for several days (Durrieu de Madron *et al.*, 2005). Soft sediments (clay and silt), and areas of low current speed, infrequent replacement of the water masses and deeper-lying areas characterized by little natural influence will be most affected.

Overlap between bottom fishing activity and Sediment OC stores:

As well as, understanding the effect of fishing gear on bottom sediments it is also important to understand were fishing activity overlaps with areas associated with high OC sediment stocks and/or sediments sensitive to OC remineralization. Progress has been made in mapping OC sediment stocks in recent years. (Seiter *et al.*, 2004; Diesing *et al.*, 2017; Lee *et al.*, 2019; Luisetti *et al.*, 2019; Atwood *et al.*, 2020; Legge *et al.*, 2020; Smeaton *et al.*, 2021). However, in Norway, only parts of the North Sea and Skagerrak have been mapped (Diesing *et al.*, 2021). Estimates of OC remineralization, accumulation and burial rates are even more limited (Berner, 1982; Burdige, 2007; Keil, 2017; Wilkinson *et al.*, 2018; Luisetti *et al.*, 2019; Legge *et al.*, 2020; Diesing *et al.*, 2021) and natural rates of OC remineralization and storage also show large spatial and temporal variability. However, OC storage is usually higher in finer sediments in areas of low hydrodynamic activity. The grain size and structure of sediment is important with muds usually associated with lower oxygen penetration, less pore water transport, lower levels of natural disturbance leading to high OC contents and Lower rates of remineralization when compared to sands and gravels (Burdige, 2007; Huettel *et al.*, 2014). In 61% of reported studies showing no significant effect of bottom trawling on sediment OC content there is a clear trend towards sandy compered to muddy study sites (Epstein *et al.*, 2022).

Recently an Institute of Marine Research Report (Løkkeborg, *et al.*, 2023) made the first attempt to better understand where bottom fishing activity in Norway overlapped with finer sediments that may be more sensitive to OC remineralization (Figure A1.2).

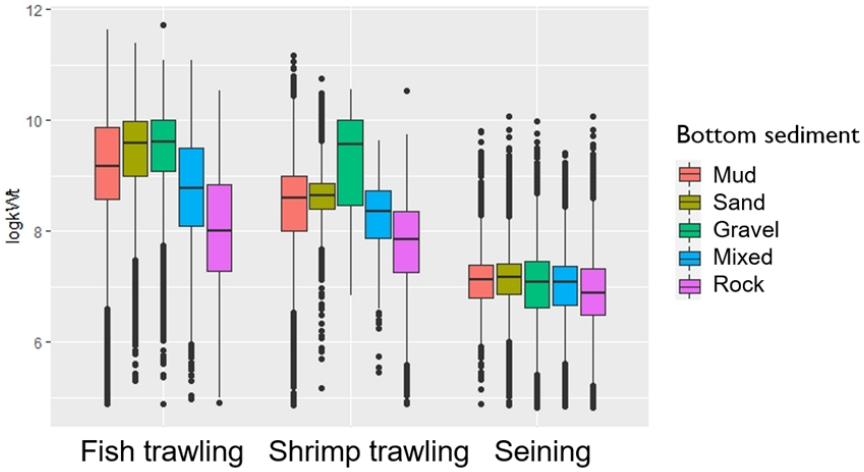


Figure A1.2 The prevalence of fishing with fishing trawls, shrimp trawls and purse-seines in relation to the type of bottom sediments. Fishing intensity is given as the logarithm of kWt (average for the period 2015-2021). The figure is made by relating the middle position of each trawl haul to the sediment type for the position in question. The distribution of bottom sediments (grain size) is obtained from NGU's sediment maps. The boxplot shows the median, lower and upper quartile (25th and 75th percentile), minimum and maximum value within 1.5 times the interquartile range (the distance between the lower and upper quartile). Black points show individual values outside this range. (from, Løkkeborg, *et al*., 2023).

Fishing trawls are most widespread on gravel/sandy bottoms. (e.g. Storbanken, Sentralbanken, Bjørnøya, south of Spitsbergen). There are less fish trawls on finer sediments in the central Barents and Skagerrak and along the south coast where higher OC stores are predicted, Figure A1.3. Shrimp trawls are on mostly gravel and to a lesser extent on sand and mud. However, in Skagerrak / south coast of Norway OC accumulates in the Norwegian trench which overlaps with shrimp trawling areas (Løkkeborg, *et al*., 2023).

