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Carbon footprint, economic benefits and sustainable fishing: Lessons for the future from the Western Mediterranean

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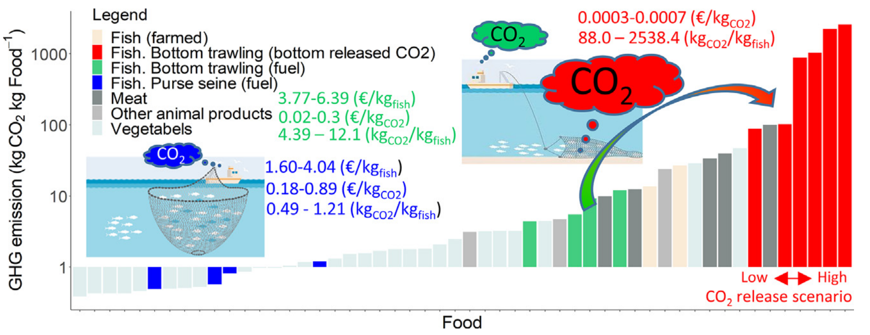
HIGHLIGHTS

- Fishery affects biosphere, hydrosphere, atmosphere and geosphere (bottom trawling).
- Labile carbon release from the seafloor by bottom trawling overrides the biological pump.
- CO_2 footprint of bottom trawling food production is the highest.
- €/kg fish is higher for bottom trawling than purse seine but net profit is similar.
- €/CO_2 emission is higher for purse seiners than for bottom trawlers.

GRAPHICAL ABSTRACT



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ABSTRACT

Ensuring an economically viable, sustainable and low CO_2 emission extractive fishery is critical in order to achieve the life below water UN sustainable development goals and the climate change commitments of Paris agreement. This challenge is even more relevant in the most overexploited region of the world: The Mediterranean Sea. Here, we use the socio-ecological system of the Spanish Mediterranean commercial fisheries (Northern Alboran Sea, Northern Spain and the Balearic Islands) to develop an integrative impact assessment, including detailed socio-economic, ecosystem indices of the trophic structure of extractive fishery and CO_2 emission analyses combining different gear, vessel size classes as well as a wide range estimation of carbon release from the seafloor by bottom trawling. Northern Alboran Sea preferentially requires reduction in purse seine fishery while in Northern Spain bottom trawling should be reduced first to reach sustainable exploitation. Fuel CO_2 footprint of purse seine and bottom trawling are among the lowest footprints of animal protein production, but considering sweeping released CO_2 from the seafloor the bottom trawling footprint becomes the animal protein production with the highest footprint. Moreover, the lowest bottom released CO_2 estimation overrides 2.7–10 times the CO_2 buried in the seafloor through the biological pump in trawled areas potentially turning the continental shelf from a CO_2 sink to a CO_2 source. Net profit per fuel derived CO_2 emission for all fleets is lower than 1€ $kgCO_2^{-1}$, being lowest for large bottom trawler (0.025 € $kgCO_2^{-1}$).

Thus, urgent mitigation and adaptation measures are necessary to obtain sustainable fishery in terms of net profit, sustainable seafood extraction and CO_2 emission reduction. Our study provides scientific bases to develop these measures such as the restriction of harmful fishing gear in carbon rich river influenced areas, reduction of bottom contact of the fishing gear, favouring purse seine fishery and smaller bottom trawlers.

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1. Introduction

Fish protein is an important food supply for human consumption from regional to global scales (Tacon and Metian, 2013; Hua et al., 2019). However, most of the target species are overexploited (Worm et al., 2006; Branch et al., 2011; FAO, 2020a), global fish stock recovery is uncertain (Britten et al., 2021) and down fishing of marine food webs occurs in many large ecosystems (Pauly, 2007; Piroddi et al., 2017). Moreover, the maintenance of landed fish at global scale is achieved by increasing fishing effort and Catch Per Unit Effort (CPUE) decreases (Rousseau et al., 2019), leading to increasing energy requirement and CO_2 footprint ($kgCO_2\ kg_{fish}^{-1}$).

Since the nineties, the landings stagnated while CO_2 emissions continued to increase (Greer et al., 2019), reducing benefits by increasing fuel cost and enhancing CO_2 emission. In fact, most extractive fishery in national waters is not lucrative and requires subsidies, which reached 35 billion USD at global scale in 2009, where the greatest subsidised part was fuel (22 %, Sumaila et al., 2016). Among the developed fishing countries, Spain subsidised extractive fishery with almost 1,5 billion USD (Sumaila et al., 2016), the greatest amount belonging to capacity enhancing subsidies that incentivise overfishing (e.g., fuel subsidies, Sumaila et al., 2019). Fuel subsidy is classified as harmful (Sumaila et al., 2019; Vargas-Machado et al., 2021), and numerous authors suggest that incentivising overcapacity should be banned by the World Trade Organization (Sumaila et al., 2021). Global CO_2 emission due to fishery fuel consumption increased from 1950 by factor 4.1 reaching 159 million tons of CO_2 in 2016 with a CO_2 footprint ($tCO_2\ tCatch^{-1}$) around 1.5 (Greer et al., 2019). The CO_2 footprint of food production is becoming an important issue (Poore and Nemecek, 2018; Sandström et al., 2018), especially for animal protein provisions that are in the spotlight due to relatively high CO_2 footprints. Some footprint studies include fish or seafood diet (Scarborough et al., 2014; Ridoutt et al., 2021). However, the CO_2 footprint of extractive fishery depends on the fishing gear and vessel size, but detailed information about extractive fishery CO_2 footprint is lacking but necessary for management purposes.

On the one hand, extractive fishery affects the marine biomass carbon compartment, funnelling biomass from the marine food-web to land. This means a biomass and energy loss of the marine ecosystem, which can lead to unstable states of the naturally encountered food-web and limiting the resilient capacities of populations to recover (Hidalgo et al., 2022a). Primary Production Required (PPR) to maintain extractive fishery (Pauly and Christensen, 1995) in upwelling and shelf systems ranged in 1995 between 24 and 35 % of Net Primary Production (NPP, Pauly and Christensen, 1995), in the same year, global PPR reached 6×10^9 tonnes (Watson et al., 2014) and global landings stagnates around 93 million metric tons (World Bank, 2022). Keeping landings above 90 million metric tonnes since 1995 has been achieved by increasing fishing effort which limits economic performance of fisheries (Chassot et al., 2010; Marshak and Link, 2021). Thus, in order to achieve sustainable fishery and improve economic performances, the needed PPR for renewal of extracted biomass must be limited to an ecosystem sustainable level (Watson et al., 2014), which can be determined by the quantitative ecosystem index based on %PPR, the Trophic Level of the catch (TLc) and ecosystem-based reference functions (Tudela et al., 2005).

Beyond the fuel-derived CO_2 emissions and the biomass carbon compartment, an additional carbon compartment has recently been described to be seriously affected by bottom trawling; the carbon buried in the seafloor (Middelburg, 2019; Sala et al., 2021; Wang et al., 2021). Trawling releases buried carbon from the seafloor into the water column and labile carbon oxidises to CO_2 increasing partial CO_2 pressure in the water column (pCO_{2water}) reducing CO_2 absorption through the ocean (Sala et al., 2021) or even emitting CO_2 to the atmosphere if pCO_{2water} is greater than pCO_{2air}. On the other hand, the CO_2 fixed in the marine food-web settled and buried in the seafloor is known as CO_2 sequestration by the biological pump (Sabine et al., 2004; Honjo et al., 2008, 2014); one of the most promising mechanisms to mitigate human CO_2 emissions through fuel consumption into the atmosphere. However, this process can be ultimately counteracted by resuspension of buried carbon caused by any human activity, especially large areas affecting fishing gears with bottom contact. Thus, bottom trawling not only damages epibenthic organisms but also disturbs the first cm of the seafloor and alters biogeochemical processes (Middelburg, 2019), negatively affecting CO_2 storage in the ocean sea floor.

