Title

The value of bottom trawling in Europe

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Abstract

Commercial bottom trawl and dredge fisheries are active across much of Europe, and their geographic footprint is extensive. More than half of seabed area is trawled every year in some parts of Europe. But these fisheries remain contentious; significant ecological and economic damages have been well documented. Yet, they remain a source of food and provide jobs and economic revenue. Considering recent pushes to ban or limit bottom trawling in European countries, we explore how the costs associated with this practice compare to the benefits it provides. We find that society is losing out to the private sector, largely because of the significant climate impacts associated with the churning of the seafloor sediment by bottom trawling. Further, we show that bottom trawling occurs in a significant portion of Marine Protected Areas (MPAs) across Europe. We argue that phasing out bottom trawling in MPAs could yield meaningful net benefits.

Keywords

Marine conservation, fisheries management, bottom trawling, CO_2 emissions, societal value

Highlights

- Average annual net value of bottom trawling in Europe is negative (–€0.33 to –€10.77 billion per year)
- CO_2 emissions from disturbed seafloor sediment yield the largest societal cost (–€3.57 to –€13.31 billion per year)
- Reducing bottom trawling effort across Europe could yield meaningful net benefits
- 12.7 % of European bottom trawling effort occurred within the boundaries of MPAs

1. Introduction

Bottom trawling has been a common fishing practice across much of the continental shelf and upper slope around Europe for centuries, targeting a range of bottom dwelling fishes, crustaceans, and bivalves (1). But the ecological impacts of bottom trawling (2–5), large carbon emissions (6,7), and need for government subsidies to prop up unprofitable operations (8,9) have led many to question whether continuing the practice is in society's best interest. Here we explore this question by providing a first estimate of the net value to society from bottom trawling in European waters, explore overlap between bottom trawling activity and marine protected areas (MPAs), and discuss potential policy pathways and implications associated with reducing bottom trawling effort.

Significant ecological damages associated with bottom trawling are well documented globally; for example, reductions in habitat complexity (4), permanent changes in the composition of seabed communities (3,10), and reduced productivity (5). Many bottom trawl fisheries are nonselective, yielding average bycatch (i.e., catch of non-target species) rates that range between 31-55% of the total catch (11,12). The discarding of undersized or non-target species also remains a problem in some bottom trawl fisheries (13), with observed discard rates of 30% or more (11,14,15). An estimated 60% of global discards come from trawl fisheries (16). These practices can introduce uncertainty in stock assessments, have serious implications for biodiversity and the structure of marine communities, and also are a source of economic loss for the fishery (or other fisheries) (17).

The climate impacts associated with active gears such as bottom trawls and dredges are also becoming more apparent. These fisheries emit large quantities of greenhouse gasses and other pollutants such as CO_2 and NO_X as byproducts of burning diesel oil (18,19) and disturbing sedimentary carbon (6,7,20). The economic costs to society of atmospheric CO_2 emissions are well documented (21), and recent studies suggest the annual emissions resulting from disturbance of sediments by bottom trawlers could equate to ~10% of annual global emissions from land-use change (7). Further, the direct economic costs associated with bottom trawl fisheries are significant. Governments spend hundreds of millions of dollars annually to manage these fisheries (22), in addition to providing the industry with large subsidies (at the taxpayer's expense) to offset the costs of fuel and other operating expenses (8). Studies suggest that some bottom trawl fisheries would not be profitable without government subsidies offsetting operating expenses (23).

Yet, the benefits derived from bottom trawl fisheries must be taken into account. Approximately 26% of wild-caught fish and shellfish globally come from bottom trawl and dredge fisheries (12), accounting for millions of dollars in profits annually. These fisheries support extensive food (and non-food) production systems and provide public benefits in the form of employment, employing an estimated 58.5 million people worldwide in 2020 (24). Such benefits are frequently touted as evidence in favor of maintaining these controversial fisheries (25).

Indeed, not all bottom trawl fisheries are equal in their impacts–there exist large differences between the impacts of different types of bottom trawl fisheries. For instance, fuel efficiency and benthic macrofauna depletion have been found to be quite different between otter trawl and dredge fisheries, due in part to differences in target species distributions and habitat type preferences (19,26). Further, gear innovations, adherence to strict data collection standards, and increased observer coverage have helped to stabilize overfished marine wildlife populations and reduce pressure on seabed habitats in some bottom trawl fisheries (12,27).

While the ecological and economic impacts of bottom trawling are well quantified, it remains unclear how the costs of these fisheries compare to their benefits. What are the trade-offs between extraction and conservation? How might reductions in bottom trawling affect these trade-offs? Our intent in exploring such questions here is to help facilitate a more informed discourse about the future of this fishing practice. Although bottom trawling is pervasive across continental shelves worldwide (28), here we focus on Europe as a case study because it is a data-rich region and the footprint of bottom trawling in this area is one of the most intense and extensive globally (1,28). Recent announcements calling for greater restrictions on bottom trawling in Europe–particularly in MPAs–make these questions of utmost policy-relevance (29–31).

2. Materials and methods

2.1. European bottom trawling fleet

We define the European bottom trawling fleet as otter trawlers, beam trawlers, and dredge fishing vessels flagged to the 27 EU Member states, the Faroe Islands, the United Kingdom, Norway, Svalbard and Jan Mayen, and Iceland. Only known fishing vessels classified by Global Fishing Watch (GFW) with AIS-predicted fishing effort in the study area (Fig. S1) between 2016 - 2021 are included. We estimate fishing effort for each vessel-year at a 0.01 x 0.01 degree resolution in units of hours and kilowatt-hours using a neural net model of AIS-inferred fishing effort developed by GFW (32)(Table S5).

We make every effort to exclude midwater trawlers from the vessel sample, though we recognize this is not always a straightforward characterization as many vessels utilize different gear types throughout the year. GFW characterizes the gear type of fishing vessels broadly (e.g., “trawlers”, “dredge fishing”), but we refine these characterizations using official registry data. We classify all vessels in our sample into three gear groups based on their primary gear: otter trawls (OT), beam trawls (BT), and dredges (TD) (Tables S1-S2).

Vessels are characterized in our model by flag state, gear group, overall length, gross tonnage, and engine power (Tables S3-S4). When available, GFW obtains characteristics from official vessel registries, and fills gaps using machine learning and regression models (32). We obtain estimates of auxiliary engine power from official registries where available, and fill gaps using machine learning models following the approach of Sala et al. (23)(SM Section 2.2).

We estimate the design speed, specific fuel consumption (SFC), gear width, and gear penetration depth of each vessel following the approach of Sala et al. (23). We estimate design speed in knots for each vessel as a function of main engine power (*KW*):

$$d = 10.4818 + (0.0012 \times KW^{main}) - (3.84710 * 10^{-8} \times KW^{main^2})$$

Most trawlers have design speeds between 7 - 15 knots; in order to prevent low estimated design speeds from unduly influencing our results, we assume the minimum design speed for vessels in our sample to be 5 knots. The average design speed across all vessels in our sample is 10.7 knots. The SFC of a vessel reflects the efficiency of the engine and varies with engine type, type of fuel used, engine age, vessel size, and type of activity (33). We estimate the SFC (g/kWh) of each vessel based on length-based estimates (23)(SM Section 2.3).

Gear width is estimated using vessel-size footprint relationships derived from Eigaard et al. (34) who studied the gear configurations of trawlers in 13 countries. They define the total width, *W*, of the gear footprint (m) as as functions of main engine power (*KW*) and total length (*L*):

$$W_{OT} = 10.6608 \times KW^{0.2921}$$

$$W_{BT} = 0.6601 \times KW^{0.5078}$$

$$W_{TD} = 0.3142 \times L^{1.2454}$$

We use the average penetration depths of each gear type from Hiddink et al. (5): 2.44 cm for otter trawls, 2.72 cm for beam trawls, and 5.47 cm for dredges.

2.2. Estimation of current net value

We estimate private costs and benefits accruing to the fishing industry, as well as public costs and benefits accruing to society associated with bottom trawling in Europe for our vessel sample. We define total net benefits for vessel *i* in year *t* ($U_{i,t}$) as:

$$U_{i,t} = \Pi_{i,t} + \Gamma_{i,t} + \Phi_{i,t} - D - S - \Omega$$

where *Π* are fishing profits, *Γ* is the value of direct employment (i.e., fishers/vessel crew), *Φ* is the value of protein provided for direct human consumption, D is the value of discarded catch, S are subsidies (the cost of which are borne by the taxpayer), and *Ω* is the value of carbon released (by way of fuel emissions and disturbed sediment carbon being released back into the atmosphere).

All private benefits and costs accruing to the fishing industry are captured within the calculation of fishing profits, *Π*, which includes revenues, subsidies that directly offset operating costs, fuel costs, labor costs, and other operating costs. We assume all remaining benefits and costs accrue to society, though some may be captured more locally (i.e., within Europe), while others have more global implications.

<u>2.2.1. Fishing profits</u>

We calculate fisheries profits as revenues minus costs, plus the value of subsidies provided directly to the fishing industry to offset costs. For each vessel *i* in year *t*, profits are calculated as:

$$\Pi_{i,t} = R_{i,t} - C_{i,t}^{total} + (E_{i,t} * s_f^{op})$$

where $R_{i,t}$ is revenue, $C_{i,t}^{total}$ are total vessel operating costs, and $E_{i,t} * s_f^{op}$ are subsidies provided by the government that directly offset operating costs. s_f^{op} is the average rate of subsidization for flag state *f* per unit effort ($/kWh) for bottom trawlers, only considering subsidies that directly offset operating costs (see Section 2.2.5. for more about subsidies).

We use landed value data from the Sea Around Us (SAU) research initiative (35) for 2016 - 2019 to estimate bottom trawl revenues for all relevant flag states fishing within the study area (SM Section 3.1). We allocate revenues proportionally to each vessel in our sample based on effort by flag state and EEZ (23). SAU estimates of catches and revenues are typically greater than official statistics published by national fisheries agencies or regional fisheries management organizations because these reconstructed catches aim to fill gaps where catches may have been un- or under-reported. We note that the use of SAU data in this study likely inflates the value of estimated private benefits.

Following the approach of Sala et al. (23), we define total operating costs as:

$$C_{i,t}^{total} = \frac{C_{i,t}^{fuel} + C_{i,t}^{labor}}{\varsigma_f^{costs}}$$

where $C_{i,t}^{fuel}$ are total fuel costs for vessel i in year *t*, $C_{i,t}^{labor}$ are total labor costs for vessel *i* in year *t*, and ς_f^{costs} is the average fraction that fuel and labor make up of total fishing costs for bottom trawlers flagged to state *f*.

We estimate fuel costs following the European Environmental Agency's method for estimating emissions from the shipping industry (18,23). For each AIS position, we calculate fuel consumption (Fig. S6A) for both the main and auxiliary engines as a function of the engine power of the vessel (in kilowatts), the specific fuel consumption (SFC, in grams per kilowatt-hour), and the load factor (expressed as a percentage) which represents the engine loading relative to its maximum continuous rate. The load factor (LF) of vessel i at any given position j can be estimated from the cubed ratio of a vessel's instantaneous speed ($\varrho_{i,j}$) at that position and the design speed of the vessel (d_i):

$$LF_{i,j} = L_{max} * \left(\frac{\frac{\varrho_{i,j}^3}{d_i} + \frac{L_{min}}{L_{max} - L_{min}}}{1 + \frac{L_{min}}{L_{max} - L_{min}}} \right)$$

We assume this to be bounded between a minimum load ($L_{min} = 0.2$) when engines are idling to a maximum load ($L_{min} = 0.9$) when vessels are operating at design speed. However, since we are dealing with trawlers, we need to account for high loading factors at relatively low speeds when vessels are towing gear in the water, so we only use the above formulation for non-fishing activity, and assume the load factor of trawlers to be equal to 0.75 when the vessel is fishing (18). We assume the load factors of the auxiliary engine to be 0.5 and 0.3 while fishing and cruising, respectively (23).

Fuel costs (Fig. S6B) are calculated for the main engine and auxiliary engine using the time spent in the AIS position, fuel consumption, and the annual global average price of fuel (SM Section 3.2). Average annual fuel prices are calculated from reported daily average prices of marine gas oil (MGO) from Bunker Index (Fig. S5) for Europe, the Middle East, and Africa.

We estimate labor costs (Fig. S7) and the average fraction of total costs made up by fuel and labor using data from the EU, Iceland, and Norway (36–38). These data provide estimates of different types of costs for trawlers by flag, vessel-size class, and gear. We calculate annual average labor costs per vessel, per kW, and per GT by flag, size class, and gear group (where available) and use these rates to estimate labor costs for each vessel-year. We also use these data to estimate the average fraction of costs made up by fuel and labor, and use these fractions to estimate total operating costs for each vessel-year (SM Section 3.2).

2.2.2. Employment

Employment is an essential component of a functioning economy and directly contributes to human well-being making it an important indicator for decision-makers. We assume the value of crew employment to be equal to the wages paid to those fishing. Though this represents a cost borne to vessel owners/operators and has an impact on their profits, it is also a benefit provided by the fishery to society.

2.2.3. Protein supply

Some portion of the fish harvested by bottom trawlers goes to direct human consumption and thus represents a source of protein–in addition to other valuable nutrients not considered here–for the population that would need to be replaced. We therefore consider the value of the protein provided for direct human consumption (Fig. S8) as a public benefit provided by bottom trawling to society. We calculate the value of protein provided by vessel i in year t as:

$$\Phi_{i,t} = H_{i,t} * \varsigma_f^{hc} * \varpi_f * p_t^{protein}$$

where $H_{i,t}$ is the total harvest from vessel i in time t (mt), ς_f^{hc} is the average fraction of harvest from flag state f going towards direct human consumption, ϖ_f is the average protein content of fish harvested by bottom trawlers flagged to state f (g protein/mt harvest) , and $p_t^{protein}$ is the market price of a substitutable protein source available domestically ($/g protein). We use data from SAU to estimate bottom trawl catches and the fraction of catches going towards human consumption for each flag state fishing within the study area (Fig. S4). We obtain the protein content of different species from *rfishbase* (39) and prices of substitutable animal proteins from the Agri-food Data Portal of the European Commission (SM Section 3.3).

2.2.4. Discards

Some portion of the fish caught by bottom trawlers ends up being discarded or returned to the sea. SAU estimates discards as a component of reconstructed catches for each EEZ area, and we use these to estimate the magnitude of discards associated with bottom trawling by flag state across our study area (Fig. S3C).

Discards are often viewed as a waste of fishery resources, particularly in cases when other fisheries operating in the same region target and retain the discarded species. For example, species discarded in industrial fisheries may be targeted by artisanal fisheries or juveniles discarded in one fishery may be targeted by another fishery as adults. In such cases, the value of discards might be quantified as the potential loss to the other fisheries (15), but this is often difficult to discern in practice. Discards may also reflect a source of uncertainty for the managers of these other fisheries. High rates of discarding may also have an ecological effect, negatively influencing the biodiversity and community structure of an area. On the flip side, some studies have shown that discards can have positive ecological impacts, such as providing food for seabirds (40). Other studies show that discarding is a more economically efficient strategy for fishers, and banning discards can cause severe economic losses for the fishery.

We conservatively estimate the value of discards from vessel i in year t as:

$$D_{i,t} = d_{i,t} * p_t^{ex-25th}$$

where $d_{i,t}$ is the total magnitude of discards from vessel i in time t (mt) and $p_t^{ex-25th}$ is the 25th percentile of the landings prices for species harvested by fleet f (\$/mt). In this way, we are assuming the economic value of discards from bottom trawling to be a fraction of that of the same magnitude of landed catches of comparable species, but not zero (Fig. S3D).

2.3.5. Subsidies

Fisheries subsidies are classified in this data based on the scheme applied to multiple iterations of global fisheries subsidies estimates made by Sumaila et al. (8,41,42). We assume that only the portion of total subsidies with the potential to be capacity enhancing ("bad" subsidies) directly offset operating costs for vessels and factor into the calculation of fisheries profits. However, we assume that the total cost of fisheries subsidies are borne by taxpayers.

We use estimates of fisheries subsidies provided by each flag state to industrial fisheries from Schuhbauer et al. (43), scaled to only include the fraction being provided to bottom trawlers within our study area. These calculations, made by SAU, were made based on the fraction of each flag-states' total landed value coming from bottom trawl fishing in the study area. We then calculate rates of subsidization by flag state and use these rates to estimate vessel-specific subsidies (Fig. S3E). This approach assumes that rates of subsidization remain constant by flag state across years, but the magnitude of subsidies provided each year will differ.

2.2.6. CO_2 emissions

We estimate two carbon costs associated with bottom trawling: the value of carbon lost via CO_2 emissions from burning fuel (gasoline or diesel), and that from disturbed sedimentary carbon being remineralized into aqueous CO_2 and then released back into the atmosphere via aqueous-atmospheric gas transfer.