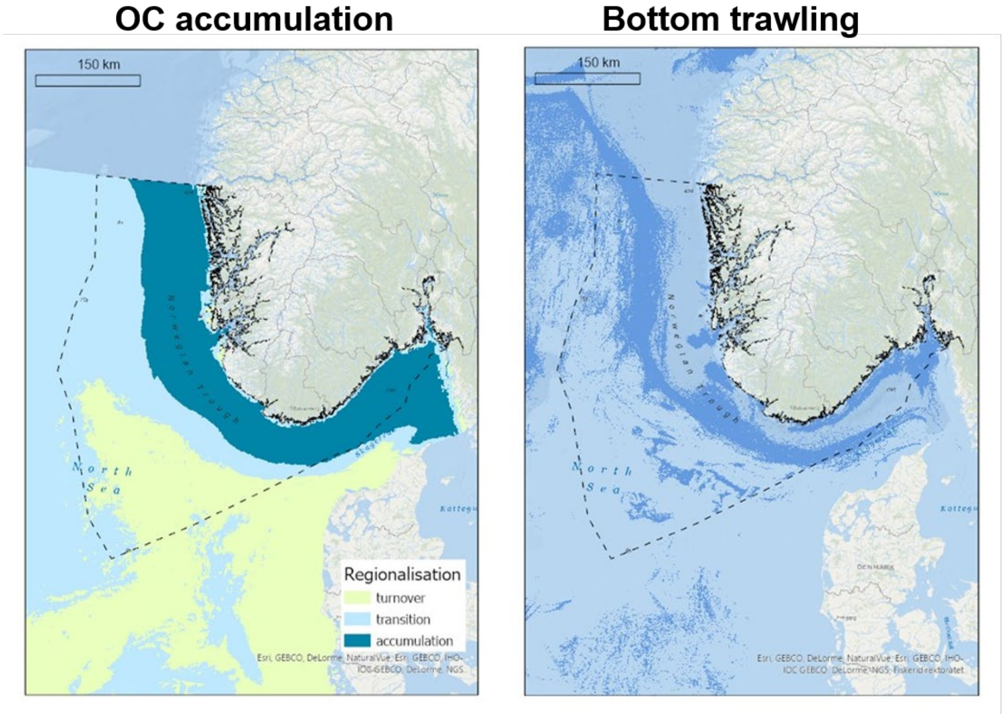


Figure A1.3 The map on the left shows in dark blue areas where organic carbon accumulates in the North Sea and Skagerrak (Diesing *et al.*, 2021). The map on the right shows where bottom trawling takes place (based on the map solution Yggdrasil from the Directorate of Fisheries; from, Løkkeborg, *et al.*, 2023).

Risk of OC remineralization in disturbed sediments:

When assessing the effect of bottom fishing activity on OC remineralization it is also important to consider the sensitive of disturbed sediments to OC remineralization. In general, continental shelf and sublittoral zone sediments in summer show the highest rates of OC remineralization (Middelburg *et al*., 1996; Tabuchi *et al*., 2010; Brin *et al*., 2015; Xue *et al*., 2015). OC remineralization in response to bottom disturbance by trawling are likely site (and perhaps seasonally) specific and dependent on local hydrodynamic activity, local sediment, (e.g. OC content, grain size, and stability) local environmental conditions (e.g. temperature and oxygenation) and local biology (e.g. production and bioturbation).

Local hydrodynamic activity:

Fine-grained deposits (clays, silts, and muds) with more OC tend to accumulate in hydrodynamically quiet settings, e.g. in deep basin/ trenches. Coarse-grained deposits (sands and gravels) with less OC tend to dominate in hydrodynamically active areas, e.g. in the coastal zone, on shelf banks and the shelf break. Local currents are also important in determining the transport of disturbed sediments.

Repeated bottom trawling can change the structure of sediments particularly in finer sediments in less hydrologically active environments (Kaiser *et al*., 2002; Trimmer *et al*., 2005; Martín *et al*., 2014a; Oberle *et al*., 2016). In less hydrologically active depositional environments, the resuspension of finer sediments from deeper layers by trawling may lead to a redeposited surface layer of fine sediments. (Palanques *et al*., 2014; Oberle *et al*., 2016; Tiano *et al*., 2020). In more hydrologically active environments the resuspension and loss of fine material due to transport can lead to an increase in coarse material towards the surface (Martín *et al*., 2014a; b; Palanques *et al*., 2014; Pusceddu *et al*., 2014; Mengual *et al*., 2016; Oberle *et al*., 2016; Paradis *et al*., 2021).

Local sediment:

Organic matter reactivity is also important to OC remineralization and can be seen as a continuum from easily degradable and short-lived (labile) to hard to degrade and long-lived (refractory) (LaRowe *et al*., 2020). The local stability of OC in the sediment depends on; OC molecular size and structure (Amon and Benner, 1996; Van Kaam-Peters *et al*., 1998), functional groups (Deng *et al*., 2019; Kleber and Lehmann, 2019), and mineral-Organic associations that may inhibit the decomposing activation of enzymes and microbes (Tietjen and G. Wetzel, 2003; Zimmerman *et al*., 2004). The local source of organic matter can also be important with terrestrial organic matter (e.g. plant litter and soil organic matter) typically considered refractory and marine organic matter (e.g. phytoplankton debris) typically considered labile and at greater risk from remineralization. OC remineralization may also increase when refractory organic matter in the sediment is mixed with more labile organic matter in a process known as priming (e.g, Bianchi, 2011). Meta-analysis has suggested that, overall, priming can increased remineralization of stable OC with the addition of labile OC (Sanches *et al*., 2021) and so the disturbance of sediment OC by bottom trawling and mixing of refractory and labile OC might possibly lead to enhanced OC remineralization.

Local environmental conditions:

Local environmental conditions such as temperature and oxygen are also very important to the risk of OC remineralization. Sediment microbial communities and their metabolic kinetics are highly influenced by temperature (Nedwell, 1999; Trevathan-Tackett *et al*., 2018, Malinverno and Martinez, 2015; Roussel *et al*., 2015; Zang *et al*., 2020). Low OC remineralization rates have been, in part, linked to lower temperatures in the deep sea (Weston and Joye, 2005; D'Hondt *et al*., 2015) and at higher latitudes (Fiedler *et al*., 2016; Bourgeois *et al*., 2017; Zhao *et al*., 2018). Increasing temperatures due to climate change have also been linked to increased OC remineralization (Yamamoto-Kawai *et al*., 2009; Qi *et al*., 2020).