Therefore, besides the importance for human protein supply, global and local economy, fishery has also an important impact on the carbon cycle through different pathways: (i) fuel consumption, (ii) PPR to sustain carbon (fish biomass) extraction from the sea, (iii) Net Primary Production (NPP) derived biological pump and (iv) releasing CO_2 from the seafloor (bottom trawling). While PPR (Pauly, 2007), NPP (Watson et al., 2014), CO_2 emission through fuel consumption (Tyedmers et al., 2005) or carbon release from the seafloor (Sala et al., 2021) have been separately evaluated at global scale. There is no study to our knowledge integrating the four carbon compartments and socioeconomic indicators simultaneously. However, this is necessary in order to determine the complete CO_2 footprint of extracted proteins and whether fishery, in a given ecosystem, is climatically, ecologically and economically sustainable.

Fishing activity in the Mediterranean is mainly coastal and a high level of fishing activity leads to generalized overexploitation (Lucchetti et al., 2021), especially in European countries (Spain, France and Italy) that account for almost 60 % of fishery production (FAO, 2020b). The most important fleet in terms of numbers of boats is the small-scale fishery (82 %), although their landings only represent 15 % of total catches (FAO, 2020b). Half of the landings come from trawlers and beam trawlers (which represent 8 % in number of boats) and more than one quarter (27 %) from purse seiners (5 % in number of boats). Thus, up to 77 % from the catches come from the two latter fleets providing most of the extracted proteins and having the highest impact on the pelagic and demersal food-web. Here, we develop a detailed analysis of the bottom trawling and purse seine fleets operating at a sub-regional level in Spanish National waters of the Western Mediterranean (Fig. 1) characterized by decreasing productivity gradient from west to east and north (cost) to south. To carry out the study, information of the following Spanish Geographical Subareas (GSA) established by the General Fisheries Commission for the Mediterranean (GFCM) was considered: Northern Alboran Sea (GSA 1), Alboran Island (GSA 2), Balearic Islands (GSA 5) and Northern Spain (GSA 6). The specific objectives of our study were to:

i) determine the burnt fuel derived CO_2 emissions
ii) compare net profit among different fleets and their relationship to CO_2 emissions.
iii) benchmark and evaluation of the trophic sustainability of extractive fishery applying a composite quantitative ecosystem index.
iv) estimate the carbon release from the seafloor due to bottom trawling and evaluate its importance compared to biological pump sequestration.
v) provide CO_2 footprint per kg food of different extractive fishery gears and compare them with other industries that provide animal proteins for the human diet.

2. Methodology

The case study is carried out in the Spanish Mediterranean GSAs (Fig. 1), as they are recognized areas for fishery management and governance is provided by only one country. Socio-economic and landing data were acquired from the Scientific, Technical and Economic Committee for Fisheries (STECF) Annual Economic Report (AER) and related database (STECF AER, 2009-2020; STECF, 2020). Temporal 2008–2018 and resolution of fleet size classes (segments) were chosen according to data availability in the AER. Due to the lack of ports at GSA2 the landings from GSA2 are included in landings of GSA1.

2.1. Fuel derived CO_2 footprint

Socioeconomic indicators and fuel consumption of bottom trawling (DTS) and Purse Seine (PS) fishing fleet and segments (DTS1 = 6–12 m,

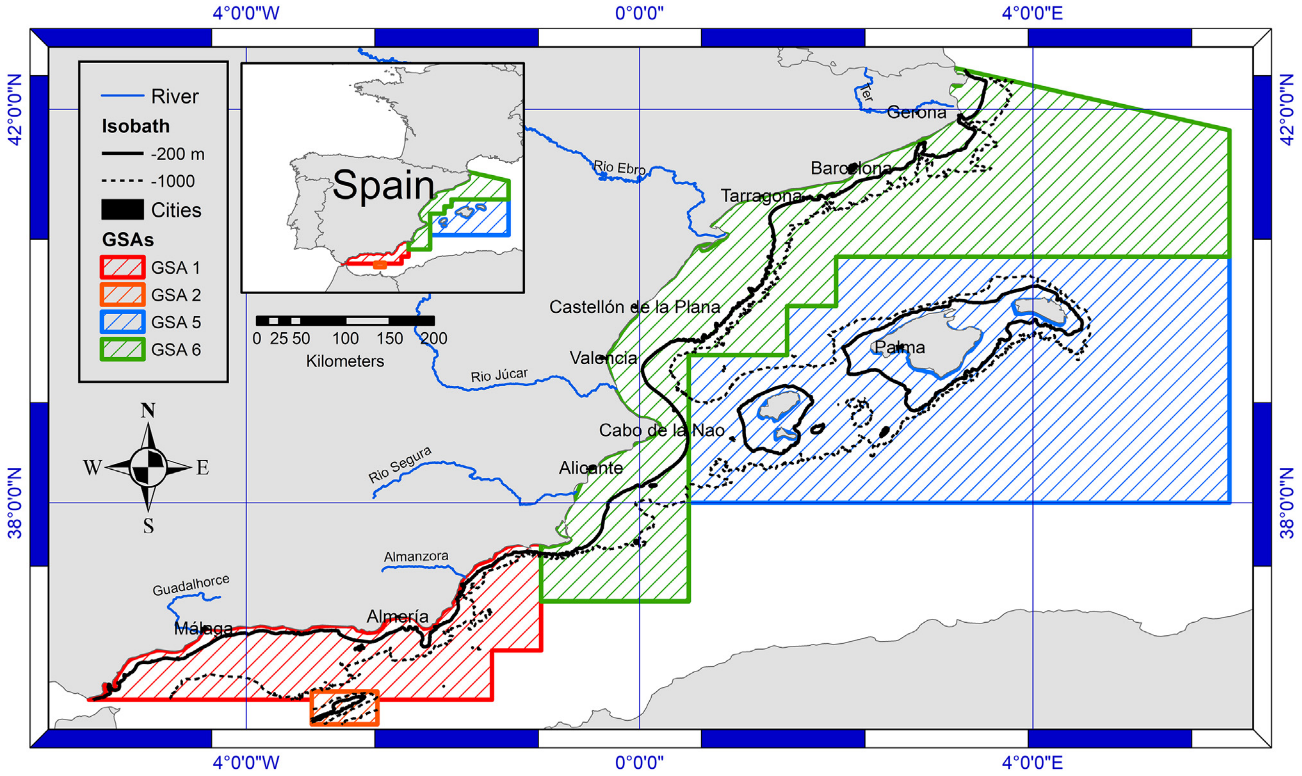


Fig. 1. Study area with the Spanish Geographical SubAreas (GSAs) considered in this study.