We assume the total value of carbon released into the atmosphere as a result of the bottom trawling activities of vessel i is equal to:

$$\Omega_{t,t} = CE_{i,t} + CD_{i,t}$$

where $CE_{i,t}$ is the total value of carbon emitted from burning fuel by vessel *i* in year *t* and $CD_{i,t}$ is the total value of organic carbon stored in ocean sediments that is remineralized into aqueous CO_2 by way of trawling and then transferred to the atmosphere.

From our formulation of fuel costs, described previously, we can estimate the amount of fuel consumed (mt) by each vessel (Fig. S6A). The total value of carbon emitted from burning fuel for vessel *i* is then given by:

$$CE_{i,t} = FC_{i,t} * \nu * \left(\frac{p_t^{CO_2}}{(1+d)^t}\right)$$

where is the emissions factor, $p_t^{CO_2}$ is the social cost of carbon in time t (\$/mt of CO_2), and *d* is the discount rate. We assume the emissions factor to be constant at 3.17 mt of CO_2 emitted per mt of fuel consumed (44,45) (Fig. S6C).

We estimate the value of disturbed sediment carbon that makes it way into the atmosphere as CO_2 as:

$$CD_{i,t} = m * \tau * I_{i,t} * \eta * \left(\frac{p_t^{CO_2}}{(1+d)^t}\right)$$

where *m* is the estimated amount of carbon stored in the first meter of sediment (mt), τ is the depletion factor accounting for historical depletion of the carbon store as a result of bottom trawling and other disruptive activities (7), $I_{f,t}$ is the fraction of carbon that is released back into the atmosphere as a result of the trawling activity of vessel *i* in time *t*, η is the ratio of the weight of C relative to that of CO_2 (3.67 mt of CO_2 equals 1 mt of carbon), $p_t^{CO_2}$ is the social cost of carbon in time *t* (\$/mt of CO_2), and *d* is the discount rate (5%).

The fraction of carbon released back into the atmosphere from vessel *i* is estimated as (6):

$$I_{i,t} = SVR_{i,t} * \delta_{crd} * \delta_{lab} * (1 - e^{-kt}) * a$$

where $SVR_{i,t}$ (swept volume ratio) is the fraction of sedimentary carbon disturbed by bottom trawling of vessel *i* in time *t*, δ_{crd} is the proportion of carbon that resettles after disturbance, δ_{lab} is the proportion of carbon that is labile, *k* is the first-order degradation rate constant, *t* represents time (1 year throughout our model), and *a* is the fraction of remineralized C that will be transferred from the ocean to the atmosphere. We estimate swept volume ratio as:

$$SVR_{i,t} = v_i * \left(\frac{\frac{E_{i,t}}{KW_i} * dist_i * W_i}{A}\right)$$

$\frac{E_{i,t}}{KW_i}$ represents the total time fished by vessel *i* in time *t* (hours), $dist_i$ is the distance fished per hour (m/h), W_i is the width of gear of vessel *i* (m), *A* is the total area of the fishing ground (m^2), and v_i is the penetration depth of the gear used by vessel *i* as a fraction of the first meter of sediment.

We utilize estimates of the amount of carbon stored in the first meter of sediment in each pixel (Fig. S10) and historical levels of depletion (Fig. S12) from Atwood et al. (46). The global dataset of organic sedimentary carbon stocks from Atwood et al. (46) has gaps for parts in Europe as a result of missing data for predictor variables. Some of these missing values are located in areas of particularly high trawling intensity (e.g., the EEZ areas of Belgium and the Netherlands). To prevent these missing data from resulting in large omissions of estimated CO_2 emissions, we interpolate missing values for organic carbon stocks using a moving-window average with a 150 x 150 pixel grid size (Fig. S11).

We assume the fraction of carbon in each cell that resettles in the same cell after trawling to be constant at 0.87 based on previous studies quantifying lost sediment loads following disruptive activities (6,7). For the remaining carbon, we use sediment type as a proxy for estimating the labile fraction of carbon in each pixel following the approach of Sala et al. (6) pixels where more than 50% of the area is made up "fine" sediments (muds or silts) are assigned a labile fraction of 0.7; pixels where more than 50% of the area is made up of "course" sediments (gravel) are assigned a fraction of 0.286; the remaining pixels with a "sandy" makeup (combinations of other sediment types) are assigned a fraction of 0.04 (Fig. S13).

We use the same first order degradation rate constants for each pixel as previous studies (6,7). These values were based on oceanic regions using the best available values from the literature as follows: North Pacific = 1.67, South Pacific = 3.84, Atlantic = 1.00, Indian = 4.76, Mediterranean = 12.3, Arctic = 0.275, Gulf of Mexico and Caribbean = 16.8 (Fig. S14). We recognize there is uncertainty associated with this parameter due to limited empirical data. The model used here is a regionally scaled version of that used by Atwood et al. (7) who explored the effects of uncertainty associated with this parameter. They found their results to be robust to an order-of-magnitude reduction in k.

We explore uncertainty associated with the reactivity of organic carbon in subsurface sediments (i.e., the first-order degradation rate, k) following the same approach as Atwood et al. (7) (Table S9). The full range considered here is comparable to those used in other studies (ranging from 10^{-3} to 3 yr^{-1})(47). There is general consensus in the literature that bottom-trawling changes the natural flux of organic carbon stored in marine sediments, most often resulting in a net increase in atmospheric CO_2 emissions. However, studies have yielded mixed estimates of the magnitude of these effects, largely reflecting the spatial variability and complexity of the process (48).

Not all remineralized carbon will make it back to the atmosphere. Based on the findings of Atwood et al. (7), we assume the fraction of remineralized carbon that will be transferred from the ocean to the atmosphere to be 0.6. CO_2 emissions from disturbances to the sediment would likely make it to the atmosphere over a 9 year horizon (7), but we attribute them here to the year in which the trawling activity occurred.

2.3. Projections of future net benefits

We explore potential outcomes associated with changes in bottom trawling effort based on the following framework that describes net benefits as a function of the fishing effort (*E)* in time *t* and the stock biomass (*B*) in time *t*:

$$U_t = \Pi_t(E_t, B_t) + \Gamma_t(E_t) + \Phi_t(E_t, B_t) - D_t(E_t, B_t) - S_t(E_t) - \Omega_t(E_t)$$

We assume fishing profits, protein supply, and discards to be functions of effort (*E*) and stock biomass (*B*). Direct employment, subsidies, and the value of emitted carbon are assumed to be functions of effort (*E*).

Our projections of future net benefits associated with European bottom trawl fisheries couple all components of the framework used to estimate current net benefits (described in Section 2.3) with a simple fisheries production model. We use the estimation of current net benefits and average characteristics of all vessels in our sample to parameterize this model. For all future projections, we use a discount rate of 5%.

2.3.1. Stock growth

We use a Pella-Tomlinson production model to describe the underlying population dynamics for stock biomass in discrete time, defined as:

$$B_{t+1} = B_t + \frac{\phi+1}{\phi} g B_t \left(1 - \left(\frac{B_t}{K}\right)^{\phi}\right) - H_t$$

where B is stock biomass (mt), $g \in (0,1)$ characterizes population growth rate, K is the carrying capacity (maximum population size for growth to be positive, mt), and H_t is total harvest across all vessels in time t. We assume the ratio of stock biomass providing the maximum sustainable yield (B_{msy}) relative to the carrying capacity to be equal to 0.4 (49), which corresponds to $\phi = 0.188$.

2.3.2. Parameterization

We parameterize the stock production model for an aggregate "trawlfish" stock, defined by the characteristics of the main species comprising bottom trawl landings in the study area. SAU estimates bottom trawl catches of more than 500 different species (or species groups) by flag states in our vessel sample within the study area between 2016-2019 (35). Nonetheless, the catches of many species are trivial. By weight, the top 10 species (or species groups) represented in the SAU bottom trawl catches included in this analysis made up 67.67% of all catches between 2016-2019. Considering the top 20, 30, and 50 species (or species groups) accounts for 81.10%, 85.3%, and 91.17% of all catches by weight respectively. We use the characteristics of the top 50 species (or species groups) by catch weight to define the aggregate stock.

Biological parameters can have significant impacts on the outcomes of simple stock projection models like the one used here. Since we are using an aggregate stock, composed of many species with different growth rates, biomasses, and carrying capacities, we consider multiple scenarios and explore the effects of how uncertainty in these parameters may impact our results (Fig. S17). In cases where the stock is faster growing and/or closer to its carrying capacity (B~K), net benefits increase (SM Section 4).

2.4. Spatial overlap between bottom trawling and MPAs

We explore spatial overlap between bottom trawling activity and marine protected areas in our study area. Using the AIS-inferred estimates of fishing effort aggregated at a 0.01 x 0.01 degree resolution for all vessels in our sample between 2016 - 2021, we calculate the portion of effort that occurred within the boundaries of European MPAs.

Following the approach of Rechberger et al. (50), we use the 2024 version of the World Database of Protected Areas (WDPA) to identify relevant MPAs. In order to be included in this analysis, a protected area must encompass a marine area that falls (at least in part) within the study area. We remove terrestrial protected areas, Other Effective area-based Conservation Measures (OECMs), and overlapping polygons from this dataset. We then clean the remaining protected areas using the *wdpa_clean()* function from the *wdpar* R package and recalculate the marine area of each MPA. Any zones smaller than 0.001 km^2 and those where less than 1% of the total area is marine are then removed. We then use two datasets of MPA guide assessments, as well as information from the ProtectedSeas initiative to classify the protections associated with each MPA (50).

3. Results and discussion

3.1. Characterizing net value

We find the average net value associated with bottom trawling activity in Europe between 2016 - 2021 to be negative: between –€10.77 and –€0.33 billion per year (Fig. 1C). Calculating net value by beneficiary (public vs. private) demonstrates a large disparity (Fig. 1B): a net benefit accrues to the private sector (€0.81 billion per year on average) while a net cost is borne by the public (–€11.58 to –€1.15 billion per year). Although annual fishing revenues (€4.54 billion on average, optimistically), the value of the protein produced for human consumption (€2.50 billion), and the value of direct fisheries employment (€1.75 billion) are significant, so are the costs. Average annual government subsidies supporting bottom trawl fisheries (€1.34 billion) and the lost value from discarded catches are not trivial (€230 million). However, we find the value of CO_2 emissions from disturbed sedimentary carbon making its way back into the atmosphere to be the largest cost falling on society, ranging between –€12.66 billion and –€3.40 billion annually depending on the value placed on emitted CO_2.

These results likely provide a conservative estimate of societal costs as we only include industrial trawlers carrying an Automated Identification System (AIS). Furthermore, we do not include the economic costs arising from the loss of benthic habitat, nor the direct and indirect impacts to other fisheries in the region, many of which are less economically advantaged than industrial bottom trawlers. If such impacts were to be included here, societal costs would likely be even greater. However, we also do not include the benefit to society associated with processing-sector employment, nor the replacement value of bottom trawl catches that go towards feeding aquaculture (which may or may not go towards human consumption). The values of these costs and benefits are more difficult to discern, though would be unlikely to be large enough to offset the omitted costs.

The uncertainty in our results surrounding the value of CO_2 emissions from disturbed sediment must be acknowledged. This uncertainty stems from the value that we place on atmospheric CO_2 emissions. We use the social cost of carbon (SCC) here to estimate the economic costs associated with CO_2 emissions from bottom trawling. The SCC is a monetary estimate of the economic damages–resulting from changes in productivity of production systems, damages associated with sea level rise, and declines in human health and labor productivity–associated with emitting one additional ton of CO_2 into the atmosphere. Estimates of the SCC vary widely depending on the assumptions put into the models used to calculate them: notably the types of damages considered, the assumed discount rate, and the scale of damages being considered. Higher estimates tend to be generated based on the assumption that damages from CO_2 emissions originating in one location affect the whole world, while lower estimates have assumed that damages are localized. Higher estimates also tend to place a higher weight on the future, thus raising the estimated economic damage and the SCC. Estimates of the SCC have been increasing through time as we have gained a better understanding of the full scale of the impacts resulting from atmospheric CO_2 emissions (21,51).

Given the variability in estimates of the SCC, we conservatively use €43 and €161 per metric tonne as low and high end estimates of the value of atmospheric CO_2 released from bottom trawling. If we value CO_2 emissions on the low end of this range, our results would suggest that bottom trawling in Europe yields a relatively neutral net benefit (though the majority of costs still fall on society, while the majority of benefits are captured by the fishing industry). However, we feel that there are a number of factors justifying the use of a higher value. The price of CO_2 under the world's largest carbon market–the EU Emissions Trading System (ETS)–was between €95.2–109.9 per tonne in March 2023 and carbon taxes in some European countries have ranged upward of €120 per tonne. Further, there is growing evidence that markets and taxes tend to undervalue CO_2 emissions and the SCC should be even higher (21,51). Under such a reality, the costs of bottom trawling far outweigh the benefits.

3.2. Projections of future value: Might less be more?

Using our characterization of current net value, we simulate how changes in fishing effort might impact the balance of costs and benefits in the future. We find that reductions in bottom trawling effort could yield greater net benefits as compared to the status quo across a wide range of potential effort scenarios (Fig. 1D). In cases where the climate impacts of bottom trawling are valued more (i.e., a higher SCC), the significant public costs arising from CO_2 emissions nearly always outweigh private benefits, suggesting the optimal level of bottom trawling would be nearly nil. Even if we value CO_2 emissions conservatively (i.e., a lower SCC), we still see gains from reducing bottom trawling effort. We find that permanently reducing bottom trawling effort in aggregate across Europe by 34% could maximize net benefits under this scenario (Fig. 1D), yet significant (albeit lesser) costs still accrue to society.

These results, although simplistic, underscore the potential for transitions away from bottom trawling to yield meaningful climate benefits. Of course, achieving such outcomes is contingent on there being no activity leakage–that is, the effort to be reduced should be permanently eliminated (as assumed in our simulations) and must not be allowed to relocate elsewhere. Reducing bottom trawling effort will likely impact the private benefits accruing to the fishing industry in the short term, but long-term benefits to the fishing industry are certainly possible, especially for fisheries targeting stocks that are already overfished or are slower growing (Fig. S17).

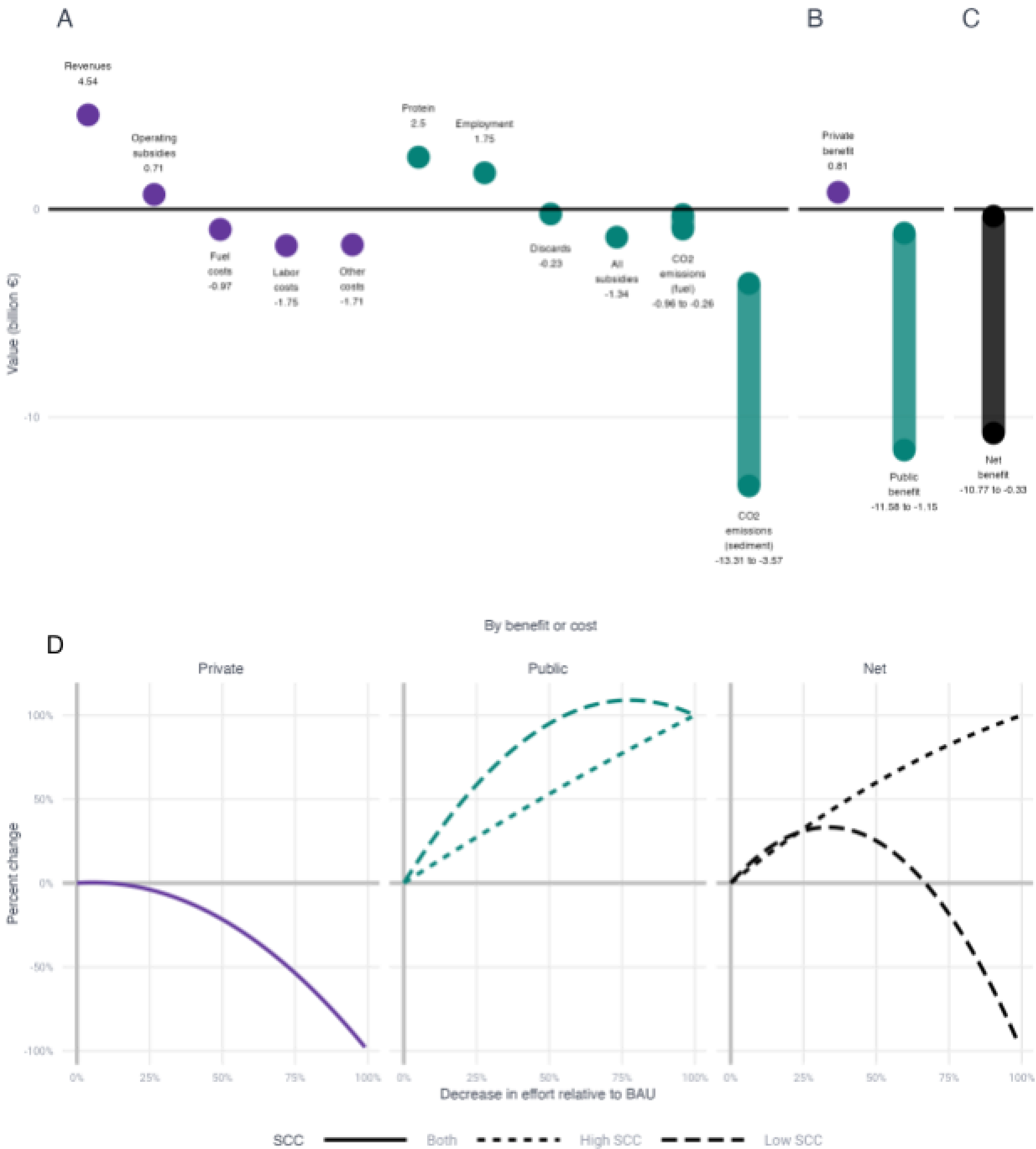

Fig. 1. Value of benefits and costs associated with bottom trawl fishing in Europe (2016-2021). The height of the bars (A-C) indicates the average magnitude of each cost or benefit annually (in billions of Euros). Bars are colored (A-B) based on the beneficiary. Ranges associated with CO_2 emissions (A-C) stem from high (€161/mt) versus low (€43/mt) assumed social costs of carbon. (D) Simulated annual net benefits (2050) are shown by beneficiary as a function of effort relative to a business as usual (BAU) scenario where effort continues unchanged. The different line types (D) depict the value placed on CO_2 emissions. SCC: Social cost of carbon.