Oxygen levels are critical in determining levels of OC remineralization (Hinojosa *et al*., 2014; Nierop *et al*., 2017; Kurian *et al*., 2020). Increased oxygen levels in the sediments can increase microbial respiration and remineralization activity (Kristensen *et al*., 1995; Dauwe *et al*., 2001; Keil, 2017; van de Velde *et al*., 2018). low oxygen in northern Pacific sediments decrease OC remineralization (Seiter *et al*., 2005; Jessen *et al*., 2017). Therefore, Increasing the depth of oxygen penetration in sediments can increases OC remineralization (Glud , 2008; Donis *et al*., 2016) and can be course by physical disturbance (e.g. Brodersen *et al*., 2019) or bioturbation (e.g. Aller and Cochran, 2019).

Local biology:

The effect of bottom trawling on OC storage/remineralization is also greatly dependent on the local community, its function, and sensitivity to trawling pressure. Intensive bottom trawling is known to increases the number small-bodied, opportunistic, motile infauna, and larger highly vagrant, scavenging macrofauna. Whale, reducing the number of large long-lived burrowing species that have the largest effect on carbon/nutrient cycling (Jennings *et al*., 2001; 2002; Kaiser *et al*., 2002; 2006; Thrush & Dayton, 2002; Tillin *et al*., 2006; Olsgard *et al*., 2008). Therefore, Intensive bottom trawling reduces local bio-turbation (reworking of sediment particles; Ekdale *et al*., 1984) and bioirrigation (reworking of sediment solutes; Meysman *et al*., 2006) by benthic invertebrates. However, the effects that this has on OC remineralization is complex. As decreased bioturbation / bioirrigation may increases OC remineralization by decreasing transportation of OC to deeper sediment increasing its chance of burial and long-term storage, or, decrease OC remineralization by decreasing concentrations of oxygen and other electron acceptors (e.g. nitrate, metal oxides and sulphate) in the sediment, and more controversially decrease priming of deeper refractory OC with more labile OC from the surface (van Nugteren *et al*., 2009; van der Molen *et al*., 2012; Middelburg, 2018; Snelgrove *et al*.,2018; Bengtsson *et al*., 2018; Riekenberg *et al*., 2020; Rühl *et al*., 2020; De Borger *et al*., 2021).

Primary production is also a driver of OC content in sediments due to vertical transport of dead material (Seiter *et al.*, 2004; Turner, 2015; Atwood *et al.*, 2020). Primary production may be stimulated by an increase in nutrients entering the water column following sediment disturbance (Fanning *et al.*, 1982; Falcão *et al.*, 2003; de Madron *et al.*, 2005; Polymenakou *et al.*, 2005; Pusceddu *et al.*, 2015). However, this will depend on the local hydrodynamic conditions and both the transport of nutrients up to the euphotic zone and transport of dead material to the seabed.

Benthic algae are also important in shallower areas increasing OC accumulation rates and in some locations the stability of sediments (Yallop *et al.*, 1994; Miller *et al.*, 1996; Montserrat *et al.*, 2008). Such shallower areas are mostly protected from bottom fishing in Norwegian waters. Ephemeral macroalgae and microphytobenthos recover quickly after trawling disturbance, depending on the frequency of disturbance (MacIntyre *et al.*, 1996; Ordines *et al.*, 2017). However, Kelp can take years to recover and coralline algae can require decades to recover (e.g. Dayton *et al.*, 1992; Fragkopoulou *et al.*, 2021). Other deeper areas important for OC accumulation include cold water coral reefs. These Increases accumulation rate and stability of sediments and build dead coral framework. In Norway these areas are protected from bottom fishing however, some trawl closure areas have very narrow boarders and the effects of transported resuspended sediments on these sensitive habitats is understudied.

Summary:

Not all fishing gear has the same effect on sediment disturbance and not all bottom fishing overlaps with areas of OC accumulation. Present estimates of the effect of trawling on OC remineralization very widely due to many uncertainties, assumptions and simplifications. This is due to a lack of site-specific understanding of the complex interactions between Local hydrodynamic activity (e.g. sediment mixing and transport), Local sediment (e.g. grain size and OC content and stability), Local environmental conditions (e.g. temperature and oxygenation), and Local Biological communities (e.g. production and bioturbation) in determining OC accumulation and sensitivity to remineralization. As the effects of bottom fishing on OC remineralization are likely likely site (and perhaps seasonally) specific the resolution of future studies should also depend on the needs of regulating bodies and fisheries. Although more research is needed on mapping OC sediment stocks and sediments sensitive to OC remineralization in Norwegian waters, it can be assumed that trawling may have a greater effect on OC remineralization in areas that are; less hydrodynamically active, have high sedimentation rates, fine-grained sediments, low levels of bioturbation, lower levels oxygen penetration, naturally low remineralization rates, sensitive habitats that store carbon. Trawling may have less effect on OC remineralization in areas that are; more hydrodynamically active, have coarse-grained sediments, deeper oxygen penetration, naturally high remineralization rates.

References:

Aller, R.C., Cochran, J.K. 2019. The critical role of Bioturbation for particle dynamics, priming potential, and organic C remineralization in marine sediments: Local and basin scales. Front. Earth Sci. 7, 157.

Amon, R.M.W., Benner, R. 1996. Bacterial utilization of different size classes of dissolved organic matter. Limnol. Oceanogr. 41, 41–51.