DTS2 = 12–18 m, DTS3 = 18–24 m, DTS4 = 24–40 m, PS1 = 6–12 m, PS2 = 12–18 m, PS3 = 18–24 m, PS4 = 24–40 m) were taken from the STECF AER annual reports 2009–2020 (STECF AER 2009-2020). Fish weight (kg) of the landed target species was taken from the AER annex data base (STECF AER 2009-2020). The Fuel Footprint of CO_2 in kg CO_2 per kg fish landed (FFP_{CO2} ($kg_{CO2}\ kg_{fish}^{-1}$)) was calculated, for each GSA and year, as:

$$FFP_{CO2} = \frac{L \times f}{LB} \tag{I}$$

where FFP_{CO2} is the fuel footprint of CO_2 per kg fish ($kg_{CO2}\ kg_{fish}^{-1}$). L = litre of fuel consumed per year by the fleet segment ($L\ yr^{-1}$); f is the conversion factor to convert litres of fuel (diesel) in kg CO_2 (2.61 kg_{CO2}/L_{fuel}) (GEI, 2011), LB is the sum of landed biomass by the fleet per year ($kg_{fish}\ yr^{-1}$).

2.2. Primary Production Required (PPR)

Primary Production Required (PPR) to sustain the landed fish was calculated according to Eq. (II) following Pauly and Christensen (1995) for each GSA_j (j = GSA1, GSA2, GSA5, GSA6), year, fishing gear and vessel size class.

$$PPR_{GSA_j} = \sum_{i=1}^{n} \frac{C_i}{CR} \times \left(\frac{1}{TE}\right)^{(TL_i - 1)} \tag{II}$$

where C_i is the wet weight of the species/genera (i) caught (kg), CR is the conversion factor of wet weight to carbon (9:1) (Pauly and Christensen, 1995), TE is the transfer efficiency between trophic level expressed in percentage (10 %) (Pauly and Christensen, 1995), TL_i is the trophic level of the species/genera (i) caught. Finally, for better comparison, for each GSA_j, PPR per km^2 was calculated dividing PPR_{GSAj} by km^2_{GSAj}. The area of each GSA_j was calculated for each shape file of Fig. 1 (GSA1 = 51,463 km^2, GSA2 = 3400 km^2, GSA5 = 191,244 km^2 GSA6 = 175,686 km^2).

Trophic Levels (TL) were taken from the estimated table of the fishbase and sealife databases (Froese and Pauly, 2022., Palomares and Pauly, 2022) applying the R-package rfishbase. Species not found in the mentioned bases were looked up in other data bases such as Sea Around Us (Pauly et al., 2020), and scientific articles (Beukhof et al., 2019; García and Contreras, 2011). Where trophic level at species level was not available, mean trophic level for the respective genera, family, order and class were calculated. The table with scientific names, english names, FAO species codes, assigned trophic level and reference/source for the 2843 items considered in this work can be found in supplementary material I (Trophic Level.xlsx).

2.3. Net Primary Production (NPP)

Daily 3D models between 2008 and 2018 of daily Net Primary Production (NPP) of the Mediterranean Sea were downloaded from Copernicus data server (Copernicus, 2021, Model: MEDSEA_MULTIYEAR_BGC_006_008). Yearly NPP in the fishing area per year was calculated for each GSA according to formulae III.

$$NPP_{GSA_j} = \int_0^{GSAj} \int_0^{T} \int_{zi}^{0} NPPd \tag{III}$$

where NPPd is the daily NPP of the 3D model, which was integrated down to the photic layer depth at each pixel (z_i = photic layer depth at pixel i), integrated over one year (T = 365 days) and then the pixels were integrated over the fishing area of each GSA_j, where j is GSA 1, 2, 5 and 6. Finally, for a better comparison, for each GSA, NPP per km^2 was calculated dividing NPP_{GSAj} by km^2_{GSAj}.

2.4. Composite quantitative ecosystem index

According to Tudela (2003) and Tudela et al. (2005) the sensitivity of an ecosystem to the effects of fishing depends on both, relative PPR (%PPR) and the Trophic Level of the catch (TLc). Tudela established %PPR-TLc reference function related to ecosystem overfishing probability, where lower TLc can be supported by lower %PPR. In order to evaluate sustainability of extractive fishery for each GSA and year the composite quantitative ecosystem index (%PPR - TLc) based on a biplot of %PPR and TLc was calculated and related to the sustainable exploitation reference function of ecosystem overfishing (Tudela et al., 2005). For each GSA and year %PPR and TLc was calculated applying the Eq. (IV) and Eq. (V) respectively.

$$\%PPR = \frac{PPR}{NPP} \times 100 \tag{IV}$$

$$TLc = \frac{\sum_{i=1}^{n} Bm_i \times TL_i}{\sum_{i=1}^{n} Bm_i} \tag{V}$$

where PPR is the Primary Production Required, NPP is Net Primary Production, Bm_i is the Biomass of species/genera i and TL_i is the trophic level of species/genera i.

Finally, the %PPR – TLc values are presented on the biplot together with the reference function indicating 50 %, 70 % and 90 % probability to belong to a sustainable ecosystem fishing situation calculated on 65 ecosystems, independently classified as overexploited or not overexploited (Tudela et al., 2005).

The %PPR depends on NPP, which in turn changes with the reference area considered. As FAO GSAs are the reference areas for fishery management we calculated the whole manuscript referring to GSAs. However, in the Mediterranean, bottom trawling is limited to waters shallower than 1000 m, thus for comparison we also present NPP and %PPR in the area of <1000 m depth in the supplementary material II Fig. S1.

2.5. Carbon release due to sediment disturbance of bottom trawling

In contrast to purse seine, bottom trawling touches and alters the seafloor disturbing the surface sediment layer. This disturbance affects epibenthic fauna, infauna as well as sedimentary and biogeochemical processes.

Carbon loss per square metre and year of buried carbon in the seafloor, due to sediment sweeping by trawling activity, was estimated for each grid cell (i) and year (y, year = 2016, 2017, 2018) based on Sala et al. (2021). The Swept-Carbon-Lost per grid cell and year ($SwCL_{i,y}$) was calculated according to Eq. (VI), where $SwCL_{i,y,s}$ is the Swept Carbon Lost per square metre in grid cell (i) and year (y) corresponding to each fleet segment (s) calculated according to Eq. (VII):

$$SwCL_{i,y}\left(\frac{gC}{yr\ m2}\right) = \Sigma_1^s SwCL_{i,y,s}\left(\frac{gC}{yr\ m2}\right) \tag{VI}$$

$$SwCL_{i,y,s}\left(\frac{gC}{yr\ m2}\right) = C_{0,i}\left(\frac{gC}{m^3}\right) \times CLF_i \times SR_{i,y,s}\left(yr^{-1}\right) \times P_{z(m)} \tag{VII}$$

where $C_{0,i}$ is the estimated mean carbon stored in the first metre (MgC km^{-2} = gC m^{-2}, Atwood, 2019) at grid cell (i). CLF_i is the Carbon Loss Factor at grid cell (i) calculated according to Eq. (VIII), $SR_{i,y,s}$ is the swept ratio of fleet (s) at gridcell (i) of the year (y), calculated according to Eq. (IX) and P_z is the average penetration depth of trawling gears into the sediment (0.0244 m) (Hiddink et al., 2017):

$$CLF_i = Pcrd_i \times Plab_i \times \left(1 - e^{-k\left(yr^{-1}\right)t(yr)}\right) \tag{VIII}$$

where $Pcrd_i$ is the fraction that settles again at grid cell (i) (set to $Pcrd_i$ = 0.87 according to Sala et al., 2021) and $Plab_i$ is the fraction of labile carbon at grid cell (i). $Plab_i$ changes according to sediment types as mentioned in Sala et al. (2021). For grid cells covered by fine sediments $Plab_i$ was 0.7; for coarse sediments $Plab_i$ was 0.286; for other sandy sediments $Plab_i$ was 0.04 (Sala et al., 2021). Sediment classification was carried out on a sediment map (EMODNET, 2019). The first order degradation rate constant (k) for the Mediterranean is 12.3 yr^{-1} (Sala et al., 2021) and t is the time, set for one year. Sediment classification criteria, spatial distribution of sediment map, Plab and CLF, are shown in Supplementary material II Fig. S2.