3.3. Bottom trawling in MPAs

The World Database of Protected Areas includes more than 6,000 implemented and designated marine protected areas in European (EU, UK, Norway and Iceland) exclusive economic zones, encompassing a total area of over 900,000 square kilometers (Fig. 2A). We estimate that the footprint of bottom trawling encompasses 23.4% (~1.71 million km^2) of the European EEZ area considered here (Fig. 3A), but MPAs offering strong protections against bottom trawling ("fully" or "highly" protected) only encompass 0.07% (~5,000 km^2) of the study area (Fig. 2B).

We find that on average, 12.7% of all trawling effort each year (Fig. 3A) between 2016-2021 occurred within the boundaries of implemented or designated MPAs in our study area. For only EU states, the figure is higher: 20.3%. However, this figure varies greatly by country–more than 25% of the annual trawling effort in the EEZs of Belgium, Bulgaria, France, Germany, Guernsey, Netherlands, Romania, and Spain occurred in MPAs (Fig. 3C). Additionally, we find trawling intensities to be similar inside of MPAs in many countries, as compared to unprotected areas where trawling occurs (Fig. 3D). These results are not surprising, as a recent study found bottom trawling effort to be greater in many MPAs in northern Europe than in nearby unprotected areas (52).

This finding supports recent policy shifts in Europe seeking to limit bottom trawling in MPAs. In 2022, the UK introduced laws banning bottom-towed gears in four marine protected areas (MPAs), and another law in 2024 that would restrict bottom trawling in an additional 13 MPAs (53). In 2023, the European Commission presented a proposal that would phase out bottom trawling in MPAs across the EU by 2030. In 2024, Greece became the first European country to announce its commitment to ban bottom trawling in all MPAs within its waters by 2030 (30). Only a few months later, Sweden announced its intention to also ban bottom trawling in Swedish territorial waters (12 nm from shore) (31). Many have been skeptical as to whether these actions would actually affect bottom trawling effort in a meaningful way–protected areas are generally imagined to confer protection against damage or harm arising from human activities. Yet many MPAs in Europe are only minimally protected (54), and as evidenced here, there is still a great deal of overlap between the footprint of European bottom trawlers and MPAs.

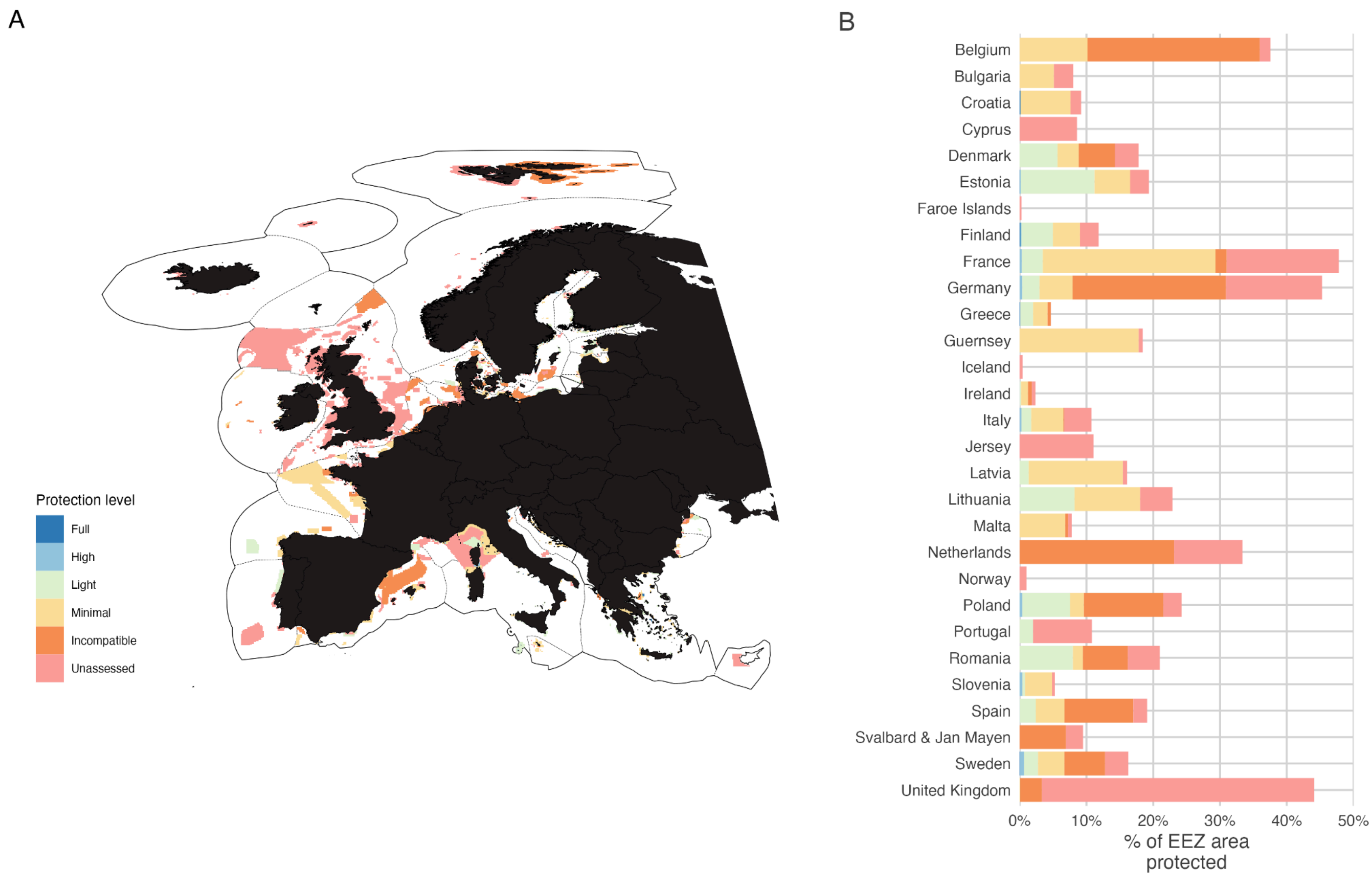

Fig. 2. Protections offered by European MPAs. (A) Map of MPAs considered here classified based on their level of protection offered. (B) Percent of each EEZ area protected by MPAs of different classifications. MPA boundaries are from the World Database of Protected Areas (2024) and classifications are from Rechberger et al. (50) based on MPA Guide.

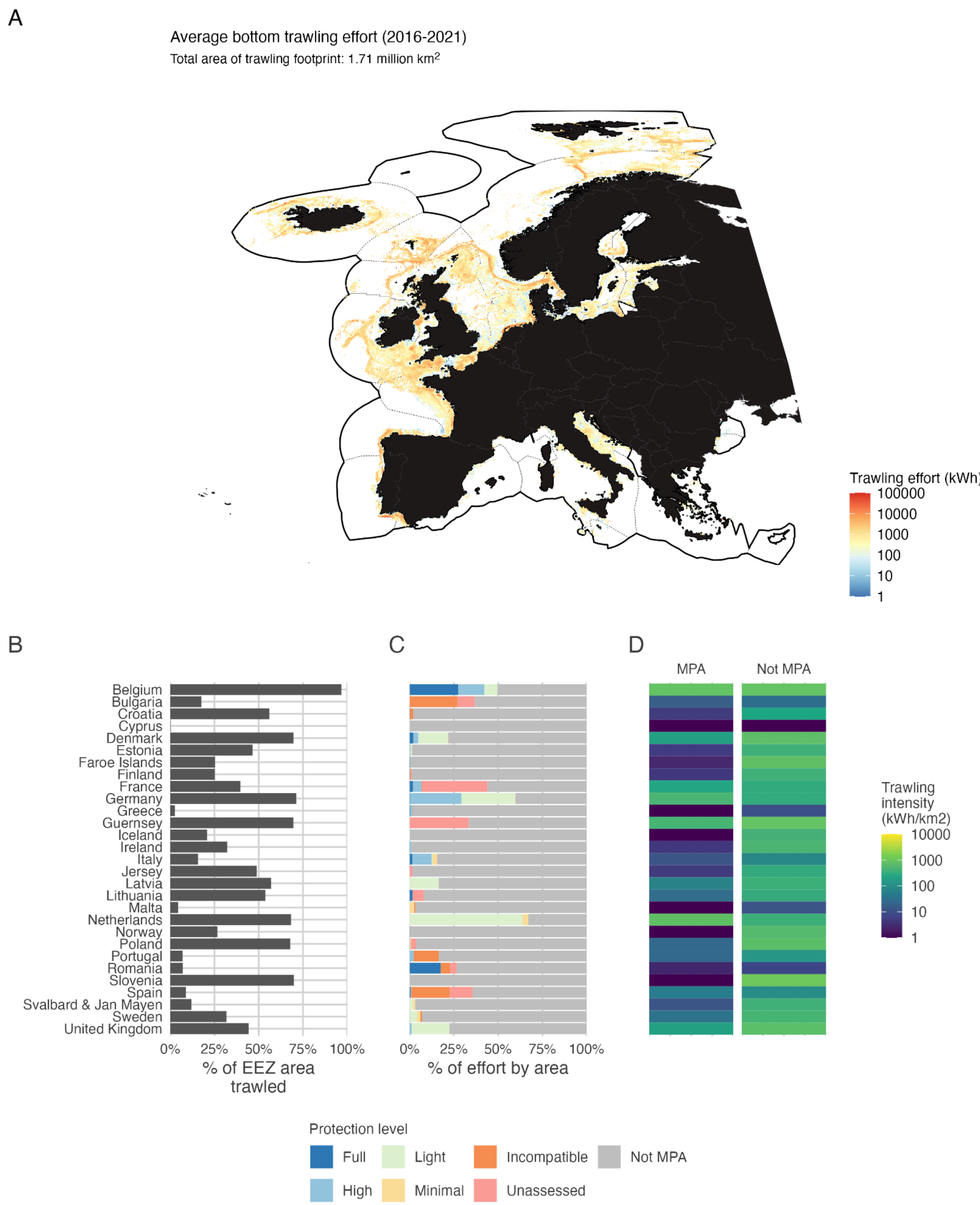

Fig. 3. Bottom trawling activity in European EEZs. (A) Average annual trawling effort between 2016 - 2021 aggregated by 0.01 x 0.01 degree. (B) Percent of total EEZ area trawled. (C) Percent of total trawling effort by protection status of area. (D) Trawling intensities (kWh/km^2) by area. MPA boundaries are from the World Database of Protected Areas (2024) and classifications are from Rechberger et al. (50) based on MPA Guide.

4. Conclusions

The cost-benefit approach utilized here has limitations; our results show that costs and benefits do not operate on the same scale, and additional costs–notably the loss of seafloor habitat and the direct and indirect impacts trawling has on other fisheries–should be considered. Nonetheless, if bottom trawling in Europe places such large economic costs on society as our incomplete accounting of costs suggests, then reducing bottom trawling effort would seem to be a logical path forward.

Reducing bottom trawling effort in Europe could realistically be achieved through numerous area-based or input-based pathways. In order to realize the greatest climate benefits by way of reduced CO_2 emissions, we see great potential in area-based approaches such as banning bottom trawling in established MPAs or banning bottom trawling in areas with carbon-rich sediments that contribute disproportionately little to food security. The first strategy would not only reduce the net cost to society, but it would also allow for the restoration of marine biodiversity within areas that are supposed to be protected and help replenish nearby fishing grounds. The success of such strategies (and realization of climate benefits) will be contingent on proper implementation and ensuring that such policies do not simply displace bottom trawling effort to other areas.

When there is limited capacity to target species individually–such as is the case with many bottom trawl fisheries–trade-offs between food production, conservation objectives, and profitability are inevitable. Undeniably, there will be short term costs associated with transitions away from bottom trawling. So how then to finance a just transition to a Europe with less bottom trawling? Redirecting harmful subsidies to buy out licenses and trawl vessels, and prepare fishers for alternative careers would be an efficient solution (9,12). A more comprehensive accounting of greenhouse gas emissions from the bottom trawling industry, including those resulting from the degradation of long-term carbon stocks in marine sediments, would help to ensure the industry is fully accountable for all its emissions. This is especially important in the EU, where emissions are regulated through a "cap and trade" system. Furthermore, recognizing emissions from the degradation of marine sediment carbon stocks in schemes like the EU Emissions Trading System could create new financing opportunities that reward fishers for adopting climate-friendly practices, or could allow nations to sell carbon credits for the emissions avoided by reducing bottom trawling permanently in specific areas. In any case, a key focus for policymakers should be to mitigate these costs so those who will be most affected have equitable access to new opportunities.

Policy makers should also assess potential employment and food security implications that may result. While bottom trawling creates jobs, it does not generate as many jobs as other fishing methods–small scale fisheries generate three times more jobs than industrial bottom trawlers (55). In the EU, only about 20,000 people are employed working on bottom trawlers (56); a far greater number are employed working in other fisheries that may be impacted negatively by bottom trawling. Bottom trawl fisheries are a source of food for people across Europe, directly or as feed for aquaculture that also goes to human consumption (12). Reductions in bottom trawling may disrupt these food systems, requiring switches to alternative food sources to meet nutritional requirements at least in the short term, before fisheries benefits that may accrue are realized. Care should be taken to ensure that the environmental costs associated with these alternative food supplies–whether they be from other fisheries, aquaculture, or terrestrial sources–are not greater than those which they are replacing (57). In Europe, the food security implications of such transitions may not be as significant, as the region depends less on marine ecosystems for nutrition than other areas (58). In any case, both the conservation and fisheries sectors should focus on identifying solutions that might achieve the best outcomes–environmentally, socially, and economically–not just for the fishing sector but for society as a whole.

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Methodology: KM, ES, JM, SO, TA

Investigation: KM, JM, SO, TA

Visualization: KM

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Supervision: ES

Writing – original draft: KM, ES

Writing – review & editing: KM, ES, JM, TA, AF, SO

Competing interests:

Authors declare that they have no competing interests.

Data and materials availability:

All data, code, and materials used in the analysis are available at https://github.com/emlab-ucsb/trawling-economics.

Supplementary material

Materials and Methods

Figs. S1 to S17

Tables S1 to S9

Supplementary Materials for

The value of bottom trawling in Europe

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The PDF file includes:

Materials and methods

Some statistics pertaining to the activities of bottom trawl fleets in Europe are available (e.g., (1,2)), but these vary greatly in their scope and level of aggregation, making it difficult to combine and/or compare these data directly. We therefore estimate private costs and benefits accruing to the fishing industry, as well as public costs and benefits accruing to society associated with bottom trawling in Europe today (2016 - 2021) using publicly available data. The estimates produced by this model will undoubtedly differ somewhat from statistics published by official sources given differences in methodologies and data availability. We compare our estimates to published values (where available) to identify where our method might yield an over- or under-estimate.

1. Study area

We consider the study area to the 200 nm EEZ areas (3) of all 27 EU Member states: Austria, Belgium, Bulgaria, Croatia, Republic of Cyprus, Czech Republic, Denmark (including the EEZ area administered by the Faroe Islands), Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal (*excluding* areas administered by the Azores and Madeira), Romania, Slovakia, Slovenia, Spain (*excluding* the Canary Islands) and Sweden. The EEZ areas of Norway (*including* areas administered by Svalbard and Jan Mayen), as well as those of the United Kingdom (*including* areas administered by Jersey and Guernsey) and Iceland are also included (Fig. S1).