Atwood, T. B., Witt, A., Mayorga, J., Hammill, E., Sala, E. 2020. Global patterns in marine sediment carbon stocks. Frontiers in Marine Science, 7, 165. https://doi.org/10.3389/fmars.2020.00165

Bastardie, F., Hornborg, S., Ziegler, F., Gislason, H., & Eigaard, O. R. (2022). Reducing the Fuel Use Intensity of Fisheries: Through Efficient Fishing Techniques and Recovered Fish Stocks. Frontiers in Marine Science, 9. https://doi.org/10.3389/FMARS.2022.817335

Bengtsson, M. M., Attermeyer, K., & Catalán, N. 2018. Interactive effects on organic matter processing from soils to the ocean: Are priming effects relevant in aquatic ecosystems? Hydrobiologia, 822(1), 1–17. https://doi.org/10.1007/s10750-018-3672-2

Berner, R. A. 1982. Burial of organic carbon and pyrite sulfur in the modern ocean; Its geochemical and environmental significance. American Journal of Science, 282(4), 451–473. https://doi.org/10.2475/ajs.282.4.451

Bianchi, T. S. (2011). The role of terrestrially derived organic carbon in the coastal ocean: A changing paradigm and the priming effect. Proceedings of the National Academy of Sciences, 108(49), 19473–19481. https://doi.org/10.1073/pnas.1017982108

Bourgeois, S., Archambault, P., Witte, U. 2017. Organic matter remineralization in marine sediments: A pan-Arctic synthesis: Pan-Arctic Benthic Remineralization. Global Biogeochem. Cycles 31, 190–213.

Bradshaw, C, Tjensvoll, I., Sköld, M., Allan, I.J., Molvaer, J., Magnusson, J., Naes, K., Nilsson, H.C. 2012. Bottom trawling resuspends sediment and releases bioavailable contaminants in a polluted fjord, Environmental Pollution, 170, 232-241. https://doi.org/10.1016/j.envpol.2012.06.019.

Brin, L.D., Giblin, A.E., Rich, J.J. 2015. Effects of experimental warming and carbon addition on nitrate reduction and respiration in coastal sediments. Biogeochemistry 125, 81–95. https://doi.org/10.1007/s10533-015-0113-4

Brodersen, K.E., Trevathan-Tackett, S.M., Nielsen, D.A., Connolly, R.M., Lovelock, C.E., Atwood, T.B., Macreadie, P.I. 2019. Oxygen consumption and sulfate reduction in Vegetated Coastal habitats: Effects of physical disturbance. Front. Mar. Sci. 6 (14).

Burdige, D.J. 2007. Preservation of organic matter in marine sediments: Controls, mechanisms, and an imbalance in sediment organic carbon budgets? Chemical Reviews, 107(2), 467–485. https://doi.org/10.1021/cr050347q

Caslake, G. (2021). Sumwing Beam Trawl Trials Report — Seafish. Seafish Technical Report. https://www.seafish.org/document/?id=288cae19-81e5-4b98-9eb8-4eebcd1e7da8

Dauwe, B., Middelburg, J.J., Herman, P.M.J. 2001. Effect of oxygen on the degradability of organic matter in subtidal and intertidal sediments of the North Sea area. Marine Ecology Progress Series, 215, 13–22. https://doi.org/10.3354/meps215013

De Borger, E., Tiano, J., Braeckman, U., Rijnsdorp, A. D., Soetaert, K. 2021. Impact of bottom trawling on sediment biogeochemistry: A modelling approach. Biogeosciences, 18, 2539–2557. https://doi.org/10.5194/bg-2020-328

Deng, J., Zhu, W., Zhou, Y., Yin, Y. 2019. Soil organic carbon chemical functional groups under different revegetation types are coupled with changes in the microbial community composition and the functional genes. Forests 10 (240).

D'Hondt, S., Inagaki, F., Zarikian, C.A., Abrams, L.J., Dubois, N., Engelhardt, T., Evans, H., Ferdelman, T., Gribsholt, B., Harris, R.N., Hoppie, B.W., Hyun, J.-H., Kallmeyer, J., Kim, J., Lynch, J.E., McKinley, C.C., Mitsunobu, S., Morono, Y., Murray, R.W., Pockalny, R., Sauvage, J., Shimono, T., Shiraishi, F., Smith, D.C., Smith-Duque, C.E., Spivack, A.J., Steinsbu, B.O., Suzuki, Y., Szpak, M., Toffin, L., Uramoto, G., Yamaguchi, Y.T., Zhang, G., Zhang, X.-H., Ziebis, W. 2015. Presence of oxygen and aerobic communities from sea floor to basement in deep-sea sediments. Nat. Geosci. 8, 299–304.

Diesing, M., Kroger, S., Parker, R., Jenkins, C., Mason, C., Weston, K. 2017. Predicting the standing stock of organic carbon in surface sediments of the North-West European continental shelf. Biogeochemistry, 135(1), 183–200. https://doi.org/10.1007/s1053 3-017-0310-4

Diesing, M., Thorsnes, T., Bjarnadóttir, L.R. 2021. Organic carbon densities and accumulation rates in surface sediments of the North Sea and Skagerrak. Biogeosciences, 18(6), 2139–2160. https://doi.org/10.5194/bg-18-2139-2021

Donis, D., McGinnis, D.F., Holtappels, M., Felden, J., Wenzhoefer, F. 2016. Assessing benthic oxygen fluxes in oligotrophic deep sea sediments (HAUSGARTEN observatory). Deep Sea Res. I: Oceanogr. Res. Pap. 111, 1–10.

Durrieu de Madron, X., Ferré, B., Le Corre, G., Grenz, C., Conan, P., PujoPay, M., Buscail, R., Bodiot, O. 2005. Trawling-induced resuspension and dispersal of muddy sediments and dissolved elements in the Gulf of Lion (NW Mediterranean). Continental Shelf Research, 25(19–20), 2387–2409. https://doi.org/10.1016/j.csr.2005.08.002

Ekdale, A., Bromley, R., Pemberton, S. 1984. Effects of bioturbation on sediment properties. In Ichnology: The use of trace fossils in sedimentology and stratigraphy. Special Publications of SEPM: Society for Sedimentary Geology, USA.