The Swept Ratio at each grid cell (i) per year (y) and fleet segment (s), ($SR_{i,y,f}$) was calculated according to Eq. (IX).

$$SR_{i,y,s}\left(yr^{-1}\right) = \frac{SA_{i,y,s}\left(\frac{m^2}{yr}\right)}{A_i\left(m^2\right)} \tag{IX}$$

where $SA_{i,y,s}$ is the swept area at grid cell (i) of the year (y) (y = 2016, 2017, 2018) and the fleet segment (s) (s = 15–18 m, 18–24 m, 24–40 m) per year (m^2 yr^{-1}) at grid cell (i), A_i is the area of grid cell (i) (m^2). $SA_{i,y,s}$ was calculated according to Eq. (X), where $T_{i,y,k,s,}$ is the total hours fished per year (h yr^{-1}) at grid cell (i) of year (y) by vessel (k) of the fleet segment (s) downloaded from Global Fishing Watch (2021); V is the average fishing speed of bottom trawler (3 knots = 5556 m h^{-1}) of the trawling fleet, $W_{,k,s,y}$ is the net spread (m) of the gear of the vessel (k) of fleet segment (s). $W_{,k,s}$ was calculated as $W_{,k,s}$ = 10.6608 × $KW_{k,s}$^0.2921 (Eigaard et al., 2017), where KW is the vessel power.

$$SA_{i,y,s}\left(\frac{m^2}{yr}\right) = \Sigma_1^k T_{i,y,k,s}\left(\frac{h}{yr}\right) \times V\left(\frac{m}{h}\right) \times W_{k,s}(\mathrm{m}) \tag{X}$$

2.6. CO_2 equivalent released by each fleet in the four GSAs

As labile carbon released in the oxygenised water column oxidise to CO_2 and to facilitate comparison among carbon compartments, once the carbon amount release to the water column per square metre in each grid cell was estimated (Eq. (VII)), the CO_2 equivalent released by each bottom trawling segment (s, s = 15-18 m, 18-24 m and 24-40 m), Geographical Subarea (j, j = 1, 2, 5, 6) and year (y, year = 2016, 2017, 2018) was calculated ($SwCO_2L_{GSA,j,s,y}$) according to Eq. (XI), where $SwCL_{i,s,y}\left(\frac{gC}{yr\ m2}\right)$ is the carbon released per square metre in each grid cell (*i*) by the bottom trawling segment (s) during the year (y). A_i is the area of the grid cell (i) (m^2), F is the conversion factor of gC to gCO_2 (3.67 ($\frac{gCO_2}{gC}$)) and N_{GSAj} the number of grid cells of GSAj (j = 1,2,5,6).

$$SwCO_2L_{GSA_{j,y,s}}\left(\frac{gCO_2}{yr}\right) = \Sigma_1^{N_{GSAj}} SwCL_{i,s,y}\left(\frac{gC}{yr\ m2}\right) \times A_i\left(m^2\right) \times F\left(\frac{gCO_2}{gC}\right) \tag{XI}$$

The calculation of bottom trawling released CO_2 was carried out during the years 2016, 2017, 2018 because in most recent years the representability of Marine Mobil Service Identifier (MMSI) increases (Global Fishing Watch, 2021). Finally, the three-year mean, standard deviation and the Coefficient of Variation was calculated over each grid cell.

2.7. Representability of MSSI data

MMSI considers only vessels ≥15 m. Thus the three fleet segments for bottom trawling CO_2 release considered are vessels of 15–18 m, 18–24 m and 24–40 m, where the last two sections coincide with AER fleet sections. The total released CO_2 correspond to bottom trawlers >15 m.

AER and MSSI vessel number can only be compared if vessel size ranges coincide (Fleet segments 18–24 and 24-40 m). MSSI data account for 96 ± 0.03 % of the AER vessels in the size range between 18–24 m and 100 ± 0.04 % of the AER vessels in the size range of 24–40 m. Thus MSSI data of fishing boat numbers can be considered as representative of the official registered fleets.

2.8. Uncertainties and different scenarios of remineralisation estimation

The carbon release calculated in Section 2.5 does not consider successive years of constant trawling, which favours organic carbon remineralisation and reduces considerably the organic carbon left to release. According to Sala et al. (2021), remineralisation rates stabilize at 40 % of the initial rate after the 8th successive year of constant trawling with one sweep per year. Furthermore, it has been suggested that the thickness of the carbon remobilization is only 10 % of the penetration depth (Hiddink et al., 2021) and the reactivity constant k is only applicable at the water sediment interface and decreases afterwards with depth (Hiddink et al., 2021; Arndt et al., 2013).

Most of the area considered in the work has been trawled >8 times. Therefore, In order to consider repetitive trawling and 10 % carbon remobilization of the penetration depth (Pz) we consider three scenario in this manuscript.

1) Upper CO_2 release estimation, ($CO2_{\_100\%}$) calculated according to the equations and parameter given in Sections 2.5 and 2.6.
2) Middle CO_2 release estimation, ($CO2_{\_40\%}$), considering 40 % of the upper CO_2 release
3) Lower CO_2 release estimation, ($CO2_{\_4\%}$), considering repetitive trawling, remobilization of carbon limited to 10 % penetration depth and application of k to sediment water interface. In this model a Pz of 0.00244 m and 40 % of CO2 release were considered.

The upper, middle and lower carbon release estimations allow comparison with the findings of Sala et al. (2021) ($CO_{2\_100\%}$) at global scale, consider organic carbon reduction of about 60 % due to previously remineralisation facilitated by repetitive trawling ($CO_{2\_40\%}$) and reported reduced carbon remobilization effect of the gear at the seafloor and k application to surface sediment ($CO_{2\_4\%}$) by Hiddink et al. (2021). As almost the whole Spanish fishing area, specially over the continental shelf, has been swept for more than eight times, the $CO_{2\_40\%}$ and $CO_{2\_4\%}$ scenarios are the most likely scenarios to apply in the area studied.

Although the CO_2 release estimations have a wide range, their consideration in carbon balance of fishery is important. Even the lowest scenario ($CO_{2\_4\%}$) release considerable amounts of CO_2 and therefore provide useful information where to apply measures for CO_2 emission reduction for decision makers.

