Supplementary Information:

Commercial fishery disturbance of the global ocean biological carbon sink

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Supplementary Methods

1. Global data analysis
The current study uses global scale satellite data to assess the spatial overlap between commercial fishing effort (Kroodsma et al., 2018) and the carbon sink (specifically particulate organic carbon, POC, export), thereby mapping the risk of impact. We analyse these data at two scales, namely a 2° x 2° grid and the nineteen major fishing areas (hereafter ‘FAO Areas’) used by the UN Food and Agricultural Organisation (FAO) for recording catch statistics. We also identify the routes by which different fishing practices might impact the carbon sink.

We used fishing intensity data (hours fished km$^{-2}$) for the years 2012 – 2016, which is published online by the Global Fishing Watch (Kroodsma et al., 2018) and covers all vessels with an automatic identification system (AIS).

Four different carbon export ratio algorithms were used to determine the mean POC export out of the surface ocean globally (Dunne et al., 2005; Henson et al., 2011; Laws et al., 2011; DeVries and Weber, 2017). Data were taken from the SIMPLE_TRIM model output (DeVries and Weber, 2017), which includes a climatology for net primary production, euphotic zone depth and temperature from satellite data for the years 1997-2008 on a 2° x 2° grid. See individual papers for the export calculations. The total export globally per year ranged from 3.2 Gt C yr$^{-1}$ from the Henson et al. 2011 algorithm, to 10.2 Gt C yr$^{-1}$ from the Dunne et al. 2005 algorithm (Fig. S1).

![Fig. S1. POC export from the upper ocean from four different algorithms. The mean POC export from all four algorithms was used to map the overlap of POC and fishing in this study.](image)

Both data sets (fishing intensity and mean POC export) were represented on a 2° x 2° grid. The area of these grid cells varies with latitude. Our mean values per unit area within each FAO Area (Table 1, Fig. 2) are therefore weighted by the areas of the individual grid cells. To allow comparison between different sized FAO Areas, we provide estimates of fishing...
intensity \((F_{int}, \text{hours km}^{-2})\) and carbon export \((C_{exp}, \text{mg C m}^{-2} \text{d}^{-1})\) per unit area, calculated as follows:

\[
F_{intj} = \frac{\sum_{i=1}^{n}(F_{intij} \times Area_{ij})}{\sum_{i=1}^{n} Area_{ij}}
\]

\[
C_{expj} = \frac{\sum_{i=1}^{n}(C_{expij} \times Area_{ij})}{\sum_{i=1}^{n} Area_{ij}}
\]

where \(Area_{ij}\) is the area of the \(i\)th of \(n\) pixels in the \(j\)th FAO area.

2. Information on catch categories and gear types

We obtained gear type data primarily from Tanocet et al. (2019), which provides total Global Fisheries Landings database (Watson, 2017) effort by gear type for 2010 to 2014. We also obtained catch data for the equivalent period from the FAO Global Capture Production database (FAO, 2019) (Table S1). This period overlaps our fishing intensity data for three years, 2012 – 2014, and fishery catch and effort data are well correlated (Fig. S2). Each of these data sources provides aggregated information by FAO area.

The Global Capture Production database provides catch information by taxon. In most cases taxon is resolved to species, but in some cases it is resolved to a lower taxonomic level (e.g. “sardinellas” or “various squids”). We identified the taxa which dominate the catch in each FAO Area (i.e. the top ranking taxa in terms of catch weight, which collectively comprise 50% or the closest value above 50% of the overall catch) (Table 1). This resulted in a list of 62 species which we assigned to one of ten categories of catch species (Table S1) on the basis of the following definitions:

Small pelagic fish (SP): pelagic fish with maximum length < 60cm;
Large pelagic fish (LF): pelagic fish with maximum length > 60cm;
Groundfish (G): all shelf-associated demersal fish;
Deep water fish (DF): bottom-associated fish found in off shelf waters (typically deeper than 500 m);
Unspecified fish (UF);
Pelagic crustaceans (PC);
Benthic crustaceans (BC): all bottom-associated crustaceans;
Unspecified crustaceans (UC);
Unspecified molluscs (UC);
Squid (S): all squid;
Bivalves (B): all bivalves.

We used a similar process (identifying the top ranking gear types in terms of catch and reporting those that collectively comprise ≥50% of the effort) to identify the dominant gear
types for each FAO Area (Table 1). Tanocet et al. (2019) do not provide gear type data for the Southern Ocean (FAO Areas 88, 48, 58), but we were able to characterise Southern Ocean catch by gear type, providing data that are comparable to the majority of other FAO Areas. The dominant Southern Ocean fisheries use either longlines to target toothfish (FAO Area 58 & 88) or trawls to target Antarctic krill and mackerel icefish (FAO Area 48, Table 1). In the case of the Northeast Atlantic, gear type data is presented in terms of percentage of fishing hours rather than percentage of catch (Taconet et al., 2019). Table 1 presents these data, which suggest that trawls are the main fishing gear in the Northeast Atlantic, comprising more than 70% of fishing hours. It is therefore plausible that trawls are also the main fishing gear by catch, although the two metrics are not strictly comparable.