Epstein, G., Middelburg, J.J., Hawkins, J.P., Norris, C.R., Roberts, C.M. 2021. The impact of mobile demersal fishing on carbon storage in seabed sediments. Global Change Biology, 28, 2875–2894. https://doi.org/10.1111/gcb.16105

Falcão, M., Gaspar, M. B., Caetano, M., Santos, M. N., Vale, C. 2003. Short-term environmental impact of clam dredging in coastal waters (south of Portugal): Chemical disturbance and subsequent recovery of seabed. Marine Environmental Research, 56(5), 649–664. https://doi.org/10.1016/s0141-1136(03)00069-2

Fanning, K.A., Carder, K.L., Betzer, P.R. 1982. Sediment resuspension by coastal waters: A potential mechanism for nutrient re-cycling on the ocean's margins. Deep Sea Research Part A. Oceanographic Research Papers, 29(8), 953–965. https://doi.org/10.1016/0198-0149(82)90020-6

Fiedler, B., Grundle, DS., Schutte, F., Karstensen, J., Loscher, C.R., Hauss, H., Wagner, H,. Loginova, A., Kiko, R., Silva, P., Tauhua, T., Kortzinger, A. 2016. Oxygen utilization and downward carbon flux in an oxygen-depleted eddy in the eastern tropical North Atlantic. Biogeosciences, 13, 5633–5647, 2016 https://doi.org/10.5194/bg-13-5633-2016

Gephart, J. A., Henriksson, P. J. G., Parker, R. W. R., Shepon, A., Gorospe, K. D., Bergman, K., Eshel, G., Golden, C. D., Halpern, B. S., Hornborg, S., Jonell, M., Metian, M., Mifflin, K., Newton, R., Tyed-mers, P., Zhang, W., Ziegler, F., & Troell, M. (2021). Environmental performance of blue foods. Nature 2021 597:7876, 597(7876), 360–365. https://doi.org/10.1038/s41586-021-03889-2

Glud, R.N. 2008. Oxygen dynamics of marine sediments. Marine Biol. Res. 4, 243–289.

Hiddink, J.G., Jennings, S., Sciberras, M., Szostek, C.L., Hughes, K.M., Ellis, N., Rijnsdorp, A.D., *et al*. 2017. Global analysis of depletion and recovery of seabed biota after bottom trawling disturbance. Proceedings of the National Academy of Science USA, 114(31), 8301-8306.

Hilborn, R., Kaiser, M.J. 2022. A path forward for analysing the impacts of marine protected areas. Nature 607, E1–E2. https://doi.org/10.1038/s41586-022-04775-1

Hinojosa, J.L., Moy, C.M., Stirling, C.H., Wilson, G.S., Eglinton, T.I. 2014. Carbon cycling and burial in New Zealand’s fjords. Geochem. Geophys. Geosyst. 15, 4047–4063.

Huettel, M., Berg, P., Kostka, J.E. 2014. Benthic exchange and biogeochemical cycling in permeable sediments. Annual Review of Marine Science, 6(1), 23–51. https://doi.org/10.1146/annurev-marine-051413-012706

Jennings, S., Dinmore, T.A., Duplisea, D.E., Warr, K.J., Lancaster, J.E. 2001. Trawling disturbance can modify benthic production processes. Journal of Animal Ecology, 70(3), 459–475. https://doi.org/10.1046/j.1365-2656.2001.00504.x

Jennings, S., Nicholson, M.D., Dinmore, T.A., Lancaster, J.E. 2002. Effects of chronic trawling disturbance on the production of infaunal communities. Marine Ecology Progress Series, 243, 251–260. https://doi.org/10.3354/meps243251

Jessen, G.L., Lichtschlag, A., Ramette, A., Pantoja, S., Rossel, P.E., Schubert, C.J., Struck, U., Boetius, A. 2017. Hypoxia causes preservation of labile organic matter and changes seafloor microbial community composition (Black Sea). Sci. Adv. 3, e1601897.

Keil, R. 2017. Anthropogenic forcing of carbonate and organic carbon preservation in marine sediments. Annual Review of Marine Science, 9(1), 151–172. https://doi.org/10.1146/annurev-marine-010816-060724

Kaiser, M.J., Clarke, K.R., Hinz, H., Austen, M.C.V., Somerfield, P.J., Karakassis, I. 2006. Global analysis of response and recovery of benthic biota to fishing. Marine Ecology Progress Series, 311, 1–14. https://doi.org/10.3354/meps311001

Kaiser, M.J., Collie, J.S., Hall, S.J., Jennings, S., Poiner, I.R. 2002. Modification of marine habitats by trawling activities prognosis and solutions. Fish and Fisheries, 3, 114–136. https://doi.org/10.1046/j.1467-2979.2002.00079.x

Kleber, M., Lehmann, J. 2019. Humic substances extracted by alkali are invalid proxies for the dynamics and functions of organic matter in terrestrial and aquatic ecosystems. J. Environ. Qual. 48, 207–216.

Kristensen, E., Ahmed, S.I., Devol, A.H. 1995. Aerobic and anaerobic decomposition of organic matter in marine sediment: Which is fastest? Limnology and Oceanography, 40(8), 1430–1437. https://doi.org/10.4319/lo.1995.40.8.1430

Kurian, S., Kessarkar, P.M., Rao, V., Purnachandra., Reshma, K., Sarkar, A., Pattan, J.N., Naqvi, S.W.A. 2020. Controls on organic matter distribution in oxygen minimum zone sediments from the continental slope off western India. J. Mar. Syst. 207, 103118.