3. Results

3.1. Economic benefits and fuel footprint of CO_2

3.1.1. Comparison among fleet segments

Yearly fuel consumption of bottom trawler fleet segments of 18–24 m (median = 4.4×10^7 L yr^{-1}) and 24–40 m (median = 2.8×10^7 L yr^{-1}) are significantly higher than the remaining fleet segments. Among the purse seine segments vessels >12 m show a fuel consumption (median > 2.38×10^6 L yr^{-1}) significantly higher than for the smallest segment (6–12 m median = 2.8×10^5 L yr^{-1}) (Fig. 2a). The higher fuel consumption indicates higher fishing effort. Fish prices are significantly higher for bottom trawler extracted fish (median = 3.7–6.4 € kg_{fish}^{-1}) and PS segment 24–40 m extracted fish (median = 4.3 € kg_{fish}^{-1}) compared with purse seine catches of the fleet segments <24 m (median 1.5–1.6 € kg_{fish}^{-1}) (supplemental material II Fig. S3). Higher fishing effort and fish prices lead to higher Gross Value of the Landings (GVL) in bottom trawler >18 m and purse seine 18–24 m (Fig. 2b). However, the GVL does not provide greater net benefit. No significant differences in net profit were found either among the fleet segments or between the fishing gears (Fig. 2c), indicating that the inverted Value of Physical Capital (VPC) and other costs, economically dampens the advantage of bottom trawling and greater sized vessels in terms of GVL. The medians of net profit ranges between 1.81×10^5 (PS 6–12 m) and 4.04×10^6 (PS 24–40 m) € yr^{-1}. Years with negative balance indicate years with high investment in VPC. The fuel derived CO_2 emission per kg landed fish is significantly higher for the three greater sized fleet segments of bottom trawling than for all fleet segments of purse seine (Fig. 2d). Normalising the gross value of landings by CO_2 emission (Fig. 2e), it can be seen that the three greater sized bottom trawling segments had significantly lower gross values per CO_2 emission than the purse seine fleet segments. The greatest sized purse seine segment reached the highest gross values per CO_2 emission (median = 3.43 € kg_{CO2}^{-1}).

The net profit per kg of CO_2 emission of the three greatest sized bottom trawling segments (12–18 m, 18–24 m and 24–40 m) showed significantly lower net profit than all purse seine fleet segments (Fig. 2f). It is remarkable that the median net profit of all fleets is lower than 1€ kg_{CO2}^{-1}, where the three greater sized bottom trawling fleets show values very close to zero (0.056, 0.022, 0.024 € kg_{CO2}^{-1} for DTS2, DTS3, and DTS4 respectively). However, purse seine values and the smallest bottom trawling segments are almost one order of magnitude higher (0.655, 0.387, 0.158 and 0.893 € kg_{CO2}^{-1} for PS1, PS2, PS3, PS4 and 0.299 for DTS1). Therefore, the bottom trawling fleets >12 m consume more fuel than purse seine fleet segments and provide a higher gross value of landings, while this does not rebound in higher net profit. The consequence of the elevated fuel consumption results in a significantly higher CO_2 footprint (kg_{CO2} kg_{fish}^{-1}), lower gross value of landed fish per CO_2 emission and lower net profit per CO_2 emission. This means that, the bottom trawling of the fleet segment >12 m significantly contaminates more than purse seine fleet in terms of consumed fuel (L) and CO_2 footprint (kg_{CO2} kg_{fish}^{-1}), without being compensated by higher net profit (€) and even a significantly lower net profit per $kgCO_2$ emission (€ kg_{CO2}^{-1}).

3.2. Evaluation of the trophic sustainability of bottom trawling and purse seine fishery

3.2.1. Net primary production and primary production required to sustain extractive fishery

Yearly Net Primary Production (NPP) per km^2 in each GSA was almost constant during the ten year (2008–2018) investigated period (Fig. 3a), where GSA1&2 had significantly higher NPP values (157,029 ± 6350 kgC km^{-2} yr^{-1}) than GSA 6 (123,167 ± 4231 kgC km^{-2} yr^{-1}). GSA 5 in turn had significantly lower NPP values than GSA 6 (115,914 ± 3534 kgC m^{-2} yr-^{1}) (One-Way ANOVA $p < 0.005$). Comparison of total PPR among the GSAs reveals a significant higher total PPR (median = 29,193 kgC km^{-2} yr^{-1}) at GSA 1&2 than at GSA 6 (median = 14,008 kgC km^{-2} yr^{-1}) and GSA 5 (median = 858 kgC km^{-2} yr^{-1}) (Kruskal Wallis One Way Anova $p < 0.001$, and tukey test ($<p < 0.05$)). At GSA 1&2, relative importance of purse seine PPR was predominant and significantly higher (median = 69 %) than at GSA 5 (median = 16 %) and GSA 6 (median = 30 %), where the PPR requirement was dominated by bottom trawling.

Time evolution of PPR to sustain the landed catch are shown for both gears (DTS and PS) and four fleet segments (Fig. 3b, c, d). A significantly decrease of total PPR (the sum of the PPR of all PS and DTS fleets) with time was observed at GSA 1&2 (total PPR = 2,408,371–1182*yr, $r = 0.70$, $n = 9$, $p < 0.05$) due to a significant decrease of purse seine PPR at GSA 1&2 (purse seine PPR = 1,834,810–902*yr, $r = 0.71$, $n = 9$, $p < 0.01$).

According to decreasing PPR and relative constant NPP in GSA 1&2, the %PPR decreases from about 20 % between 2008 and 2013 to about 14 % between 2014 and 2018 (Fig. 3b). In GSA 5 in contrast %PPR always remains very low (<1 %) and constant throughout the years (Fig. 3c). In GSA 6 %PPR remains constant around values between 13 and 15 %.

3.2.2. Trophic level of catch and quantitative ecosystem index

In all GSAs, the average trophic level of the catch (TLc) was higher for bottom trawling (DTS TLc >3.6) than for purse seine (PS TLc <3.5, Fig. 4a). While bottom trawling TLc remained constant in time (no significant trend, $p > 0.05$) or even augmented significantly (DTS GSA6, Fig. 4a), purse seine TLc decreased in the three GSAs from 2008 to 2018, in two of them, GSA 5 and GSA 6, significantly (Fig. 4a).

The quantitative ecosystem index combines the relative PPR (%PPR) and TLc in a bi-plot and allows to benchmark the evaluation of the trophic sustainability of extractive fishery with the reference functions for a 50 %,