Table S1. Classification of dominant taxa recorded in the FAO Global Capture Production database (FAO, 2019) into the catch categories used in the current study.

| Taxa                           | Category            | Abbreviation |
|--------------------------------|---------------------|--------------|
| American lobster               | Benthic crustacean  | BC           |
| Argentine red shrimp           | Benthic crustacean  | BC           |
| Northern prawn                 | Benthic crustacean  | BC           |
| Marine crustaceans nei         | Unspecified crustaceans | UC   |
| Antarctic toothfish            | Deep water fish     | DF           |
| Blue grenadier                 | Deep water fish     | DF           |
| Bombay-duck                    | Deep water fish     | DF           |
| Patagonian grenadier           | Deep water fish     | DF           |
| Patagonian toothfish           | Deep water fish     | DF           |
| Alaska pollock (=Walleye poll.) | Groundfish       | G            |
| Argentine hake                 | Groundfish          | G            |
| Atlantic cod                   | Groundfish          | G            |
| Cape hakes                     | Groundfish          | G            |
| Croakers, drums nei            | Groundfish          | G            |
| Hairtails, scabbardfishes nei  | Groundfish          | G            |
| Largehead hairtail             | Groundfish          | G            |
| Pacific cod                    | Groundfish          | G            |
| Whitemouth croaker             | Groundfish          | G            |
| Seerfishes nei                 | Large pelagic fish  | LP           |
| Skipjack tuna                  | Large pelagic fish  | LP           |
| Yellowfin tuna                 | Large pelagic fish  | LP           |
| Akiami paste shrimp            | Pelagic crustacean  | PC           |
| Antarctic krill                | Pelagic crustacean  | PC           |
| Natantian decapods nei         | Pelagic crustacean  | PC           |
| Anchoveta (=Peruvian anchovy)  | Small pelagic fish  | SF           |
| Atlantic chub mackerel         | Small pelagic fish  | SP           |
| Atlantic herring               | Small pelagic fish  | SP           |
| Atlantic mackerel              | Small pelagic fish  | SP           |
| Atlantic menhaden              | Small pelagic fish  | SP           |
| Bonga shad                     | Small pelagic fish  | SP           |
| California pilchard            | Small pelagic fish  | SP           |
| Cape horse mackerel            | Small pelagic fish  | SP           |
| Capelin                        | Small pelagic fish  | SP           |
3. Indicators of carbon sink intensity and fishing intensity

There are no data available that provide reliable measures of either the ultimate benefit of the ocean biological carbon sink (the rate of deep carbon sequestration) or the ecosystem impact of fishing at the spatial resolution of our analysis. We therefore used available indicator variables. Here we briefly discuss the relationship between our indicator variables and the variables that they indicate.

The phytoplankton-driven carbon sink initially depends on the amount of primary production in the euphotic zone, and the proportion of this which gets exported out of the euphotic zone (i.e. export efficiency). Unlike carbon sequestration (or transfer efficiency through the mesopelagic) there is a consensus about how export efficiency varies across the global oceans, and hence we deem this the most appropriate metric of the potential carbon sink on a global scale. However, exported sinking carbon then attenuates rapidly through the mesopelagic zone, being consumed by heterotrophs such as zooplankton and bacteria, meaning only ~ 15% reaches the deep ocean (i.e. > permanent thermocline, in deep water masses or the sediments) (Turner, 2015; Weber et al., 2016). How this varies across the
global oceans is not clear, with some meta-analyses suggesting an inverse relationship with temperature (Henson et al., 2012) and others a positive relationship (Marsay et al., 2015). In addition, the varying depth of the permanent thermocline needs to be considered (Palevsky and Doney, 2018). To realise global maps of deep ocean phytoplankton-derived carbon sequestration more needs to be understood on the controls of mesopelagic carbon attenuation (Cavan et al., 2019).

Some of the identified routes of fishery disturbance to the carbon sink (such as removing low-mid trophic level pellet-producing species) are directly related to catch (i.e. the amount of biomass removed). Others (e.g. sediment disturbance) are more directly related to effort (i.e. the amount of time spent fishing). Global effort data are available at the spatial resolution of our analysis (Fig. 2) whereas available catch data are generally aggregated at coarser spatial scales, including the FAO Areas. The catch achieved per unit effort depends on the local biomass of fish and the efficiency of the fishing gear. Effort is therefore an imperfect indicator of catch. Nonetheless it is well correlated with catch at the scale of FAO Areas (Fig S2). An important caveat with the effort data is that the ecosystem impact per unit fishing time varies with multiple factors including gear type (which is considered in our discussion), where it is deployed (above or below the thermocline, in the water column or on the sea bed), size of vessel, and other technologies used (e.g. fish finders and fish aggregation devices). Thus our analysis, based on effort data, provides an indication, rather than a definitive identification, of the potential spatial distribution of fishery impacts on the carbon sink and areas of high risk.

**Fig. S2.** The relationship between our indicator of fishing impact (effort) and direct impact on target species biomass (catch) at the scale of FAO Areas (Pearson correlation coefficient=0.75, P<0.001), with key outliers labelled. The non-area-adjusted data (catch in tons yr⁻¹ versus effort in hours yr⁻¹) are also correlated (Pearson correlation coefficient=0.72, P<0.001).
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