LaRowe, D.E., Arndt, S., Bradley, J.A., Estes, E.R., Hoarfrost, A., Lang, S.Q., Lloyd, K.G., Mahmoudi, N., Orsi, W.D., Shah Walter, S.R., Steen, A.D., Zhao, R. 2020. The fate of organic carbon in marine sediments—New insights from recent data and analysis. EarthScience Reviews, 204, 103146. https://doi.org/10.1016/j.earscirev. 2020.103146

Lee, T.R., Wood, W.T., Phrampus, B.J. 2019. A machine learning (kNN) approach to predicting global seafloor total organic carbon. Global Biogeochemical Cycles, 33(1), 37–46. https://doi.org/10.1029/2018gb005992

Legge, O., Johnson, M., Hicks, N., Jickells, T., Diesing, M., Aldridge, J., Andrews, J., Artioli, Y., Bakker, D.C.E., Burrows, M.T., Carr, N., Cripps, G., Felgate, S. L., Fernand, L., Greenwood, N., Hartman, S., Kröger, S., Lessin, G., Mahaffey, C., Williamson, P. 2020. Carbon on the Northwest European Shelf: Contemporary budget and future influences. Frontiers in Marine Science, 7, Article 143. https://doi.org/10.3389/fmars.2020.00143

Luisetti, T., Turner, R.K., Andrews, J.E., Jickells, T.D., Kröger, S., Diesing, M., Paltriguera, L., Johnson, M.T., Parker, E.R., Bakker, D.C.E., Weston, K. 2019. Quantifying and valuing carbon flows and stores in coastal and shelf ecosystems in the UK. Ecosystem Services, 35, 67–76. https://doi.org/10.1016/j.ecoser.2018.10.013

Løkkeborg S., Kjell Bakkeplass, Diesing, M.,K., Gjøsæter, H., Gonzales-Mirelis, G., Hvingel, H., Jørgensen, L., Even Moland, E., Norderhaug, K., Rastrick S. 2023 Institute of Marine Research Norway, Report series: Marine Research Report 2023-1 ISSN: 1893-4536 www.hi.no/hi/nettrapporter/rapport-fra-havforskningen-2023-1

Malinverno, A., Martinez, E.A. 2015. The effect of temperature on organic carbon degradation in marine sediments. Sci. Rep. 5 (17861).

Martín, J., Puig, P., Masque, P., Palanques, A., Sanchez-Gomez, A. 2014a. Impact of bottom trawling on deep-sea sediment properties along the flanks of a submarine canyon. PLoS One, 9(8), e104536. https://doi.org/10.1371/journal.pone.0104536

Martín, J., Puig, P., Palanques, A., Giamportone, A. 2014b. Commercial bottom trawling as a driver of sediment dynamics and deep seascape evolution in the Anthropocene. Anthropocene, 7, 1–15. https://doi.org/10.1016/j.ancene.2015.01.002

Mengual, B., Cayocca, F., Le Hir, P., Draye, R., Laffargue, P., Vincent, B., & Garlan, T. 2016. Influence of bottom trawling on sediment resuspension in the ‘Grande-Vasière’ area (Bay of Biscay, France). Ocean Dynamics, 66(9), 1181–1207. https://doi.org/10.1007/s10236-016-0974-7

Meysman, F.J.R., Middelburg, J.J., Heip, C.H.R. 2006. Bioturbation: A fresh look at Darwin's last idea. Trends in Ecology & Evolution, 21(12), 688–695. https://doi.org/10.1016/j.tree.2006.08.002

Middelburg, J.J. 2018. Reviews and syntheses: To the bottom of carbon processing at the seafloor. Biogeosciences, 15(2), 413–427. https://doi.org/10.5194/bg-15-413-2018

Nedwell, D.B. 1999. Effect of low temperature on microbial growth: lowered affinity for substrates limits growth at low temperature. FEMS Microbiol. Ecol. 30, 101–111.

Nierop, K.G.J., Reichart, G.-J., Veld, H., Sinninghe Damsté, .J.S. 2017. The influence of oxygen exposure time on the composition of macromolecular organic matter as revealed by surface sediments on the Murray Ridge (Arabian Sea). Geochim. Cosmochim. Acta 206, 40–56.

Oberle, F.K.J., Swarzenski, P.W., Reddy, C.M., Nelson, R.K., Baasch, B., Hanebuth, T.J.J. 2016. Deciphering the lithological consequences of bottom trawling to sedimentary habitats on the shelf. Journal of Marine Systems, 159, 120–131. https://doi.org/10.1016/j. jmarsys.2015.12.008

Olsgard, F., Schaanning, M.T., Widdicombe, S., Kendall, M.A., Austen, M.C. 2008. Effects of bottom trawling on ecosystem functioning, Journal of Experimental Marine Biology and Ecology, 366, (1–2) 123-133, https://doi.org/10.1016/j.jembe.2008.07.036.