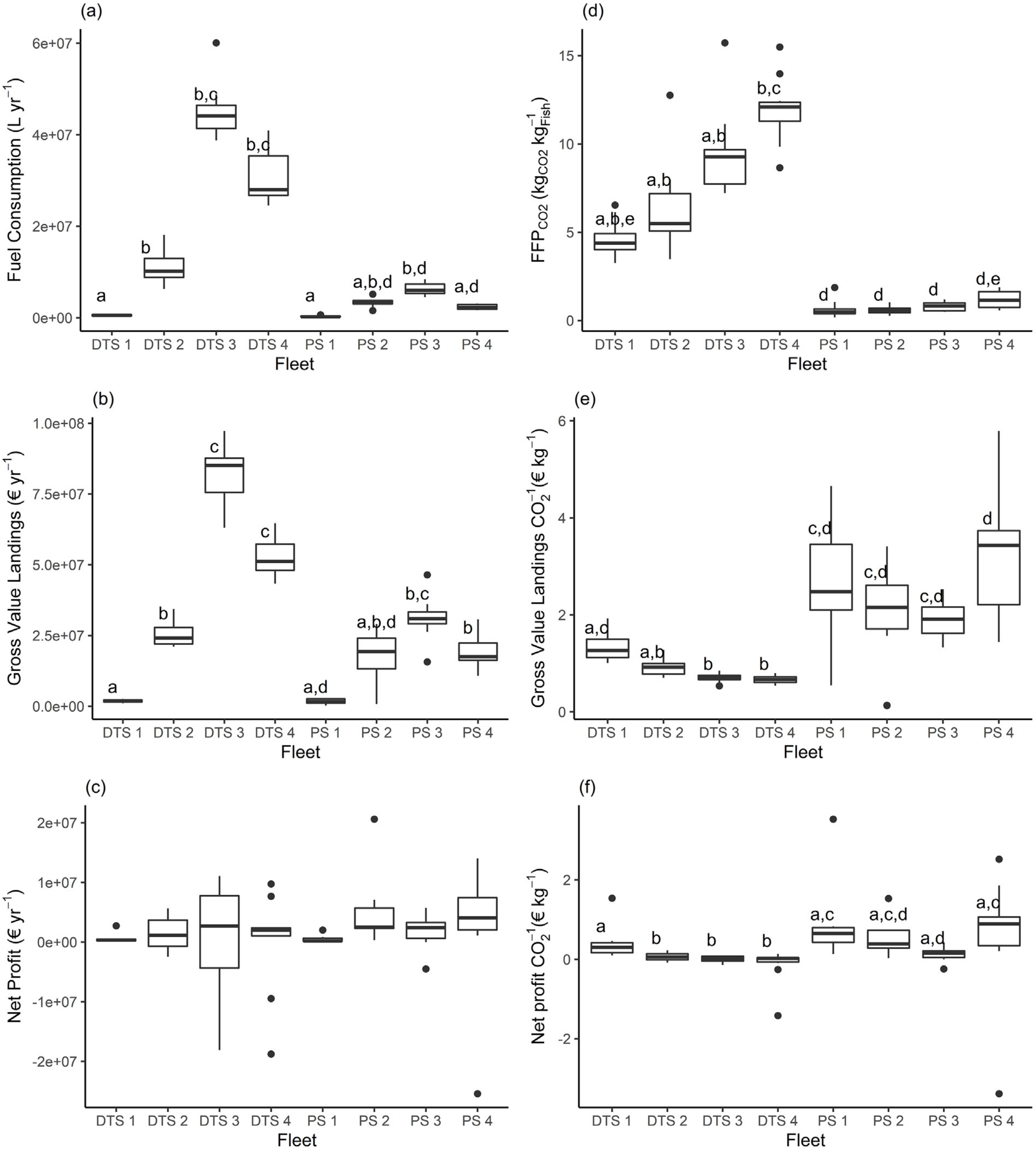


Fig. 2. Boxplot of fuel consumption (a), gross value of landings (b), net profit (c) fuel footprint of CO_2 (d), gross value of landings per CO_2 emission (e) and net profit per CO_2 emission (f). Bottom trawling (DTS) and Purse seine (PS) fleet are subdivided in 4 size classes: 1 = 06–12 m, 2 = 12–18 m, 3 = 28–24 m and 4 = 24–40 m). For comparison, Kruskal-Wallis One-way ANOVA on ranks ($p < 0.05$) and Dunnes test (*p < 0.05, B-H adjustment), was carried out with the R FSA package (Ogle et al., 2021). Boxplot with the same letters belongs to the same group which are significantly different to the groups with other letters.

70 % and 90 % probability to belong to a sustainable fishing reference scenario (Tudela et al., 2005).

Applying the quantitative ecosystem index to the three GSAs over the ten-year interval (2008–2018) studied, it can be observed that seven (GSA1&2) and four (GSA6) out of nine years are above or on the 50 % probability line to be sustainably exploited (Fig. 4b). The remaining years of both GSAs, predominantly more recent, are located between the 50 % and 70 % probability lines, but still show recent points clearly above the 50 % probability. Thus, from the trophic point of view, the ecosystem of GSA 1&2 and GSA 6 are at risk of being overfished ecosystems, with improvement in recent years. GSA 5 in contrast shows a sustainable ecosystem exploitation by bottom trawling and purse seine fisheries.

The %PPR is referred to NPP, which changes with the reference area considered. If, instead of GSA surface, which can include greater oligotrophic area offshore, %PPR is referred to NPP production in trawlable 0–1000 m bathymetry, where legal fishing activity is carried out the % PPR increases. In our case %PPR increases by factor 1.96 ± 0.069 in GSA 1&2, by factor 3.91 ± 0.094 in GSA 5 and by factor 2.89 ± 0.084 in GSA 6. Consequently, in GSA 1&2 and in GSA 6 in all years %PPR is higher than 20 and located above the 50 % reference line for sustainable fishing (Supplementary material Fig. S4). Although, at GSA 5 %PPR increases by the highest factor, it still remains under the 90 % reference line and is from the trophic point of view a sustainable fished area. Thus, either if the recognized FAO GSAs management area or only 0–1000 m depth