2. Vessel sample and characteristics

Following the latest guidance from Global Fishing Watch (GFW), we filter the raw database to only include vessels listed on the best known fishing list that have been active for at least 125 hours (5 days) in a given year and have spent at least 24 hours fishing. We also remove any positions corresponding to bad segments identified by GFW. These criteria help to remove inactive vessels, as well as non-fishing vessels that may have been misclassified. We then filter to only include trawlers and dredge fishing vessels flagged to our states of interest that have AIS-predicted fishing effort in the study area between 2016-2021. We find 32,615 vessel-years meeting these criteria from 6,789 unique vessels.

We are able to find refined gear type information for many of our vessels of interest from official vessel registries of the EU, Iceland, Norway, the Faroe Islands, and Regional Fisheries Management Organizations. We use these records to identify and remove midwater and pelagic trawlers from our sample. For vessels where we are unable to obtain more detailed gear type information, we assume vessels classified as “trawlers” by GFW to be otter trawlers as these are most common, and vessels classified as “dredge_fishing” to be using towed dredges. After removing midwater trawlers and other non-relevant gear types, our final vessel sample includes 19,735 vessel-years from 4,367 unique vessels (Tables S1-S2). 224 of the vessels in our sample (5.13%) use beam trawls, 4,140 (94.80%) use otter trawls, and 3 (0.07%) use dredges (Table S1). 25 flag states are represented in our vessel sample (Table S2). The greatest number of trawlers in our sample are flagged to the United Kingdom (787 vessels), and the fewest are flagged to Cyprus and Malta (2 vessels each).

2.1. Vessel characteristics from GFW

For length, gross tonnage, main engine power, and crew size, we use the “best” characteristics for each vessel as determined by GFW (priority is given to characteristics reported on official vessel registries and gaps are filled with modeled values). Across all vessels in our sample, average length is 31 m, tonnage is 507 gt, main engine power is 925 kW (Tables S3-S4).

2.2. Auxiliary engine power

Estimates of auxiliary engine power are available for 794 relevant bottom-trawl vessels from EU and RFMO registries. Where multiple estimates of auxiliary engine power are available for the same vessel, we used the median value. We used a conditional random forest to fill in data gaps for the remaining vessels. We randomly split our sample into training (70%) and testing (30%) sets following the approach of Sala et al. (4). We compare two sets of predictor variables for auxiliary engine power. Their first model used vessel length, gross tonnage, and gear group. Gear group was missing for some of their vessels so a second model used only vessel length and engine power. They found that the model including gear group as a predictor performed best.

We run two models comparing the same sets of predictor variables. Both models use 500 trees and 10-fold cross validation resampling with 5 repeats. The RMSE is used to tune the mtry parameter and select the optimal model. We find both models to perform similarly, but the model without gear group as a predictor variable performs slightly better (Fig. S2, RMSE = 307; $R^2 = 0.82$) and we use that to fill in data gaps for our vessel sample. Tonnage is the most important predictor of auxiliary engine power in our model.

We calculate a ratio of auxiliary engine power to main engine power for both gap filled data and across the entire vessel sample to validate against existing estimates. The European Environmental Agency estimated the average ratio of auxiliary engine power to main engine power to be 0.39 in 2010. They also reported that this estimate was lower than a previous study in 2006 looking at the Mediterranean Sea fleet that found the ratio to be 0.47 for fishing vessels. On average across our gap filled data, we find this ratio to be 0.332; across our entire vessel sample, the ratio is 0.343. This suggests that we might be slightly underestimating auxiliary engine power in this analysis and thus providing a conservative estimate of auxiliary engine fuel consumption.

2.3. Specific fuel consumption

96% of the world's fishing fleet uses marine diesel oil (MDO) and 84% have medium-speed diesel engines (5). Specific fuel consumption (SFC) ranges between 203 to 280 g/kWh for vessels with this type of engine using MDO.

We explore upper and lower bound values of SFC based on flag-state and length (4), but ultimately find the estimates of fuel consumption produced by the lower bound values to be more realistic for the vessels in our sample. We use length-based SFC estimates of 240 g/kWh for vessels < 12 meters in length, 220 g/kWh for vessels between 12-24 meters, and 180 g/kWh for vessels over 24 meters. We assume the SFC for auxiliary engines to be 217 g/kWh for all vessels (6). For comparison, we also considered using upper bound flag-based SFC values as proposed by Sala et al. (4): 250 g/kWh for vessels flagged to Norway and 270 g/kWh for vessels flagged to all other European states in our sample.

3. Estimation of current net benefits

3.1. Revenues

The SAU database includes reconstructed global catch data for every fishing country and maritime territory. These reconstructions were done by SAU or by over 300 colleagues around the world, following a general catch reconstruction approach with the goal of filling identified gaps in a country's fishing record (7). For each EEZ area within the study area, we extract all catches and landed value data from the SAU database (7) made by fishing entities (flag states) represented in our vessel sample. Only catches from industrial fisheries using the following gear types are included in this analysis (hereafter "bottom trawl landings"): bottom trawl, shrimp trawl, beam trawl, otter trawl, and dredge. We aggregate bottom trawl landings by flag state and EEZ area.

SAU estimates the landed value of catches by multiplying the reconstructed catches by a global ex-vessel price database. We aggregate landed value by flag state and EEZ area in the same way as catches, keeping only the portion associated with industrial bottom trawling for this analysis.

We estimate catch and revenue rates (mt/kWh and $/kWh) for each flag state-EEZ area for all years between 2016 - 2019 based on the total observed bottom trawling effort in each area annually. We then use these rates to estimate vessel-specific catches and revenues for all flag state-EEZ area pairings represented in our effort data. For pairings where we don't have estimated bottom trawl catches or revenues from SAU, we instead calculate average rates by flag state across all EEZ areas and use those to fill in missing values. We are missing SAU estimates of bottom trawl catches for Malta and Lithuania. It's likely that the SAU model didn't have enough information to differentiate by gear type for these states, so trawl catches were likely branded as "other fishing" or something that we didn't include. We therefore apply the average catch and revenue rates across all flag states to estimate catches and revenues for these states. Since the SAU database does not include catches and landed value for 2020 and 2021, we use the average catch and revenue rates from previous years to extrapolate these values across all years based on differences in effort (Fig. S5A-B).

3.2. Fishing costs

Fuel consumption is calculated for each AIS-derived vessel position for both the main and auxiliary engines as a function of the engine power of the vessel (in kilowatts), the specific fuel consumption (in grams per kilowatt-hour), and the load factor (expressed as a percentage) which represents the engine loading relative to its maximum continuous rate.

We consider fuel consumption and fuel costs associated with two SFC values (Section 2.3): an upper-bound flag-state specific value, and a lower-bound length-based value. From these, we estimate that all vessels in our sample consumed between 2.61 - 3.55 billion liters of fuel in 2020 and between 3.00 - 4.11 billion liters of fuel in 2021. For only vessels flagged to EU states, the ranges are 1.19 - 1.61 billion liters and 1.29 - 1.75 billion liters for 2020 and 2021. It has been reported that the entire EU fishing fleet consumed 1.9 billion liters of fuel in 2020 (1).

For both SFC values, we estimate fuel costs for all vessels in our sample to between 768 - 1045 million EUR in 2020 and 1164 - 1594 million EUR in 2021. For only vessels flagged to EU states, the ranges are 351 - 474 million EUR and 500 - 679 million EUR for 2020 and 2021. It was reported that the entire EU large scale fleet (LSF), of which our vessels sample is only a part, spent 515 and 704 million EUR on fuel in 2020 and 2021.

Given these statistics, our lower bound estimates of SFC are likely more realistic. We therefore utilize the lower bound SFC estimates to estimate total fuel costs and CO_2 emissions from fuel per vessel-year.

For labor costs, we apply average labor costs per vessel, per kW, and per GT by flag and size class for each year where data is available using the following gap-filling approach:

1. Fill with cost rates for Norwegian, Icelandic, and Faroese vessels by year
2. Fill with cost rates for all other flag states by year, flag, length class, and gear group
3. Fill with cost rates for all other flag states by year and length class

We then calculate an upper and lower bound estimate of total labor costs for each vessel-year (Fig. S9). For 2020 and 2021, total personnel costs (+ value of unpaid labor) for the entire EU LSF (excluding Greece) were estimated to be 1382 million and 1420 million EUR (in 2020 prices). We estimate labor costs for vessels flagged to EU states (except Greece) to be between 555 - 970 million EUR for 2020 and

566 - 992 million EUR for 2021. Given these statistics, our upper bound estimates of labor costs are likely more realistic and we therefore utilize these when estimating total labor costs per vessel-year.

To estimate costs other than fuel and labor (e.g., energy, repair, maintenance, access rights, other variable costs, and other non-variable costs), we determine the average fraction of total costs made up by fuel and labor for different flags, gear types, and size classes from data from the EU, Iceland, and Norway (1,8,9). We then match these fractions back to our vessel sample using a similar gap filling protocol as for labor costs:

1. Fill with fractions for Norwegian and Icelandic vessels by year
2. Fill with fractions for all other flag states by year and length class

The average fraction of total costs made up by fuel and labor across our vessel sample is 0.55. Total costs for each vessel-year are then calculated by adding together fuel and labor costs and dividing by the estimated fraction of total costs made up by fuel and labor.

3.3. Protein supply

SAU classifies the end destination of catches in their database. From these data, we estimate the fraction of total bottom trawl landings by each flag state within our study area going toward direct human consumption. Nearly all flag states in our sample are estimated to have more than 75% of bottom trawl landings going to direct human consumption, except for Malta, Norway, Poland, and Sweden (Fig. S4, blue points).

We compare these estimated fractions with those from the official EU data accessed through the Eurostat portal. From this data we can estimate the fraction of total landings by REGION (across all gear types, not just bottom trawlers) for each flag state going toward direct human consumption for comparison. We find that the fractions of landings for direct human consumption estimated from the Eurostat data are lower for many flag states than those estimated from the SAU data (Fig. S4, purple points). The largest discrepancies are observed for Germany, Denmark, Finland, Iceland, Lithuania, and Sweden. It is likely that some of these discrepancies are a result of the corresponding states having large midwater trawl or purse seine bait fish fisheries (commonly destined for aquaculture feed or similar industrial uses). Therefore, we choose to use the SAU estimates for this analysis as they are specific to bottom trawling.

We estimate the portion of landings going toward direct human consumption by applying the fractions calculated from the SAU data by flag state to the estimated catches by vessel-year. We then estimate the protein content of these landings based on the relative protein content of the different species that make up the bottom trawl landed catches. We obtain estimates of the protein content for as many of the species caught by European bottom trawlers as possible from Fishbase. On average, we find the catch-weighted average protein content of species caught by European bottom trawlers to be 18 g protein per 100 g of fish.

We then use the prices of other animal protein products (poultry, sheep and goat meat, and beef) downloaded from the Agri-food Data Portal of the European Commission to estimate the market price of a gram of readily available non-seafood protein. The average price of chicken-based protein is lower than that of other sources for nearly all EU countries (except for Austria where the price of pork is slightly cheaper by weight). We use the average price of one gram of chicken-based protein to estimate the replacement value of the protein produced from trawling for human consumption (Fig. S8).

3.4. Discards

Discards–defined here as the portion of catches that are brought onboard, but then returned to the sea for whatever reason (dead or alive) before the vessel reaches port–have been banned in various European trawl fisheries since the 1980s. A discard ban was first implemented for cod in Norway in 1983, and has since been expanded to include many other species. Iceland implemented a mandatory landing policy in 1989, and the Faroese Islands first implemented a full discard ban in 1994. When it was decided to reform the EU Common Fisheries Policy (CFP) in 2008, reducing discards was a major action item. The version of the CFP adopted in 2013 prohibits the discarding of species subject to catch limits, as well as those subject to size limits in the Mediterranean Sea. Nonetheless, exemptions apply, and the practice of discarding unwanted catches continues in European trawl fisheries, albeit to a lesser degree than in the 1990s and early 2000s.

Historically, discarding was common practice when a species had low (or no) commercial value as compared to other target species ("high-grading") or when fishers wanted to avoid violating restrictions such as total allowable catches (TACs) or minimum size limits imposed by national or international regulations. The amount of discards can be influenced by environmental factors (e.g., primary productivity, depth, habitat type), characteristics of the gear employed by the fishery (e.g., selectivity), and fishing tactics (e.g., soak time, areas fished, adherence to regulations).

As with catches and landed value, we estimate discard and discard value rates from SAU data (mt/kWh and $/kWh) for each flag state-EEZ area for all years between 2016 - 2019 based on total bottom trawling effort. We then use these rates to estimate vessel-specific discards and value based on effort by flag state and EEZ area. We also use the same protocol of applying average rates by flag to fill in missing values where flag state-EEZ area pairings from our effort data don't exist in the SAU data. Since the SAU database does not include data for 2020 and 2021, we again use the average rates across all years to extrapolate these values (Fig. S5C-D).

<u>3.5. Subsidies</u>

The estimates of fisheries subsidies used here (10) are from 2018, and thus we only estimate subsidy rates ($/kWh) for each flag state based on fishing effort from that year. We then apply these rates to estimate vessel-specific subsidies based on effort for all years (Fig. S5E). This approach assumes that rates of subsidization remain constant, but subsidy amounts will vary year-to-year depending on effort.

4. Projections of future net benefits

For the reference case scenario (REF), we obtain estimates of biomass, growth rate, and carrying capacity from the data-limited stock assessment database created by Costello et al. (40) (Fig. S15A).

Since many European stocks are formally assessed, we also extract the most recent estimates of biomass for any European stocks of the main bottom trawl species available from the Ram Legacy Stock Assessment Database (RAMLDB, v 4.44, accessed through the ramlegacy package for R). We then aggregate biomass by species and obtain estimates of population growth rates and carrying capacity from the FishBase database (Table S7). For the alternative scenario (ALT), we give priority to values from the RAMLDB and FishBase for a given species where available, and then use the values from Costello et al. (40) to fill in gaps for species not represented in the RAMLDB (Fig. S15B).

Under both scenarios, we are able to obtain estimates of biomass, growth rate, and/or carrying capacity for 35 of the 50 main bottom trawl species, representing 71.07% of total bottom trawl catches between 2016-2019 from SAU. We then define the characteristics of the aggregate "trawlfish" stock for both scenarios (Table S8). We assume biomass to be the sum of biomass across all species, adjusted to account for only 71.07% of catches being represented. We calculate growth rate as the catch-weighted average growth rate across all species, and assume carrying capacity to be the sum of carrying capacity across all species, adjusted to account for only 71.07% of catches being represented

Supplementary Figures

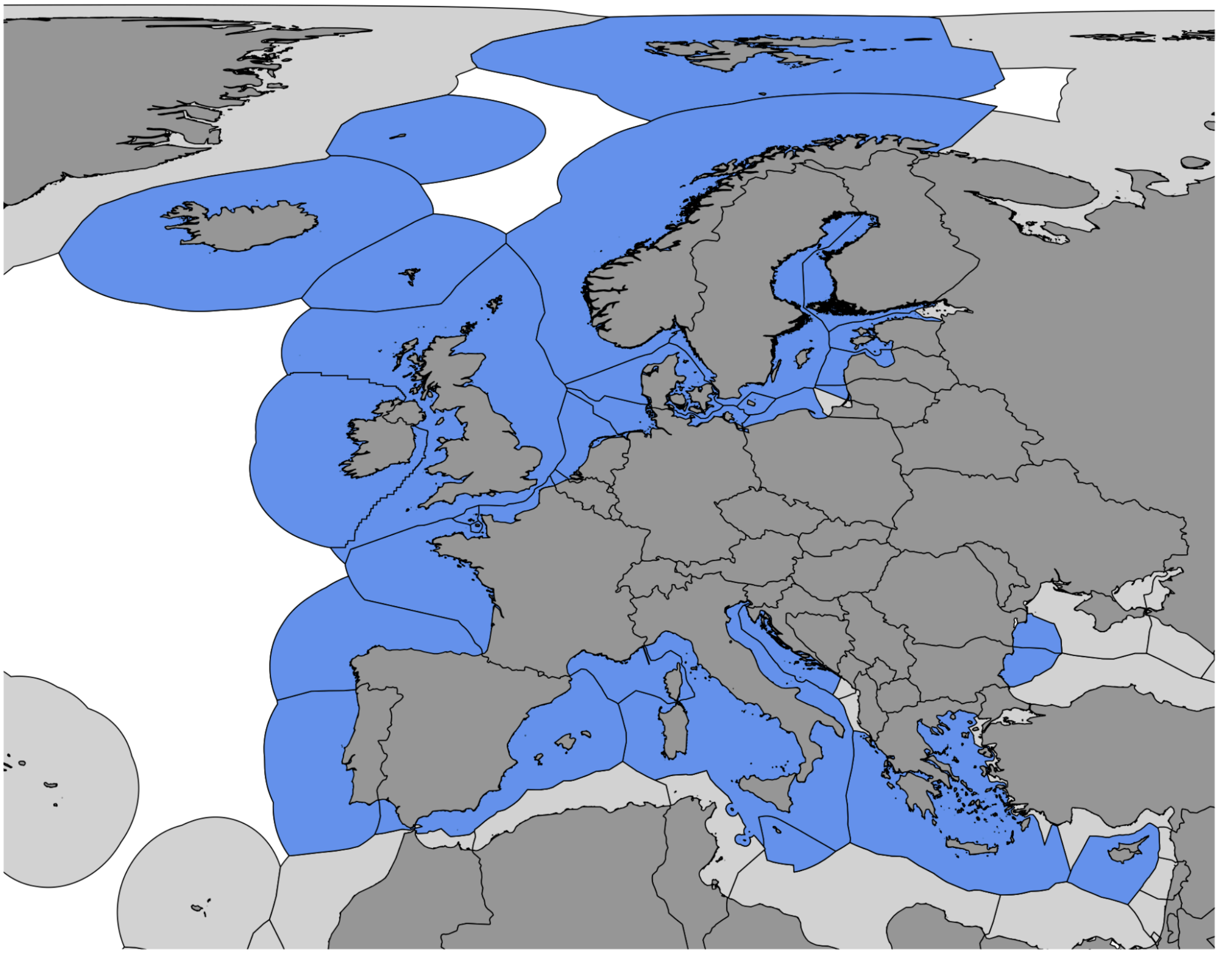


Fig. S1

Study areas included in this analysis. EEZ Boundaries are from the Maritime Boundaries Database from marineregions.org (3)