Palanques, A., Puig, P., Guillén, J., Demestre, M., Martín, J. 2014. Effects of bottom trawling on the Ebro continental shelf sedimentary system (NW Mediterranean). Continental Shelf Research, 72, 83–98. https://doi.org/10.1016/j.csr.2013.10.008

Paradis, S., Goñi, M., Masqué, P., Durán, R., Arjona-Camas, M., Palanques, A. Puig, P. 2021. Persistence of biogeochemical alterations of deep-sea sediments by bottom trawling. Geophysical Research Letters, 48(2), e2020GL091279. https://doi.org/10.1029/2020g l091279

Parker, R., Blanchard, J. L., Gardner, C., Green, BS., Hartmann, K., Tyedmers, PH., & Watson, RA. (2018). Fuel use and greenhouse gas emissions of world fisheries. Nature Climate Change, 8(4), 333–337. https://doi.org/10.1038/s41558-018-0117-x

Polymenakou, P.N., Pusceddu, A., Tselepides, A., Polychronaki, T., Giannakourou, A., Fiordelmondo, C., Hatziyanni, E., Danovaro, R. 2005. Benthic microbial abundance and activities in an intensively trawled ecosystem (Thermaikos Gulf, Aegean Sea). Continental Shelf Research, 25(19–20), 2570–2584. https://doi.org/10.1016/j.csr.2005.08.018

Pusceddu, A., Bianchelli, S. Danovaro, R. 2015. Quantity and biochemical composition of particulate organic matter in a highly trawled area (Thermaikos Gulf, Eastern Mediterranean Sea). Advances in Oceanography and Limnology, 6(1/2), 21–34. https://doi.org/10.4081/aiol.2015.5448

Pusceddu, A., Bianchelli, S., Martin, J., Puig, P., Palanques, A., Masque, P., & Danovaro, R. 2014. Chronic and intensive bottom trawling impairs deep-sea biodiversity and ecosystem functioning. Proceedings of the National Academy of Sciences of the United States of America, 111(24), 8861–8866. https://doi.org/10.1073/pnas.1405454111

Qi, D., Chen, B., Chen, L., Lin, H., Gao, Z., Sun, H., Zhang, Y., Sun, X., Cai, W. 2020. Coastal acidification induced by biogeochemical processes driven by sea-ice melt in the western Arctic. Polar Science. 23, 100504. https://doi.org/10.1016/j.polar.2020.100504

Riekenberg, P.M., Oakes, J.M., Eyre, B.D. 2020. Shining light on priming in euphotic sediments: Nutrient enrichment stimulates export of stored organic matter. Environmental Science & Technology, 54(18), 11165–11172. https://doi.org/10.1021/acs.est.0c01914

Roussel, E.G., Cragg, B.A., Webster, G., Sass, H., Tang, X., Williams, A.S., Gorra, R., Weightman, A.J., Parkes, R.J. 2015. Complex coupled metabolic and prokaryotic community responses to increasing temperatures in anaerobic marine sediments: critical temperatures and substrate changes. FEMS Microbiol.Ecol. 91, fiv084.

Rühl, S., Thompson, C., Queirós, A.M., Widdicombe, S. 2020. Missing links in the study of solute and particle exchange between the sea floor and water column. ICES Journal of Marine Science, 77(5), 1602–1616. https://doi.org/10.1093/icesjms/fsaa060

Sala, E., Mayorga, J., Bradley, D., Cabral, R.B., Atwood, T.B., Auber, A., Cheung, W., Costello, C., Ferretti, F., Friedlander, A.M., Gaines, S.D., Garilao, C., Goodell, W., Halpern, B.S., Hinson, A., Kaschner, K., Kesner-Reyes, K., Leprieur, F., McGowan, J., Lubchenco, J. 2021. Protecting the global ocean for biodiversity, food and climate. Nature, 592, 397–402. https://doi.org/10.1038/s41586-021-03371-z

Sanches, L. F., Guenet, B., dos Anjos Cristiano Marino, N., de Assis Esteves, F. 2021. Exploring the drivers controlling the priming effect and its magnitude in aquatic systems. J. Geophys.ical Res.: Biogeosci. 126, e2020JG006201. https://doi:10.1029/2020JG006201

Seiter, K., Hensen, C., Schröter, J., Zabel, M. 2004. Organic carbon content in surface sediments—Defining regional provinces. Deep Sea Research Part I: Oceanographic Research Papers, 51(12), 2001– 2026. https://doi.org/10.1016/j.dsr.2004.06.014

Seiter, K., Hensen, C., Zabel, M. 2005. Benthic carbon mineralization on a global scale. Global Biogeochem. Cycles 19, GB1010.

Smeaton, C., Austin, W.E.N. 2022. Quality not quantity: Prioritizing the management of sedimentary organic matter across continental shelf seas. Geophysical Research Letters, 49, e2021GL097481. https://doi.org/10.1029/2021GL097481

Smeaton, C., Hunt, C.A., Turrell, W.R., Austin, W.E.N. 2021. Marine sedimentary carbon stocks of the United Kingdom's exclusive economic zone. Frontiers in Earth Science, 9, 50. https://doi.org/10.3389/feart.2021.593324

Snelgrove, P.V.R., Soetaert, K., Solan, M., Thrush, S., Wei, C.-L., Danovaro, R., Fulweiler, R.W., Kitazato, H., Ingole, B., Norkko, A., Parkes, R.J., Volkenborn, N. 2018. Global carbon cycling on a heterogeneous seafloor. Trends in Ecology & Evolution, 33(2), 96– 105. https://doi.org/10.1016/j.tree.2017.11.004

Tabuchi, K., Kojima, H., Fukui, M. 2010. Seasonal Changes in Organic Matter Mineralization in a Sublittoral Sediment and Temperature-Driven Decoupling of Key Processes. Microb Ecol 60, 551–560. https://doi.org/10.1007/s00248-010-9659-9

Thrush, S.F., Dayton, P.K. 2002. Disturbance to marine benthic habitats by trawling and dredging: Implications for marine biodiversity. Annual Review of Ecology and Systematics, 33(1), 449–473. https://doi.org/10.1146/annurev.ecolsys.33.010802.150515

Tiano, J.C., van der Reijden, K.J., O'Flynn, S., Beauchard, O., van der Ree, S., van der Wees, J., Ysebaert, T., Soetaert, K. 2020. Experimental bottom trawling finds resilience in large-bodied infauna but vulnerability for epifauna and juveniles in the Frisian Front. Marine Environmental Research, 159, 104964. https://doi.org/10.1016/j.marenvres.2020.104964

Tietjen, T., G. Wetzel, R., 2003. Extracellular enzyme-clay mineral complexes: Enzyme adsorption, alteration of enzyme activity, and protection from photodegradation. Aquat. Ecol. 37, 331–339.