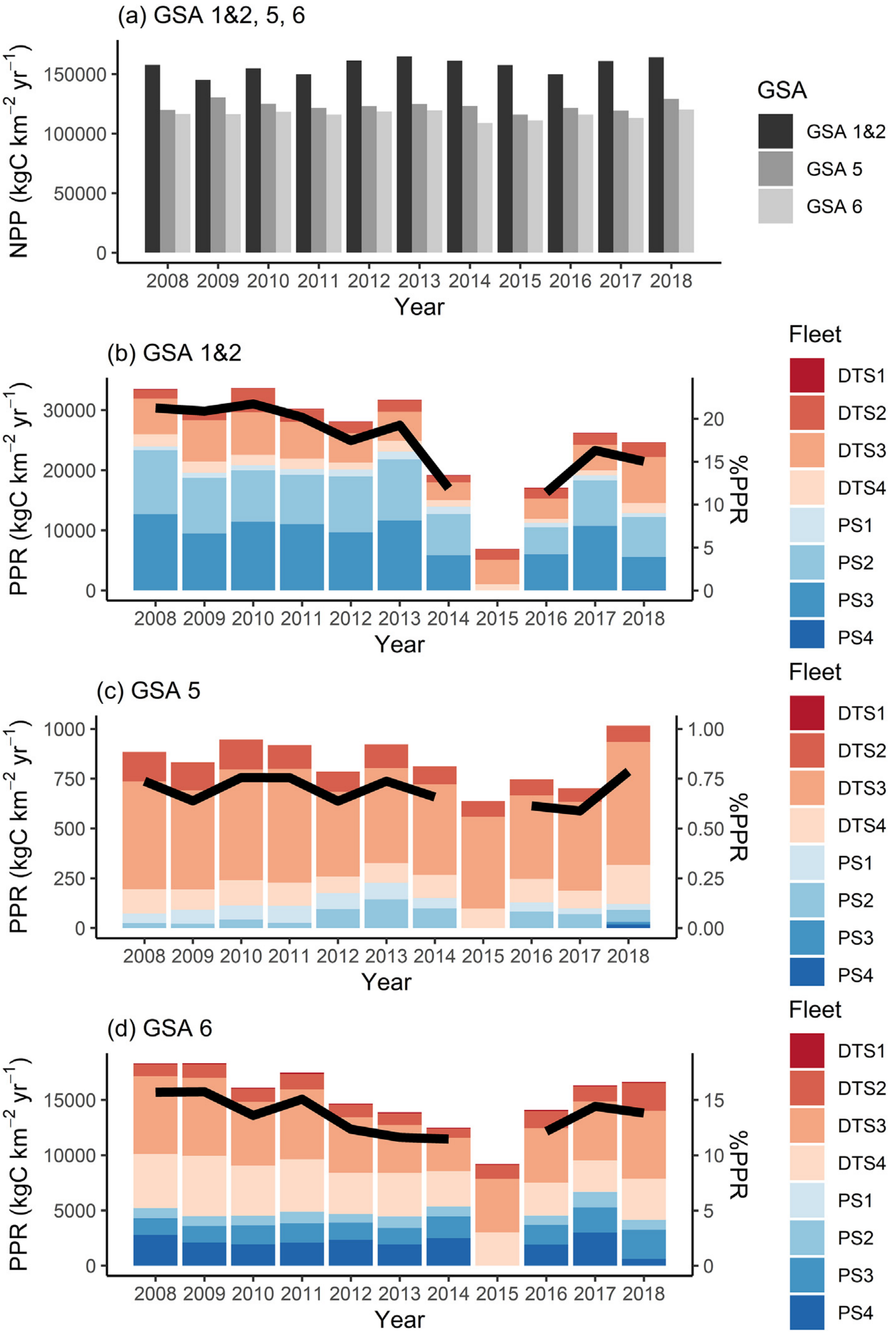


Fig. 3. (a) Net Primary Production (NPP, kgC km^{-2} yr^{-1}) for each GSA. Primary Production Required (PPR, kgC km^{-2} yr^{-1}) referred to all GSAs and subdivided in fishing gears (DTS = Bottom trawling in red, PS = Purse seine in blue) and vessel size (1 = 6–12 m, 2 = 12–18 m, 3 = 18–24 m and 4 = 24–40 m) for GSA 1&2 (b), GSA 5 (c) and GSA 6 (d). In 2015 PS data were not available and only DTS data are shown. The sum of the PPR of all gears and fleets (value of the stacked columns) refers to total PPR. The black line in b, c and d refers to %PPR. Note PPR and %PPR scales change among the figures. (Same figure referred to depth interval 0-1000 m in each GSA can be found in supplementary, Fig. S1). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

covered area in each GSA is considered the conclusions of overexploited and sustainable fishery areas remains the same.

3.3. Carbon release due to sediment disturbance of bottom trawling

Calculated swept per year ratio shows elevated trawling activity above the continental shelf (above 200 m depth, Fig. 5a), along the coastal area of GSA 6 around Cape of Nao, between Tarragona and Castellón de la Peña which includes the Ebro Delta, between Alicante and Valencia. Additionally, locally high swept per year values are also observed near Girona. In GSA 1&2, highest swept per year values are observed on the continental shelf of Malaga Bay, the western part of Almeria Bay, and at the west of Almanzora Delta. It is worth noting that along the Spanish coast of GSA 1 and GSA 6 vast areas have a swept per year ratio higher than one and can reach values up to 10. This means that most of the coastal areas are being swept several times a year. In comparison, GSA 2 and GSA 5 show relatively low swept per year ratio, although there are also areas with swept per year ratio greater than one (Fig. 5a).

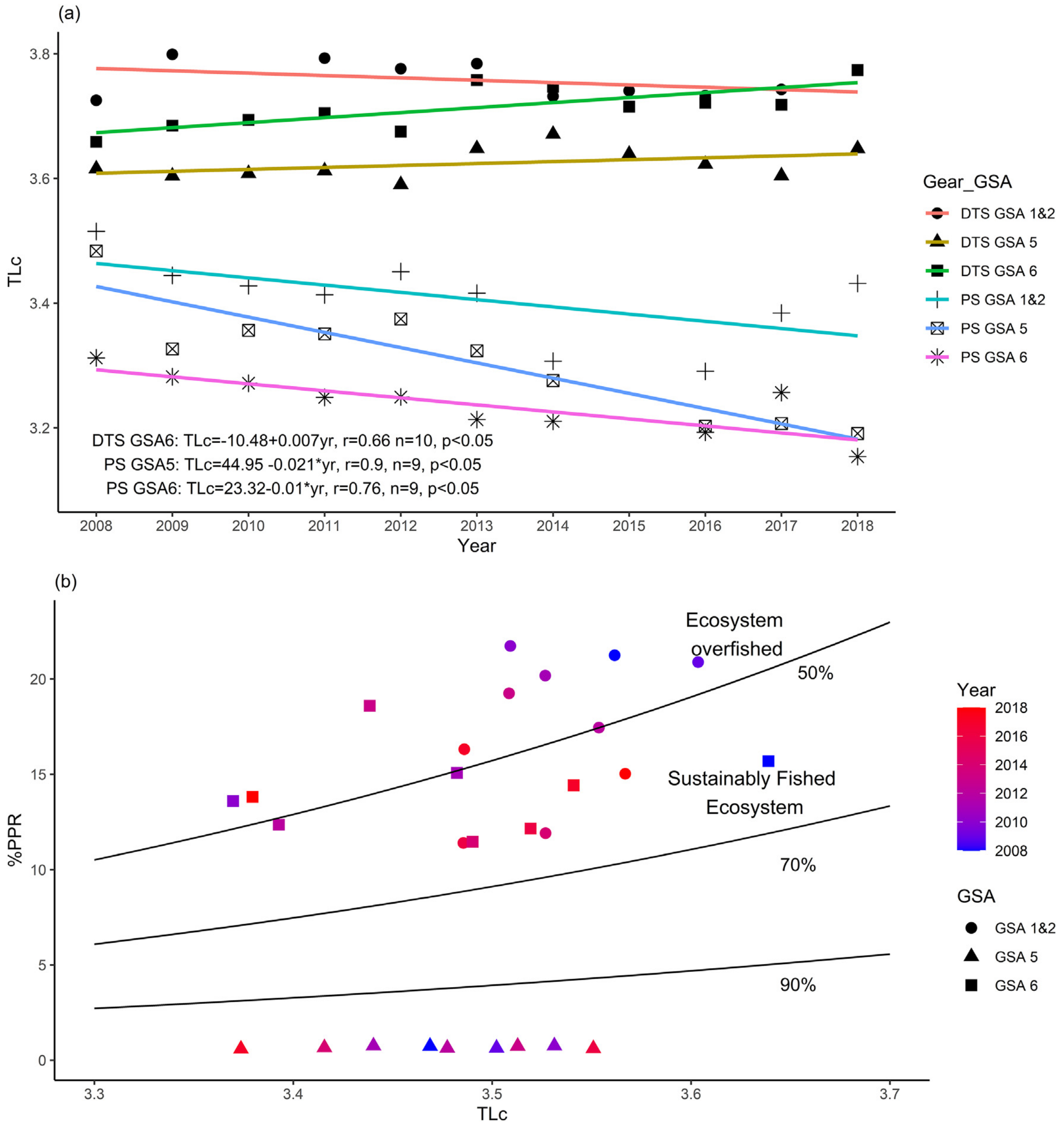


Fig. 4. (a) Time evolution of the Trophic Level of the catch (TLc) for each gear and vessel size. Significant linear regressions are indicated on the plot. (b) Quantitative ecosystem index (%PPR-TLc biplot) for each GSA with reference function (Tudela et al., 2005) related to 50 % ($y = 0.003x^{68361}$), 70 % ($y = 0.0017x^{6.8543}$) and 90 % ($y = 0.0015x^{6.2825}$) probability to belong to a sustainable ecosystem fishing situation. (Same figure refereed to depth interval 0-1000 m depth in each GSA Fig. S4 supplementary material II).