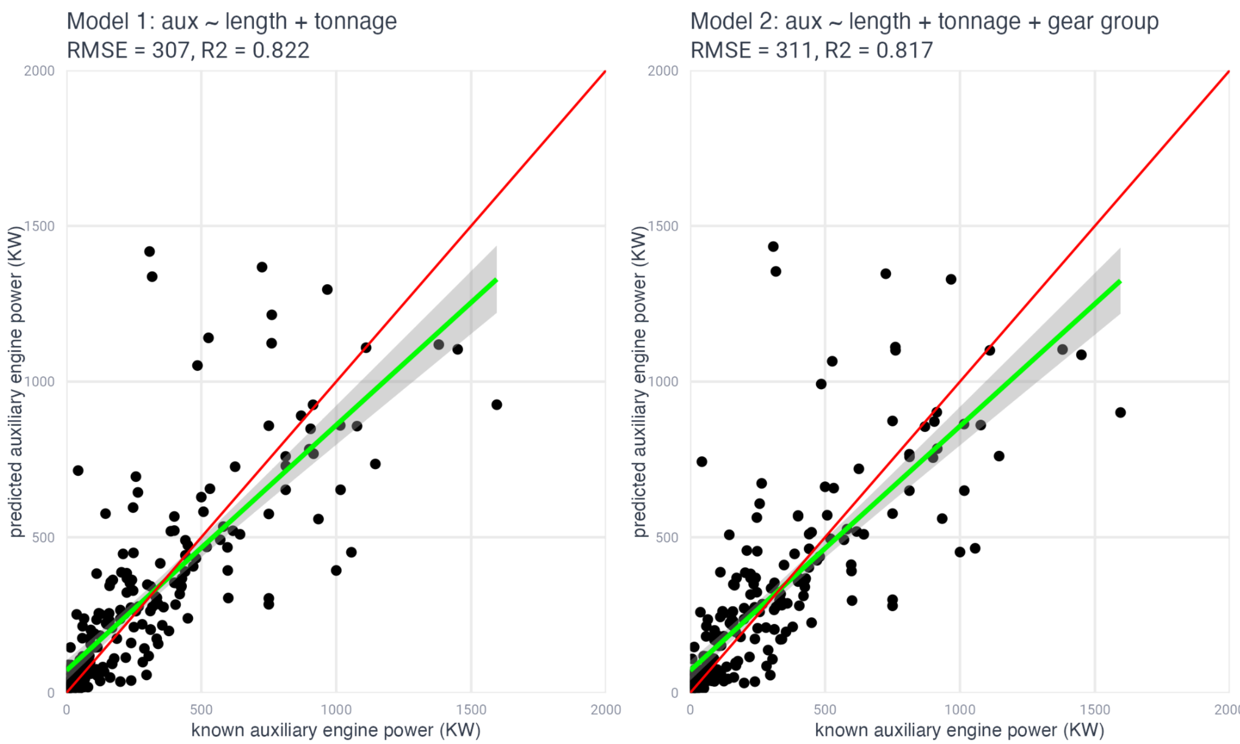


Fig. S2

Performance of conditional random forest models used to predict auxiliary engine power. The left panel shows the fit of model #1, which includes total length (m) and tonnage (gt) as predictor variables; the right panel shows the fit of model #2 which includes total length (m), tonnage (gt), and gear group as predictor variables. The red line shows a 1:1 relationship; the green line shows model fits. Model #1 was used to fill data gaps.

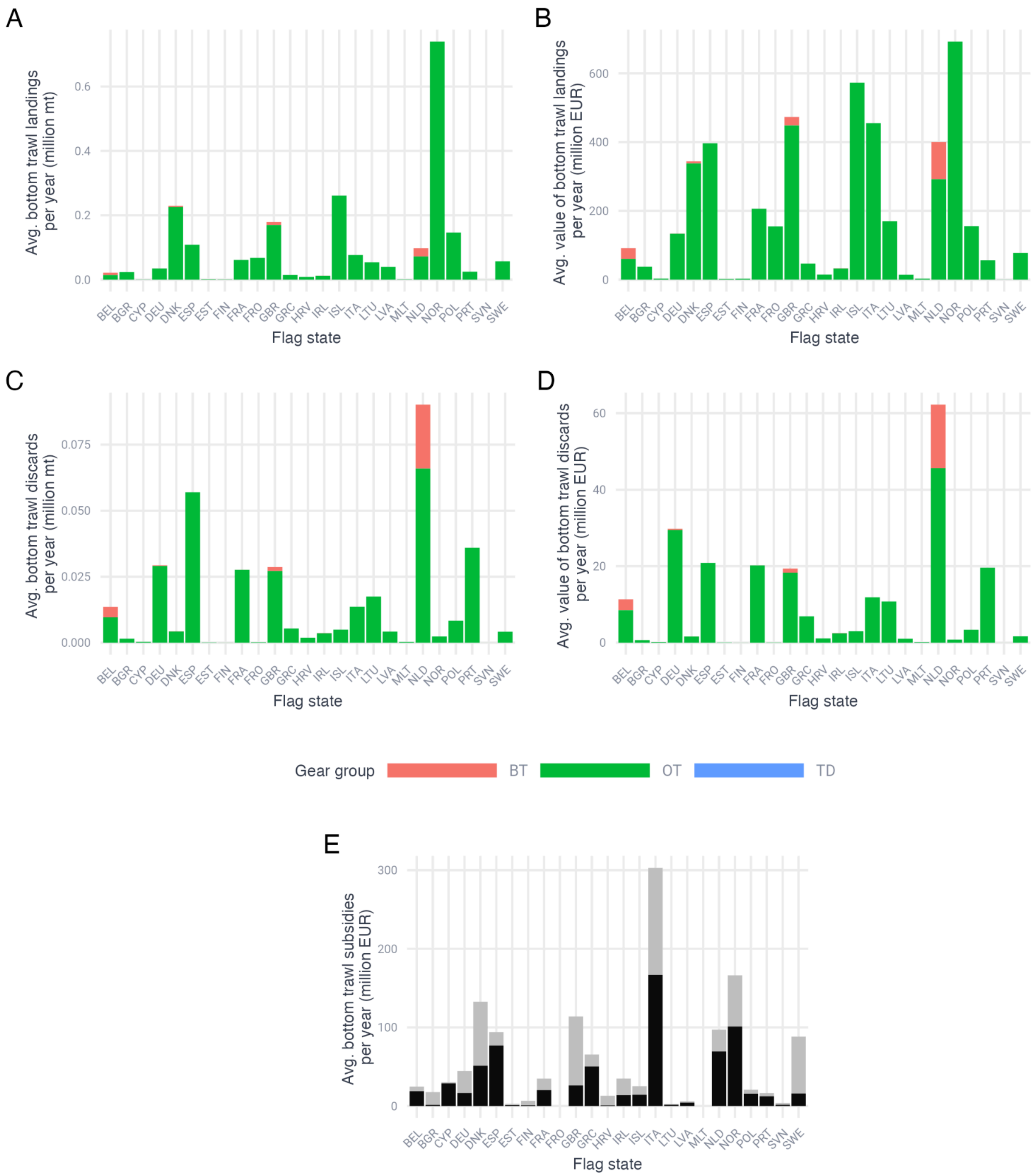


Fig. S3

Average annual bottom trawl (A) catches, (B) landed value, (C) discards, (D) discard value, and (E) subsidies by flag state attributed to study area (2016 - 2021). Bars in panels A-D are colored by gear group. The light gray shaded portion of bars in panel E represent capacity-enhancing subsidies, the black shaded portion represents other subsidies.

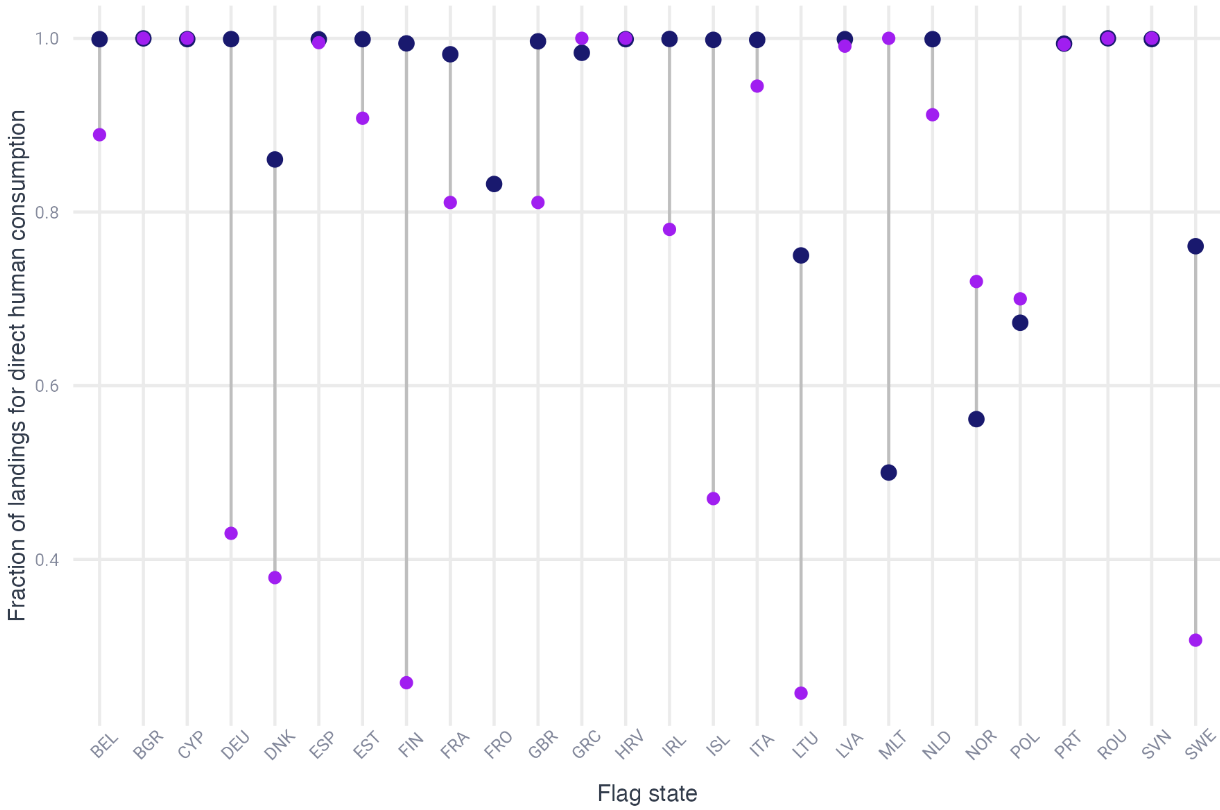


Fig. S4

Estimated fraction of catches going to direct human consumption by flag state. Blue points represent the average across all years (2016-2021) for bottom trawlers fishing within the study area from SAU. Purple points represent the average for all gear types by flag state from EuroStat.

Fig. S5

Average daily prices of marine diesel oil and marine gas oil from Bunker Index for Europe, the Middle East, and Africa (EMEA) (2013 - 2022).

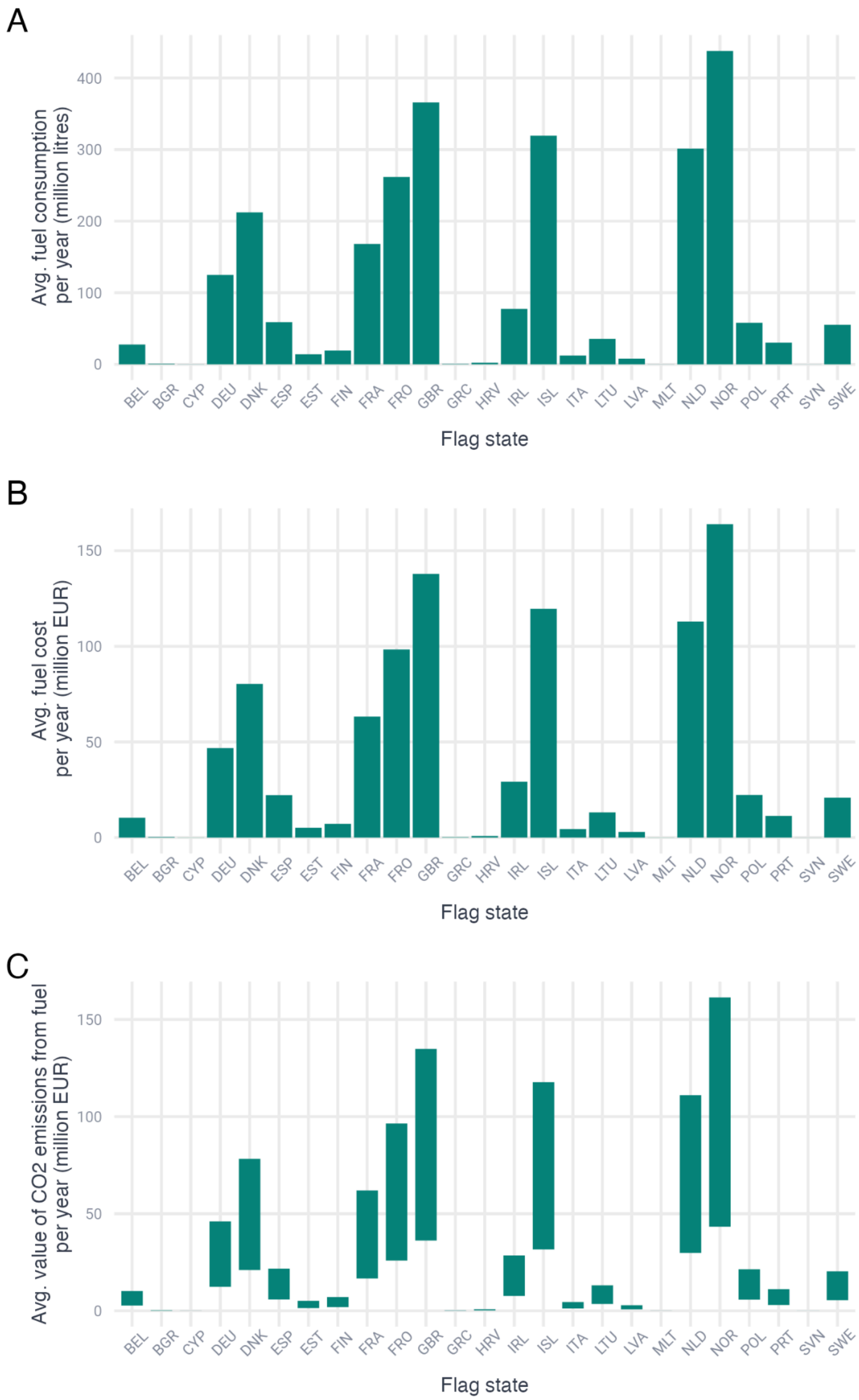


Fig. S6

Average annual (A) fuel consumption, (B) costs, and (C) CO_2 emissions from fuel by flag state for bottom trawling activity within study area (2016 - 2021). Ranges associated with the value of CO_2 emissions (C) stem from high (€161/mt) versus low (€43/mt) assumed social costs of carbon.