Tillin, H.M., Hiddink, J.G., Jennings, S., Kaiser, M.J. 2006. Chronic bottom trawling alters the functional composition of benthic invertebrate communities on a sea-basin scale. Marine Ecology Progress Series, 318, 31–45. https://doi.org/10.3354/meps318031

Trevathan-Tackett, S.M., Thomson, A.C.G., Ralph, P.J., Macreadie, P.I. 2018. Fresh carbon inputs to seagrass sediments induce variable microbial priming responses. Sci. Total Environ. 621, 663–669.

Trimmer, M., Petersen, J., Sivyer, D.B., Mills, C., Young, E., Parker, E.R. 2005. Impact of long-term benthic trawl disturbance on sediment sorting and biogeochemistry in the southern North Sea. Marine Ecology Progress Series, 298, 79–94. https://doi.org/10.3354/meps2 98079

Turner, J.T. 2015. Zooplankton fecal pellets, marine snow, phytodetritus and the ocean's biological pump. Progress in Oceanography, 130, 205–248. https://doi.org/10.1016/j.pocean.2014.08.005

Van der Molen, J., Aldridge, J.N., Coughlan, C., Parker, E.R., Stephens, D., Ruardij, P. 2012. Modelling marine ecosystem response to climate change and trawling in the North Sea. Biogeochemistry, 113(1–3), 213–236. https://doi.org/10.1007/s10533-012-9763-7

Van de Velde, S., Van Lancker, V., Hidalgo-Martinez, S., Berelson, W. M., Meysman, F J.R. 2018. Anthropogenic disturbance keeps the coastal seafloor biogeochemistry in a transient state. Scientific Reports, 8(1), 5582. https://doi.org/10.1038/s41598-018-23925-y

Van Kaam-Peters, H.M.E., Schouten, S., Köster, J., Sinninghe Damstè, J.S. 1998. Controls on the molecular and carbon isotopic composition of organic matter deposited in a Kimmeridgian euxinic shelf sea: evidence for preservation of carbohydrates through sulfurisation. Geochim. Cosmochim. Acta., 62, 3259–3283.

Van Nugteren, P., Moodley, L., Brummer, G.-J., Heip, C.H.R., Herman, P.M.J., Middelburg, J.J. 2009. Seafloor ecosystem functioning: The importance of organic matter priming. Marine Biology, 156(11), 2277–2287. https://doi.org/10.1007/s00227-009-1255-5

Weston, N.B., Joye, S.B. 2005. Temperature-driven decoupling of key phases of organic matter degradation in marine sediments. Proc. Natl. Acad. Sci. 102, 17036–17040.

Wilkinson, G.M., Besterman, A., Buelo, C., Gephart, J., Pace, M.L. 2018. A synthesis of modern organic carbon accumulation rates in coastal and aquatic inland ecosystems. Scientific Reports, 8(1), 15736. https://doi.org/10.1038/s41598-018-34126-y

Xue, J., Cai, W., Hu, X., Huang, W., Lohrenz, S.E., Gundersen, K. 2015. Temporal variation and stoichiometric ratios of organic matter remineralization in bottom waters of the northern Gulf of Mexico during late spring and summer. J. Geophys. Res. Oceans 120, 8304–8326.

Yamamoto-Kawai, M., McLaughlin, F.A., Carmack, E.C., Nishino, S., Shimada, K. 2009. Aragonite undersaturation in the Arctic ocean: effects of ocean acidification and sea ice melt. Science 326, 1098–1100.

Zang, H., Blagodatskaya, E., Wen, Y., Shi, L., Cheng, F., Chen, H., Zhao, B., Zhang, F., Fan, M., Kuzyakov, Y. 2020. Temperature sensitivity of soil organic matter mineralization decreases with long-term N fertilization: Evidence from four Q10 estimation approaches. Land Degrad. Dev. 31, 683–693.

Zhao, B., Yao, P., Bianchi, T.S., Arellano, A.R., Wang, X., Yang, J., Su, R., Wang, J., Xu, Y., Huang, X., Chen, L., Ye, J., Yu, Z. 2018. The remineralization of sedimentary organic carbon in different sedimentary regimes of the Yellow and East China Seas. Chemical Geology, 495, 104-117. https://doi.org/10.1016/j.chemgeo.2018.08.012

Ziegler, F., Eigaard, O. R., Parker, R. W. R., Tyedmers, P. H., Hognes, E. S., & Jafarzadeh, S. (2019). Adding perspectives to: “Global trends in carbon dioxide (CO2) emissions from fuel combustion in marine fisheries from 1950 - 2016". Marine Policy, 107. https://doi.org/10.1016/j.marpol.2019.03.001Zimmerman, A.R., Chorover, J., Goyne, K.W., Brantley, S.L. 2004. Protection of mesopore-adsorbed organic matter from enzymatic degradation. Environ. Sci. Technol. 38, 4542–4548.