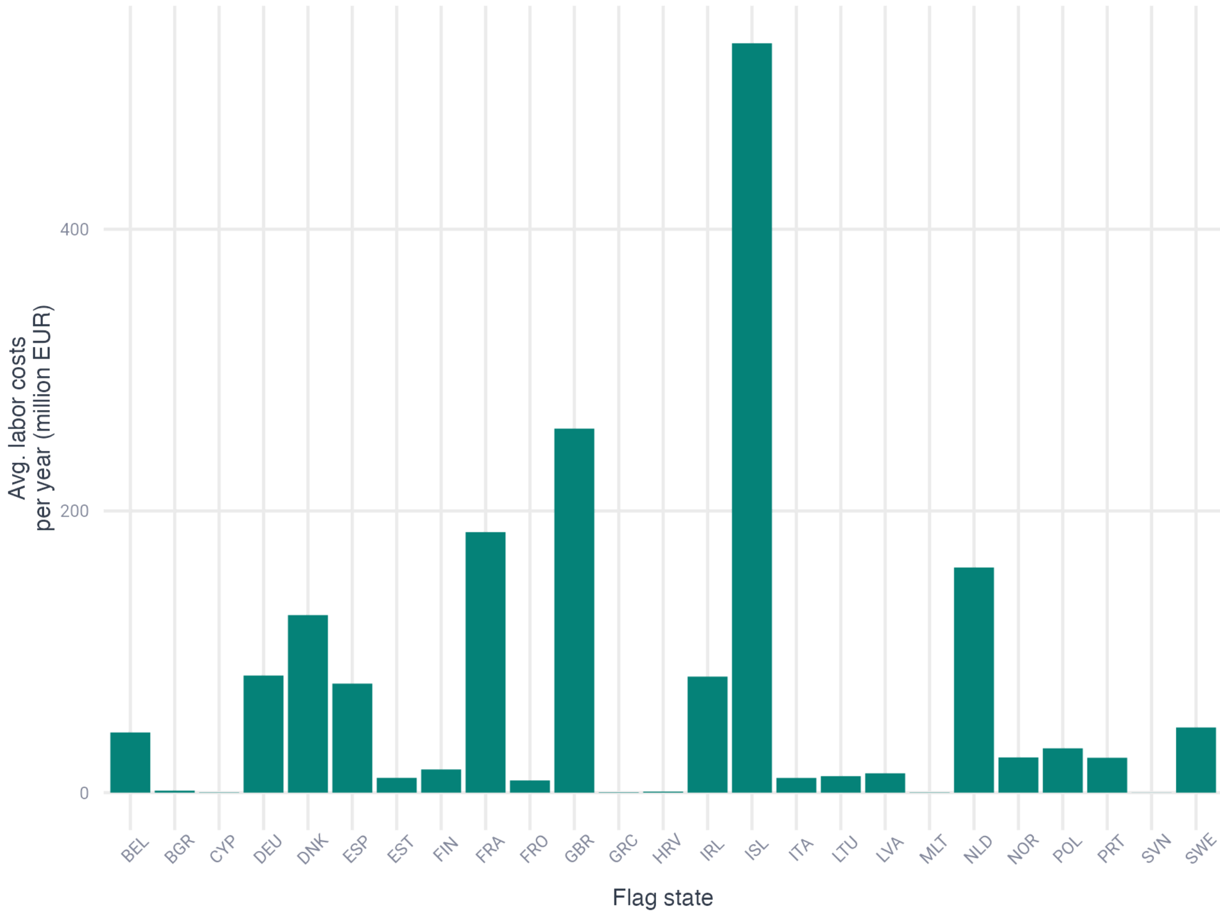


Fig. S7

Average annual labor cost by flag state for bottom trawling activity within study area (2016 - 2021).

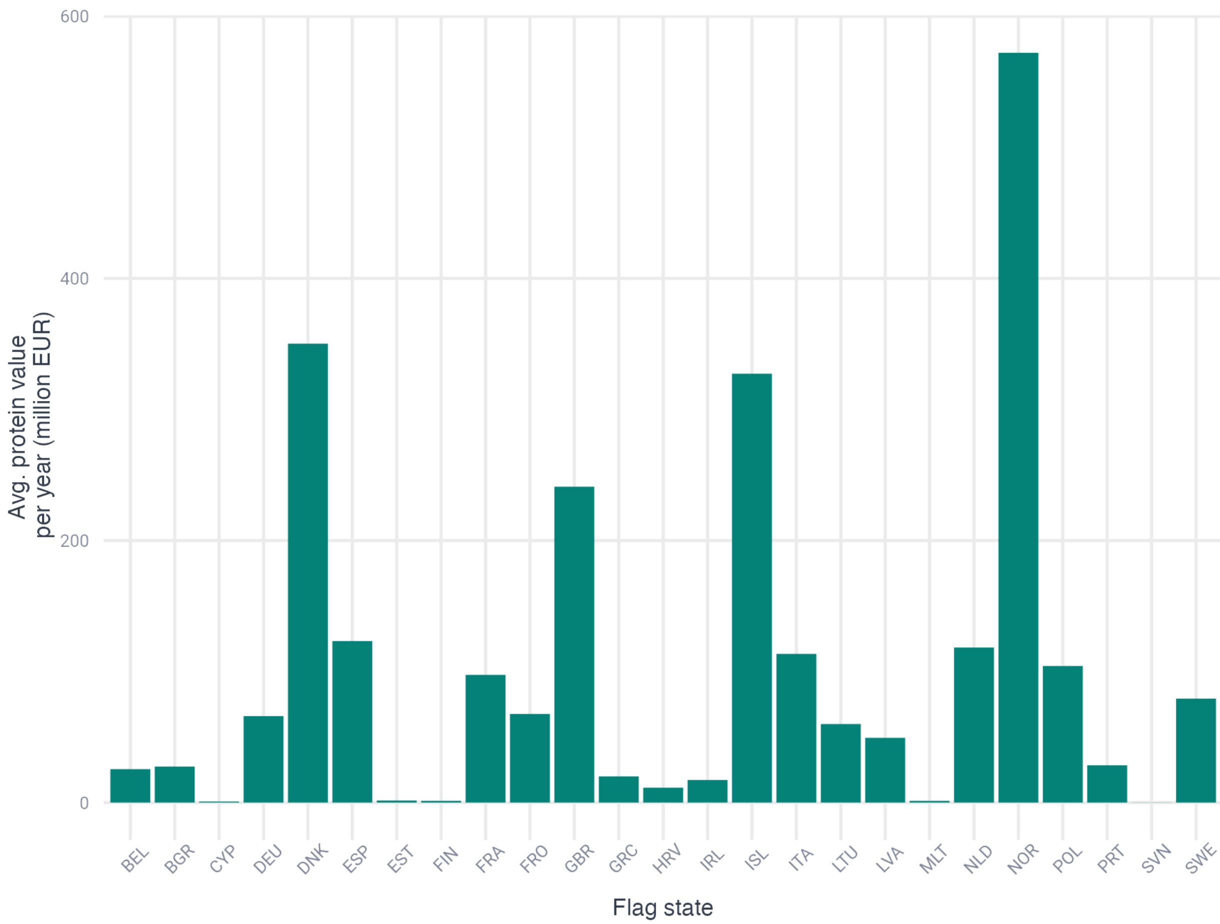


Fig. S8

Average annual value of protein produced by flag state for bottom trawling activity in study area (2016 - 2021).

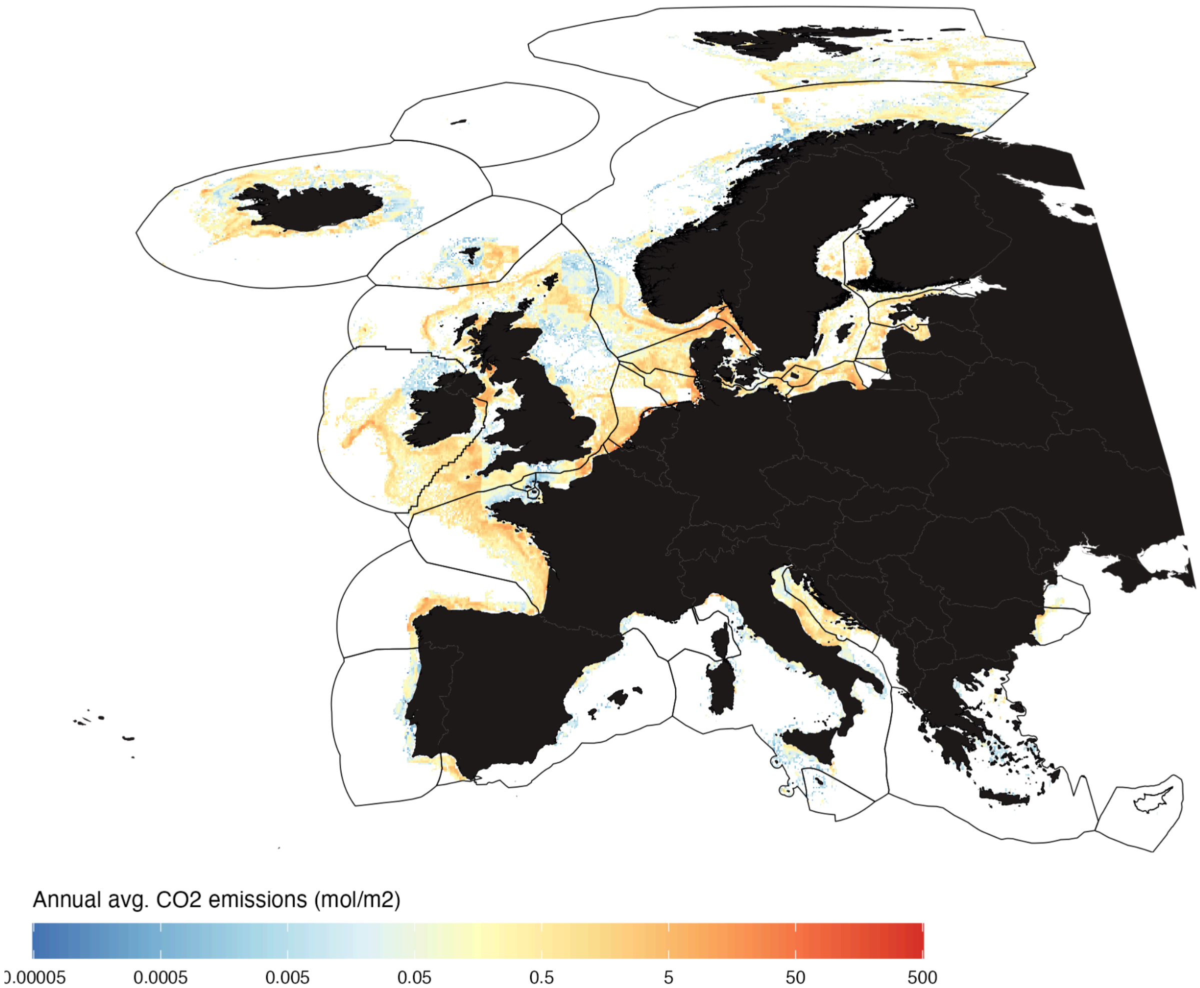
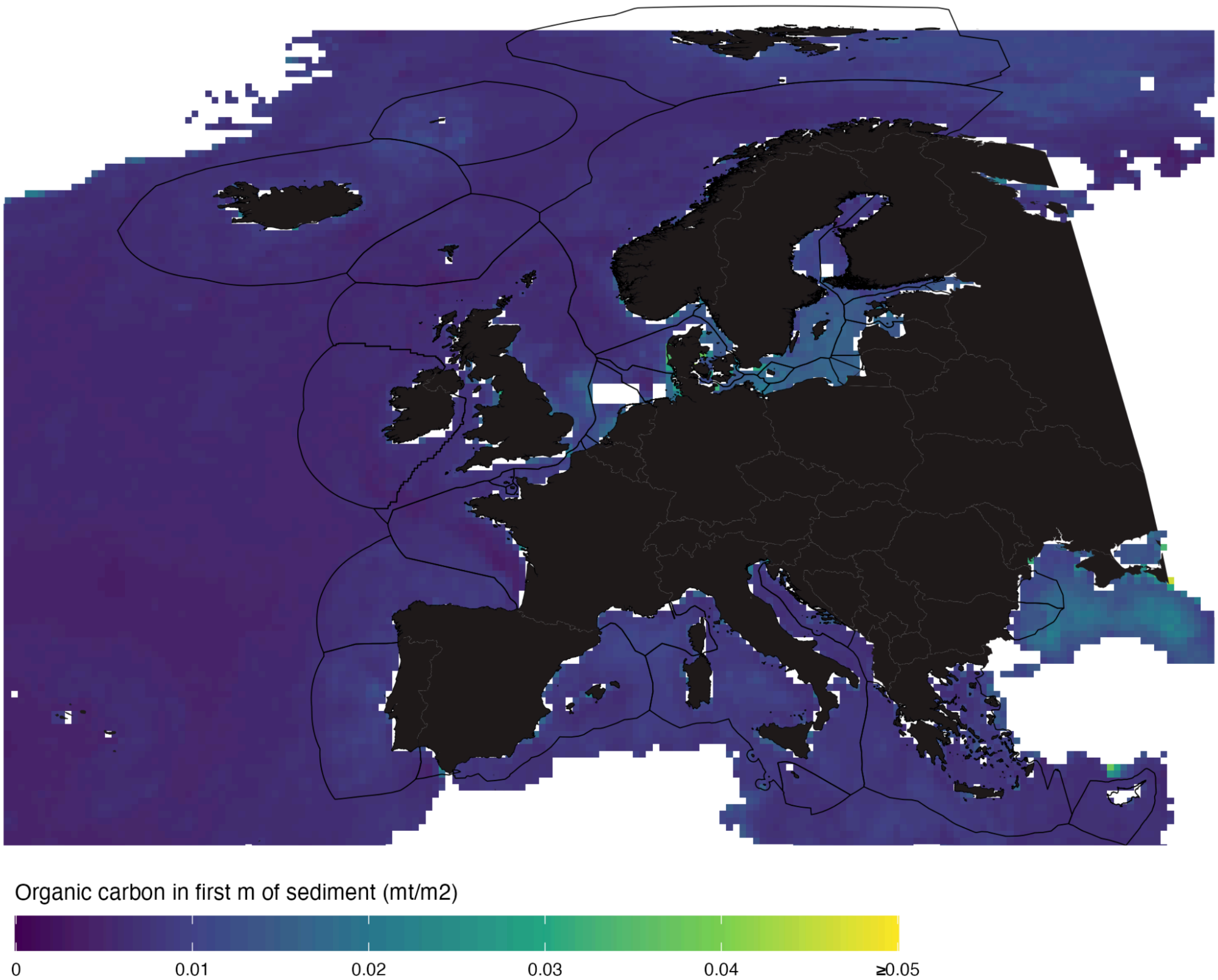


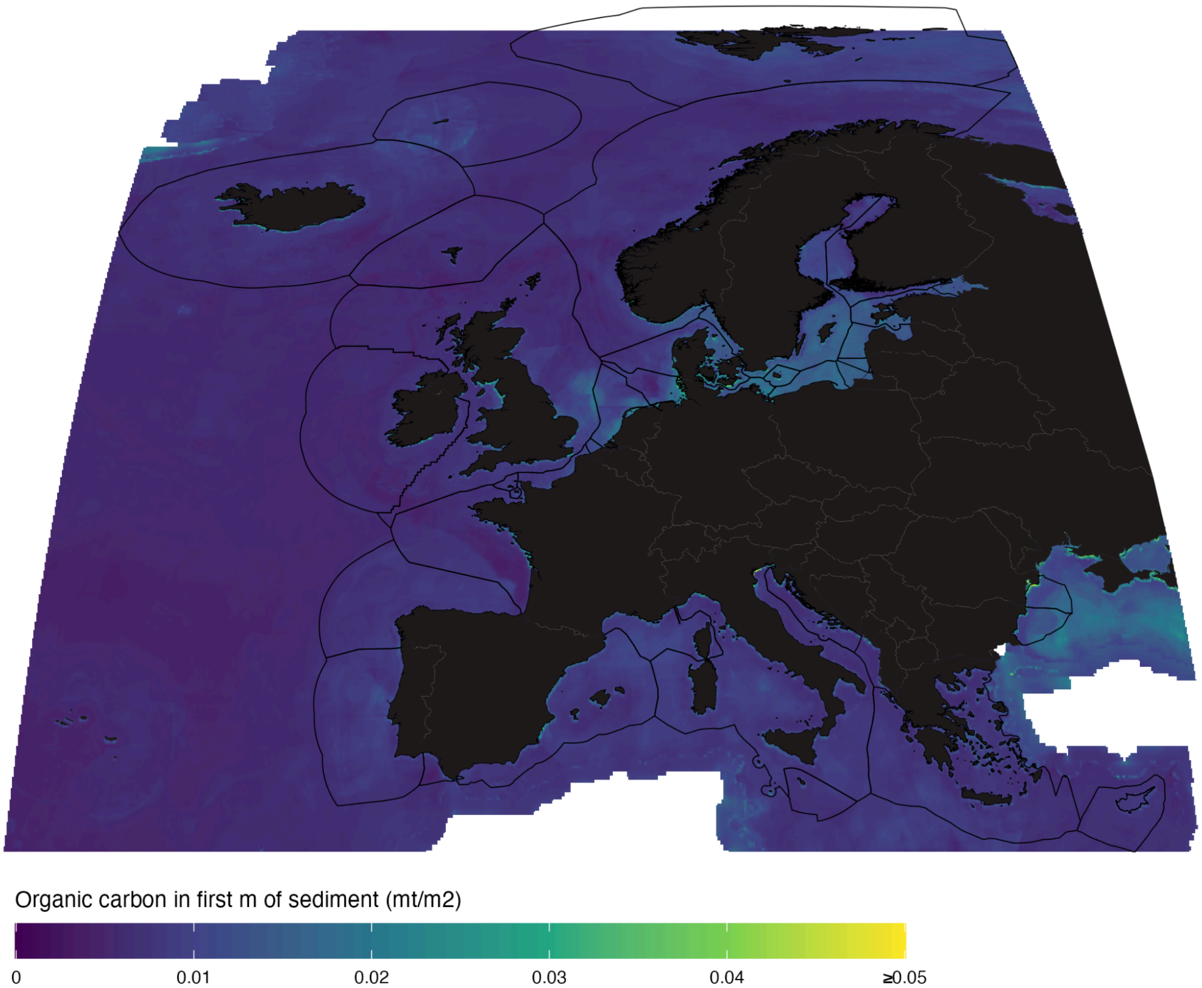
Fig. S9

Average annual atmospheric CO_2 emissions per pixel (0.1 x 0.1 degree) from disturbed sedimentary carbon as a result of bottom trawling activity in study area (2016 - 2021).



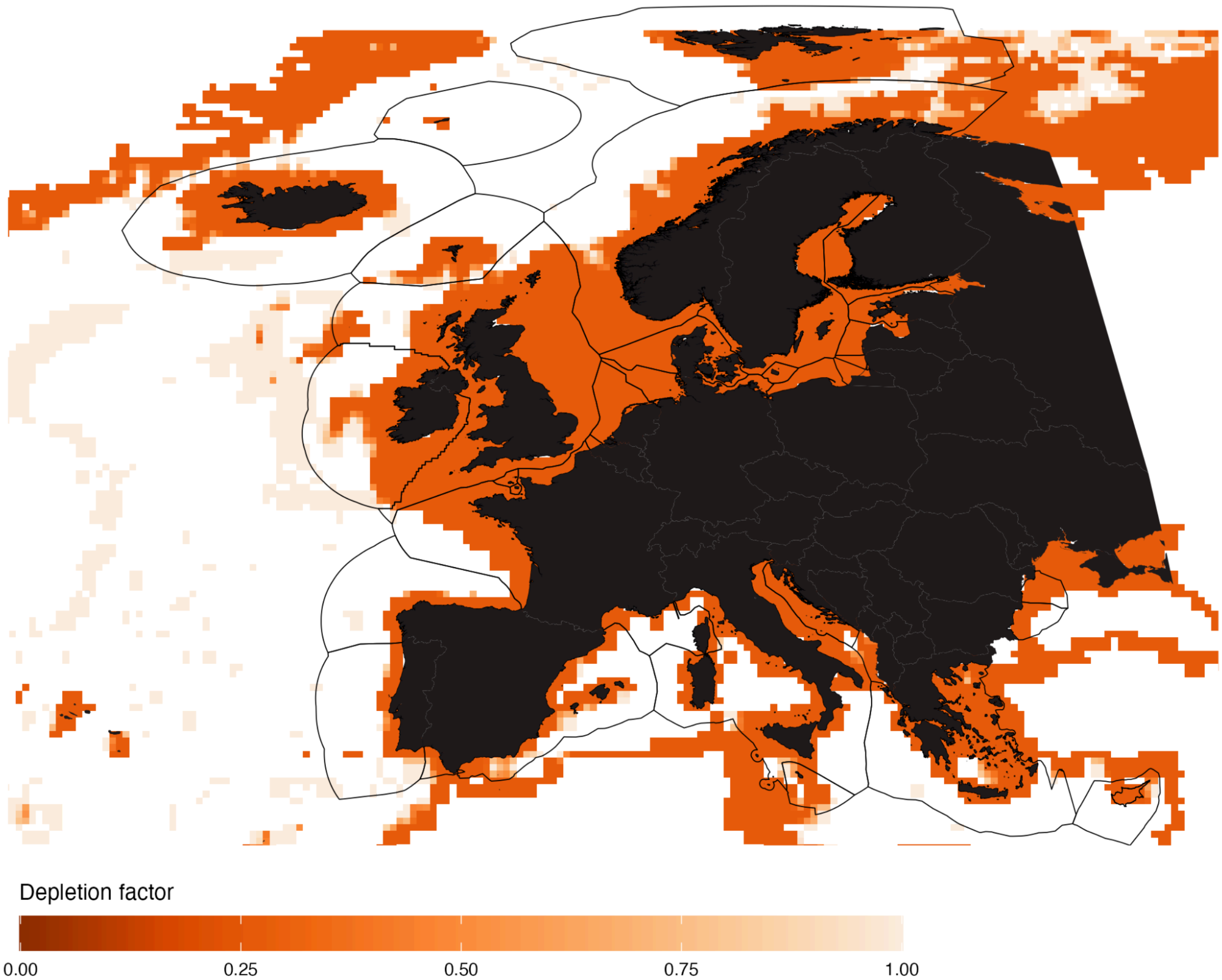
S10.

Organic carbon stores in the first meter of sediment (mt/m^2). Source: Atwood et al. (11).



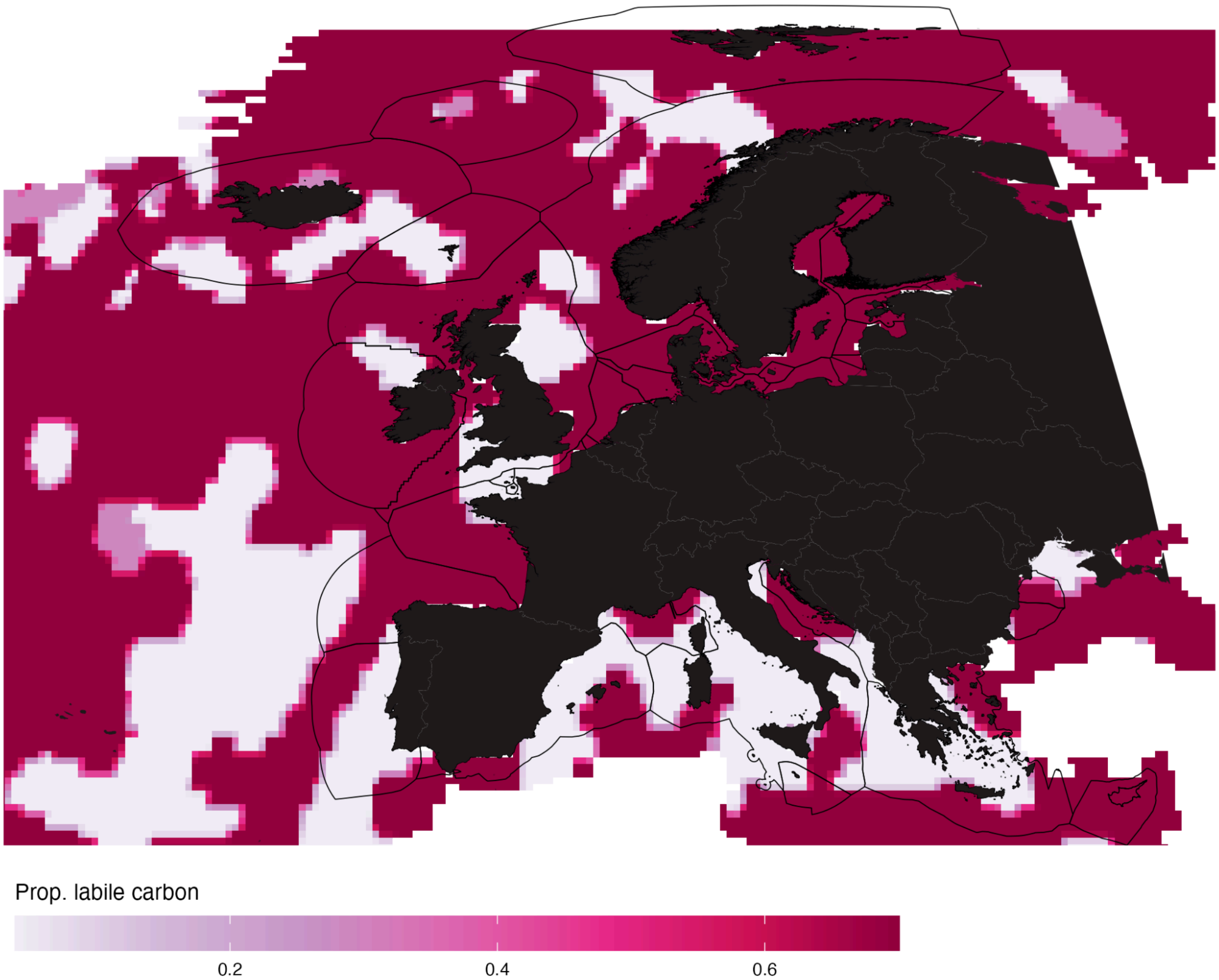
S11.

Interpolated organic carbon stores in the first meter of sediment (mt/m^2). Interpolation was done using a moving-window average with a 150 x 150 pixel grid. Original data from Atwood et al. (11).



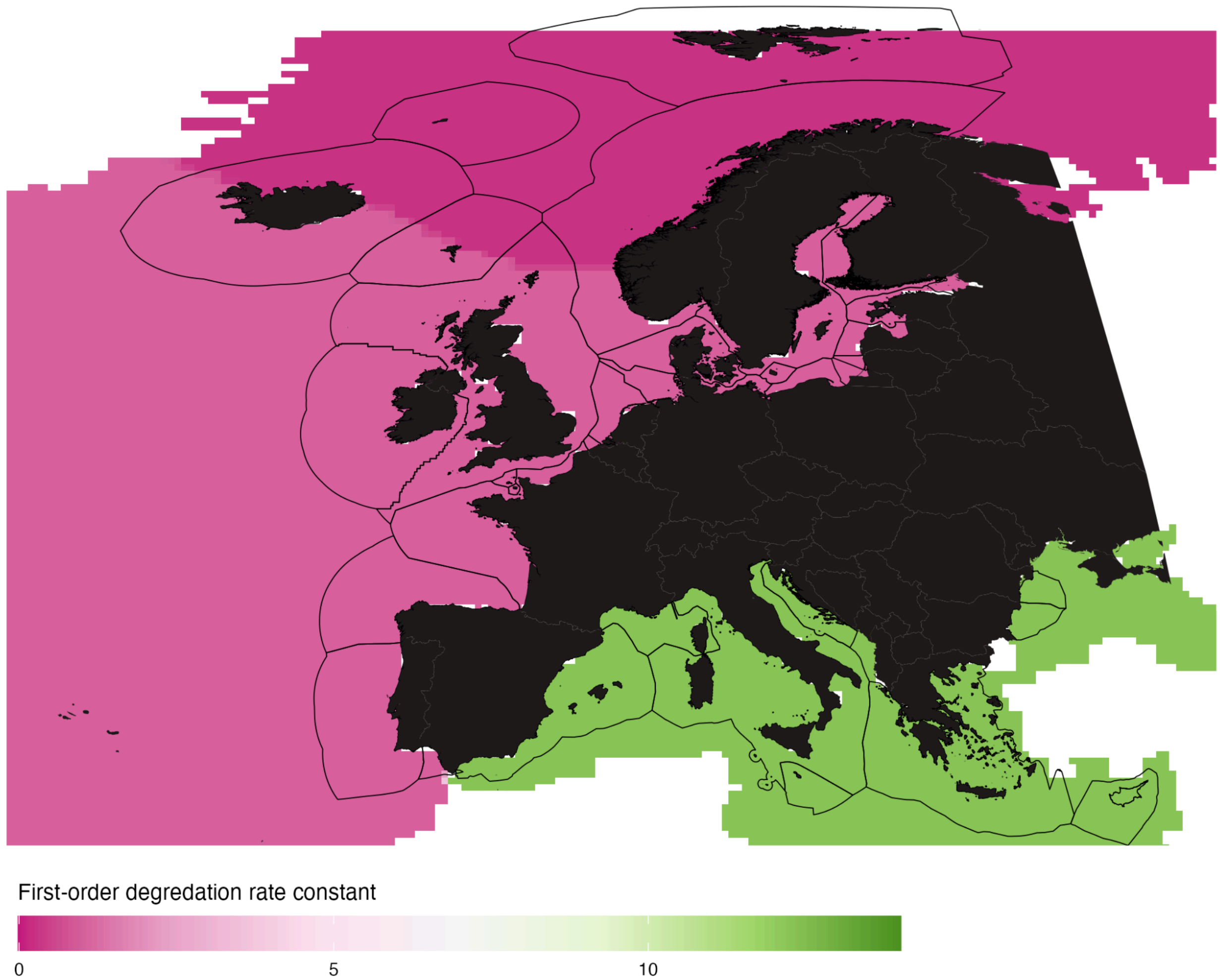
S12.

Organic carbon depletion factors to account for historical trawling activity. Source: Atwood et al. (11).



S13.

Fraction of organic carbon assumed to be labile based on sediment type: fine sediments: 0.7, coarse sediments: 0.286, and sandy sediments: 0.04. Source: Sala et al. (12).



S14.

Reference case first order degradation rates (*k*) from literature reported values. These values were based on oceanic regions using the best available values from the literature as follows: North Pacific = 1.67, South Pacific = 3.84, Atlantic = 1.00, Indian = 4.76, Mediterranean = 12.3, Arctic = 0.275, Gulf of Mexico and Caribbean = 16.8. Sources: Sala et al. (12) and Atwood et al. (13).

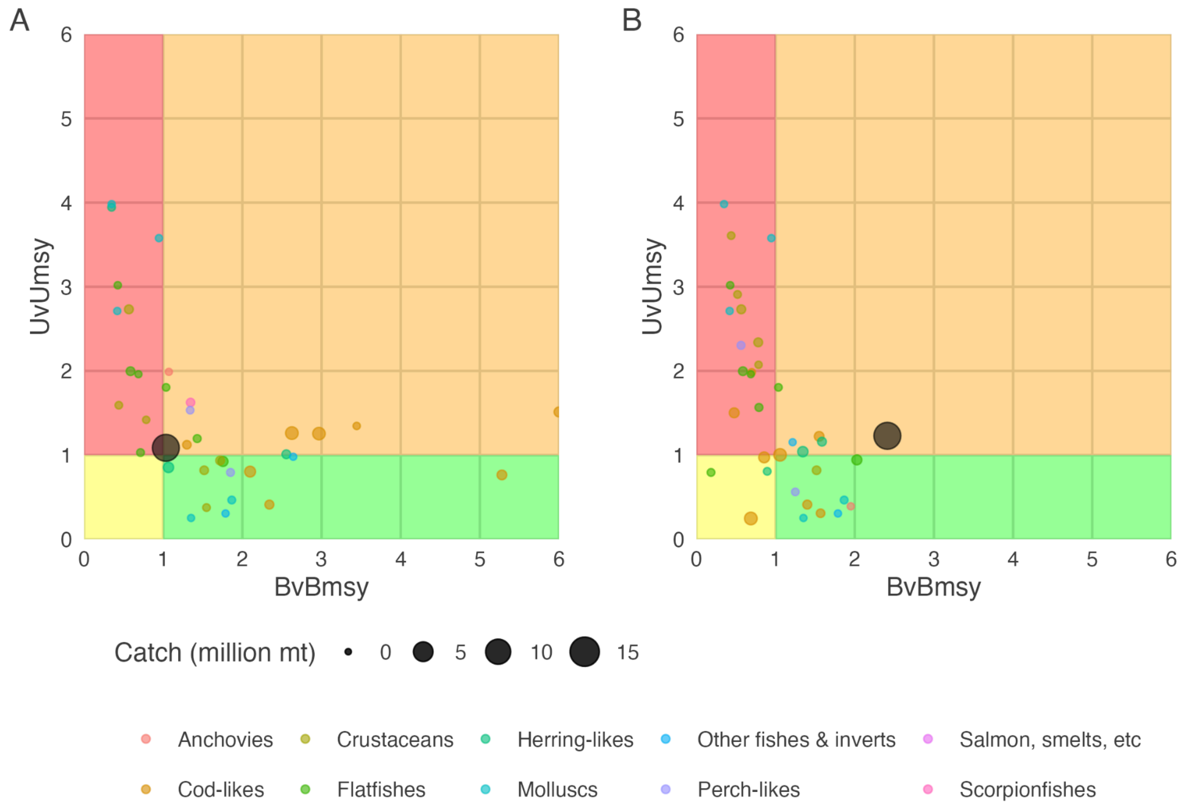


Fig. S15.

Statuses of the composite species making up the aggregate trawlfish stock under the (A) reference and (B) alternative scenarios. The dark gray point shows the catch-weighted mean status of the aggregate stock.

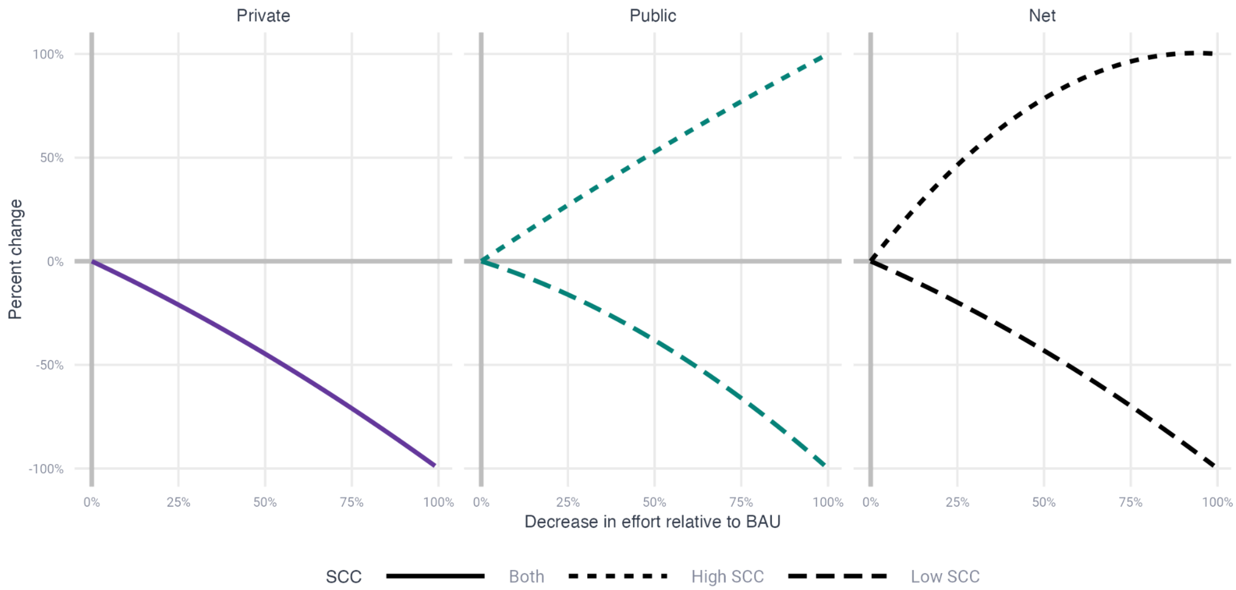


Fig. S16.

Projection model results for the alternative scenario.

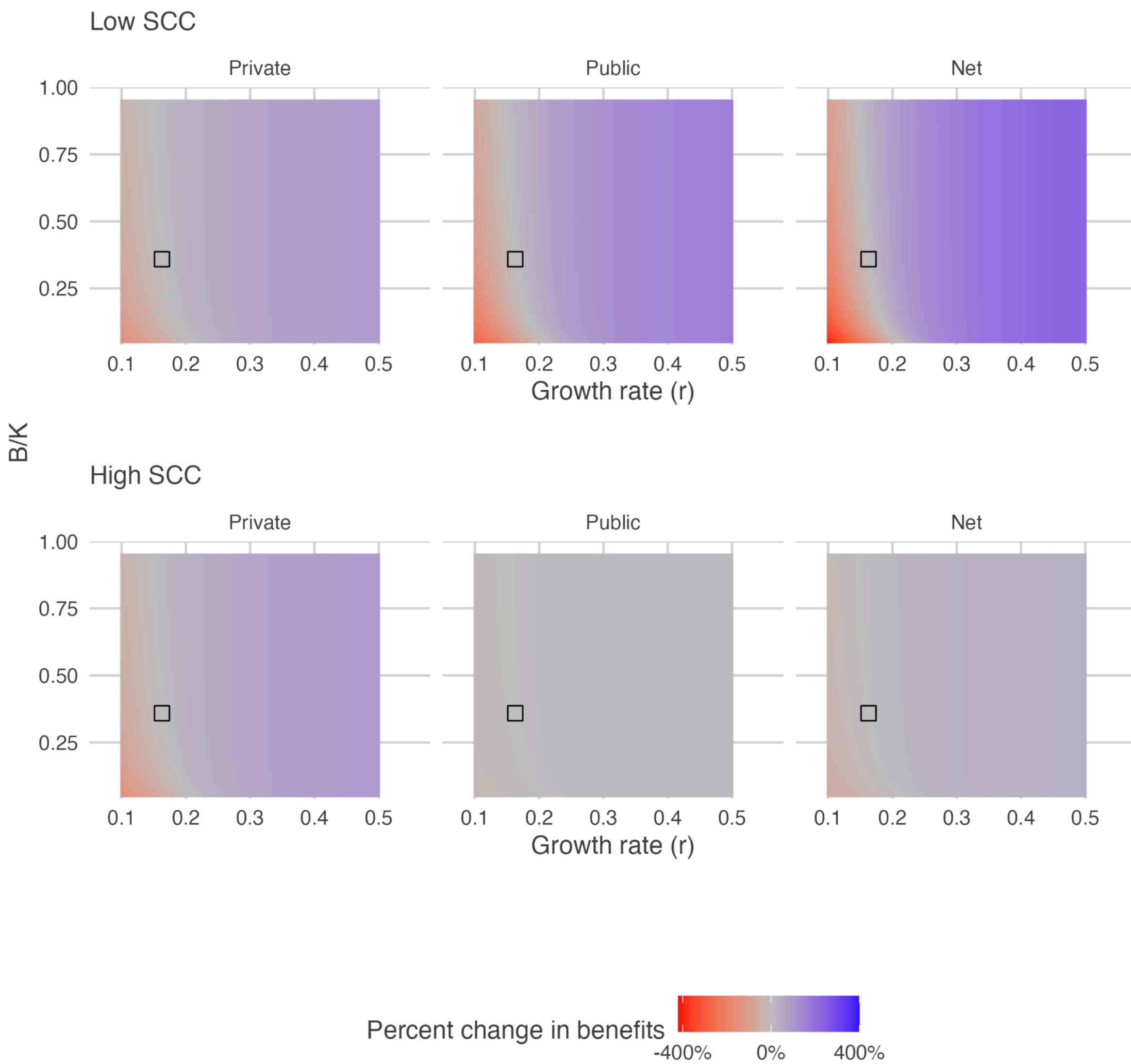


Fig. S17.

Sensitivity analysis of reference case simulation results to biological input parameters. Outcomes arising from variation in population growth rate (r) and starting biomass relative to carrying capacity (B/K) are shown. Outcomes from the reference case scenario are denoted by the black squares. Sensitivity is shown for both the low and high SCC scenarios.

Supplementary Tables

Table S1.

Number of bottom trawl and dredge vessels by year and gear group included in final vessel sample.

Year	Beam trawlers (BT)	Otter trawlers (OT)	Dredges (TD)	Total
2016	199	3114	1	**3314**
2017	204	3176	3	**3383**
2018	208	3068	3	**3279**
2019	210	3084	2	**3296**
2020	207	3025	1	**3233**
2021	211	3017	2	**3230**

Table S2.

Number of bottom trawl and dredge vessels by year and flag state included in final vessel sample.

Flag state	Beam trawlers (BT)	Otter trawlers (OT)	Dredges (TD)	Total
BEL	20	62	-	**82**
BGR	-	27	-	**27**
CYP	-	2	-	**2**
DEU	9	238	1	**248**
DNK	12	350	-	**362**
ESP	-	343	-	**343**
EST	-	39	-	**39**
FIN	-	61	-	**61**
FRA	1	665	1	**667**
FRO	-	71	-	**71**
GBR	28	758	1	**787**
GRC	-	7	-	**7**
HRV	-	46	-	**46**
IRL	6	203	-	**209**
ISL	-	113	-	**113**
ITA	-	250	-	**250**
LTU	-	31	-	**31**
LVA	-	60	-	**60**
MLT	-	2	-	**2**
NLD	148	158	-	**306**
NOR	-	209	-	**209**
POL	-	158	-	**158**
PRT	-	95	-	**95**
SVN	-	3	-	**3**
SWE	-	189	-	**189**

Table S3.

Average vessel characteristics by year across all vessels in the final sample.

Year	Length (m)	GT	Main engine power (kW)	Aux. engine power(kW)	Design speed (knots)	Gear width (m)
2016	30.50	475.03	880.79	365.29	10.70	64.24
2017	30.63	489.90	898.42	375.66	10.68	64.20
2018	30.65	500.15	908.69	385.69	10.67	64.16
2019	30.77	513.62	937.42	399.94	10.66	64.71
2020	30.69	519.62	947.96	405.72	10.65	64.56
2021	31.01	543.20	979.60	416.04	10.61	64.65

Table S4.

Average vessel characteristics by gear group across all vessels in the final sample.

Flag state	Length (m)	GT	Main engine power (kW)	Aux. engine power(kW)	Design speed (knots)	Gear width (m)
BEL	30.97	243.82	772.54	230.62	11.10	51.87
BGR	15.21	25.92	171.41	73.04	10.67	47.22
CYP	24.85	116.39	331.83	82.78	10.84	57.75
DEU	34.14	815.54	957.14	416.63	10.46	64.72
DNK	29.87	470.07	924.05	407.71	10.66	66.88
ESP	31.84	390.82	536.99	280.13	10.88	61.19
EST	33.04	506.80	967.37	317.30	10.48	68.14
FIN	30.48	263.11	780.67	285.19	11.13	72.55
FRA	22.19	206.69	496.02	172.46	10.88	61.71
FRO	59.20	1800.13	3360.05	1447.98	9.06	107.35
GBR	26.94	423.51	854.63	362.03	10.57	62.43
GRC	28.79	133.80	355.95	146.27	10.85	58.71
HRV	19.36	52.97	245.60	41.41	10.75	52.52
IRL	29.59	343.73	788.39	310.23	10.93	68.17
ISL	55.08	1548.88	2675.40	1154.50	9.80	100.94
ITA	18.80	50.82	254.36	61.95	10.75	52.13
LTU	41.66	1109.44	1461.82	471.47	10.33	72.95
LVA	25.38	166.22	375.31	97.02	10.84	57.66
MLT	22.29	128.92	358.55	92.03	10.86	59.08
NLD	35.99	685.16	1001.54	530.61	10.67	46.10
NOR	42.58	1145.24	2123.38	906.87	10.06	90.35
POL	25.51	352.28	537.77	219.70	10.72	59.00
PRT	35.82	553.50	822.32	462.50	11.02	71.50
SVN	11.81	8.55	192.24	101.62	10.70	49.52
SWE	27.40	315.16	895.96	295.11	10.86	69.90

Table S5.

AIS-derived estimates of average annual fishing effort by flag state (2016 - 2021)

Flag state	Fishing hours	Fishing kWh (million)
BEL	55,937	29.21
BGR	6,788	1.14
CYP	60	0.02
DEU	126,616	68.50
DNK	322,770	148.80
ESP	317,374	109.49
EST	24,001	23.55
FIN	38,951	33.09
FRA	765,138	356.87
FRO	109,763	171.04
GBR	548,839	225.25
GRC	4,199	1.46
HRV	23,773	6.37
IRL	192,099	80.62
ISL	151,549	287.50
ITA	131,206	30.60
LTU	12,582	14.70
LVA	28,753	8.70
MLT	747	0.24
NLD	316,332	111.85
NOR	163,689	508.45
POL	80,834	34.37
PRT	113,010	55.11
SVN	1,228	0.23
SWE	83,944	48.08

Table S6.

Carbon tax rates in European countries from the World Bank's carbon pricing dashboard. Values were as of March 31, 2023. The emissions trading scheme (ETS) price is subject to daily changes and this may not reflect its current value. Tax rates were converted using the EUR-USD rate of 0.9186.

Country	Carbon tax rate (per ton of CO_2 emitted)	
	Euros (€)	U.S. Dollars ($)
Austria	32.50	35.38
Denmark	24.37	26.53
Estonia	2.00	2.18
Finland	76.92	83.74
France	44.55	48.50
Germany	30.00	35.38
Iceland	35.40	38.53
Ireland	48.45	52.74
Latvia	14.98	16.31
Liechtenstein	120.16	130.81
Luxembourg	44.19	48.11
Netherlands	51.07	55.59
Norway	83.47	90.86
Poland	13.27	14.44
Portugal	23.90	26.01
Slovenia	17.30	18.83
Spain	14.98	16.31
Sweden	115.34	125.56
Switzerland	120.16	130.81
Ukraine	0.75	0.82
United Kingdom	20.46	22.28
EU ETS (for reference)	***88.46***	***96.30***

Table S7.

Stock and life history parameters for relevant bottom trawl species from the Ram Legacy Stock Assessment Database.

Scientific name	Common name	NE Atlantic	Med. & Black Sea	B	B/B_{MSY}	MSY (mt)	r	K (mt)
Trachurus picturatus	Blue jack mackerel	✓					0.43	17133.46
Trachurus trachurus	Horse mackerel	✓		1070000	0.86		0.43	300114.94
Scomber scombrus	Mackerel	✓		4750000	1.34		0.45	1135994.61
Nephrops norvegicus	Norway lobster	✓	✓	3242.6	0.38			
Engraulis encrasicolus	Anchovy	✓	✓	610170	0.96	2359	0.62	8141.76
Sardina pilchardus	European pilchard [Sardine]	✓	✓	1018300	0.4	5307	0.59	92181.4
Clupea harengus	Herring	✓		11973300	1.05		0.45	832120.4
Sprattus sprattus	Sprat	✓	✓	4540000	2.64		0.5	607323.73
Gadus morhua	Atlantic cod	✓		4505501	1.93	33300	0.52	432447.79
Micromesistius poutassou	Blue whiting	✓	✓	8540000	2.63		0.49	1157978.32
Melanogrammus aeglefinus	Haddock	✓		1593100	3.29	44000	0.52	202471.79
Merluccius merluccius	Hake	✓	✓	401200	4.48		0.52	113357.49
Molva molva	Ling	✓		56100	3.44		0.49	184.23
Trisopterus esmarkii	Norway pout	✓		497000	2.34		0.63	1733.89
Pollachius virens	Pollock [Saithe]	✓		1685000	2.24	265000	0.5	260960.1
Merlangius merlangus	Whiting	✓	✓	397640	0.8	21000	0.52	49206.99
Lophius piscatorius	White anglerfish	✓	✓	137300	2.28		0.49	76981.36
Solea solea	Common sole	✓	✓	114090	1.12		0.54	11090.24
Limanda limanda	Dab	✓		1.88			0.71	4577.41
Pleuronectes platessa	European Plaice	✓		1097955	2.25		0.52	13107.78
Platichthys flesus	European flounder	✓					0.6	39.5
Reinhardtius hippoglossoides	Greenland halibut	✓		666000			0.28	125980.29
Microstomus kitt	Lemon sole	✓					0.71	37.94
Scophthalmus maximus	Turbot	✓	✓				0.51	4684.14
Sebastes norvegicus	Golden redfish	✓		468400	1.35		0.26	568.32
Parapenaeus longirostris	Deep-water rose shrimp		✓	6091				
Pandalus borealis	Northern shrimp	✓		29402	1.46			
Squilla mantis	Spottail mantis shrimp		✓					

Table S8.

Stock and life history parameters for aggregate "trawlfish" stock under different scenarios.

Scenario	Biomass (million mt)	B/B_{MSY}	F/F_{MSY}	r	K (million mt)	B/K
REF	49.46	1.03	1.09	0.16	137.83	0.36
ALT	70.04	2.41	1.23	0.44	187.3	0.37

Table S9.

Atmospheric CO_2 emissions from disturbed sedimentary carbon by year under different first-order degradation rates (*k*) .

	CO2 emissions (mt)		CO2 value (low SCC, billion €)		CO2 value (high SCC, billion €)	
Year	10th k	k	10th k	k	10th k	k
2016	15,595,729	83,753,356	0.68	3.63	2.52	13.53
2017	15,069,732	82,930,190	0.65	3.60	2.43	13.39
2018	13,539,678	84,315,984	0.59	3.66	2.19	13.62
2019	13,110,401	80,583,619	0.57	3.49	2.12	13.01
2020	12,945,209	79,359,502	0.56	3.44	2.09	12.82
2021	13,654,035	83,458,861	0.59	3.62	2.21	13.48

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