The mean carbon release per square metre above the Spanish continental shelf (between the coast and 200 m depth) (100 % scenario) is 134 gC m^{-2} yr^{-1}. If repeated trawling is considered (40 % scenario) mean carbon release is 53.6 (gC m^{-2} yr^{-1}), considering reduced carbon remobilization to 10 % of penetration depth (4 % scenario), the carbon release is 5.36 (gC m^{-2} yr^{-1}).

Concerning spatial heterogeneity, carbon release due to bottom trawling sweeping of the seafloor is especially high where carbon content and the fraction of labile carbon are high. Thus, the swept per year pattern of Fig. 5a is enhanced where carbon rich and fine sediments are found. Therefore, especially high carbon release is observed at the intensively trawled continental shelf areas around the mouth of the Ter, the Ebro, the Jucar, the Segura and the Guadalhorce river (Fig. 5b). Additionally, high carbon release was observed around the Cape of Nao area, located between the Jucar and Segura Delta (Fig. 5b) and characterized by a wide continental shelf (Fig. 5a). According to less intensive trawling activity and the absence of carbon rich sediments due to oligotrophy of surrounding waters or absence of river input, the carbon release from the seafloor in GSA 2 and GSA 5 is low.

Highest standard deviations are observed at grid cells where highest trawling intensity and carbon release occurs (Fig. 6a). However the Coefficient of Variance (CV) show low relative importance of the standard deviation referred to the mean carbon release at each grid over the continental shelf (inside 200 m isobaths) (Fig. 6b). Thus, mean spatial distribution of bottom sweeping and carbon emission estimation over the continental shelf can be considered as representative. Beyond the −1000 m isobaths, in contrast, CV reaches values higher than 100 and the standard deviation overrides the mean carbon release at these grid cells. This can be explained by the low fishing activity offshore of the legal trawling area (Fig. 5a) which changes in space and time. Thus the spatial pattern of the small, almost irrelevant, carbon release values observed offshore of the −1000 m isobaths (Fig. 5b) is not representative.

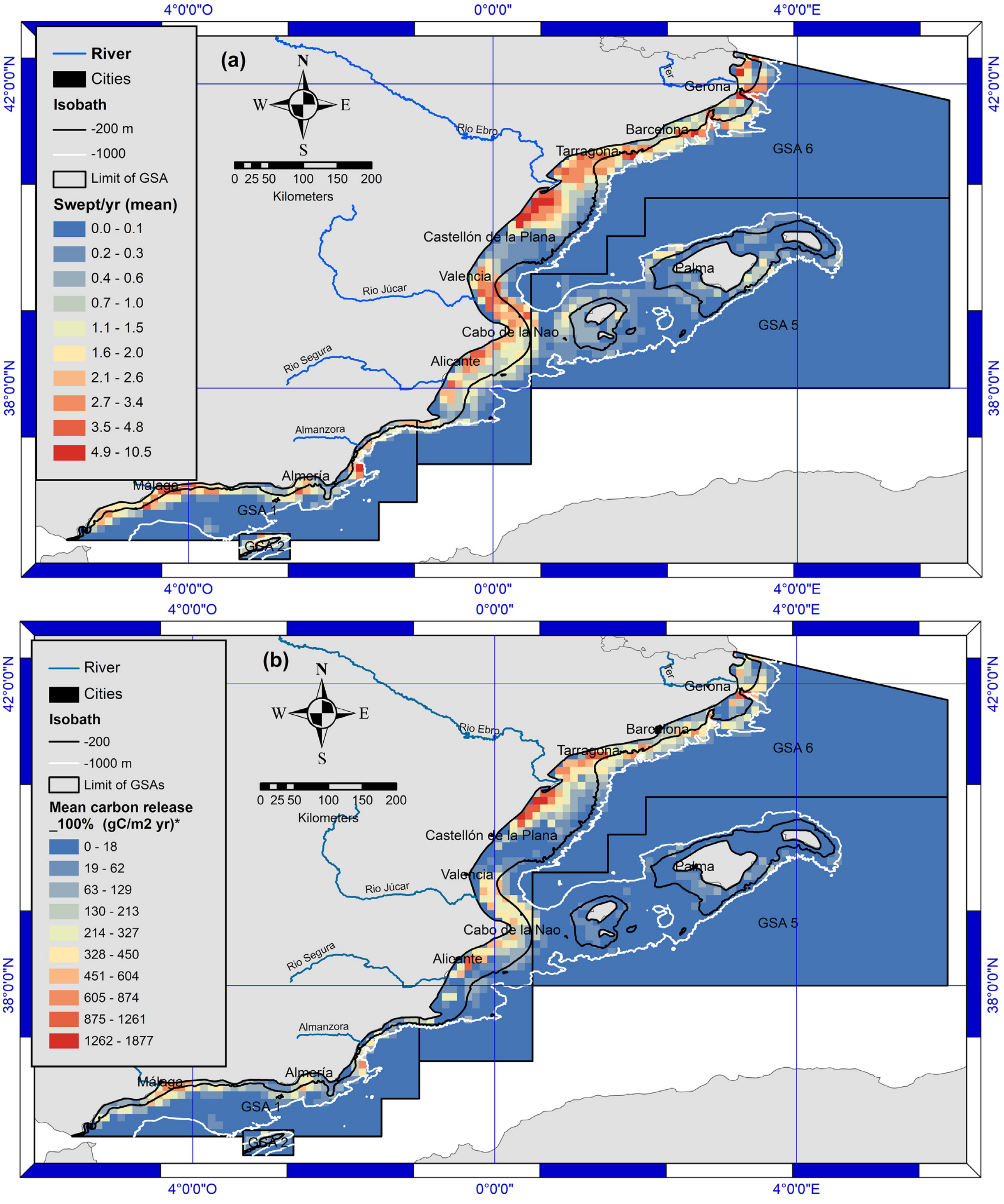


Fig. 5. (a) Mean Swept per year (2016–2018) of the sea bottom calculated from MMSI bottom trawling data of vessels between 15 and 40 m. (b) Mean carbon released of the scenario of 100 % release (gC m^{-2} yr^{-1}). * if the scenario of 40 % release is considered the scale ranges between 0 and 750 gC m^{-2} yr^{-1} (Sala et al., 2021) and if the 4 % scenario is considered the scale ranges between 0 and 75.08 gC m^{-2} yr^{-1}.

Regarding vessel-size and GSA considered in this work, GSA 5 shows the lowest release of CO_2 per year, followed by GSA 1&2 and GSA 6 (Fig. 7a). In all GSAs the fleet between 18 and 24 m was the major contributor to CO_2 release (Fig. 7a). Dividing the mean CO_2 bottom release of all GSAs (2016–2018) of DTS 3 (18-24 m) and DTS 4 (24-40 m) by the mean net profit (€)(2016–2018), the lowest CO_2 emission per € was found for DTS 3 and DTS 4 applying the lowest CO_2 emission scenario ($CO_{2\_4\%\_DTS3\&4}$/€ = 1399 ± 0.661 kg_{CO2} $€^{-1}$) and the highest CO_2 emission per € was found for DTS 3 and DTS 4 applying the highest CO_2 emission scenario ($CO_{2\_100\%\_DTS3\&4}$/€ = 3498 ± 1.65 kg_{CO2} $€^{-1}$).

Normalising the values by vessel number, the smallest fleet section becomes the main contributor to CO_2 release in GSA 5, and GSA 6, while in

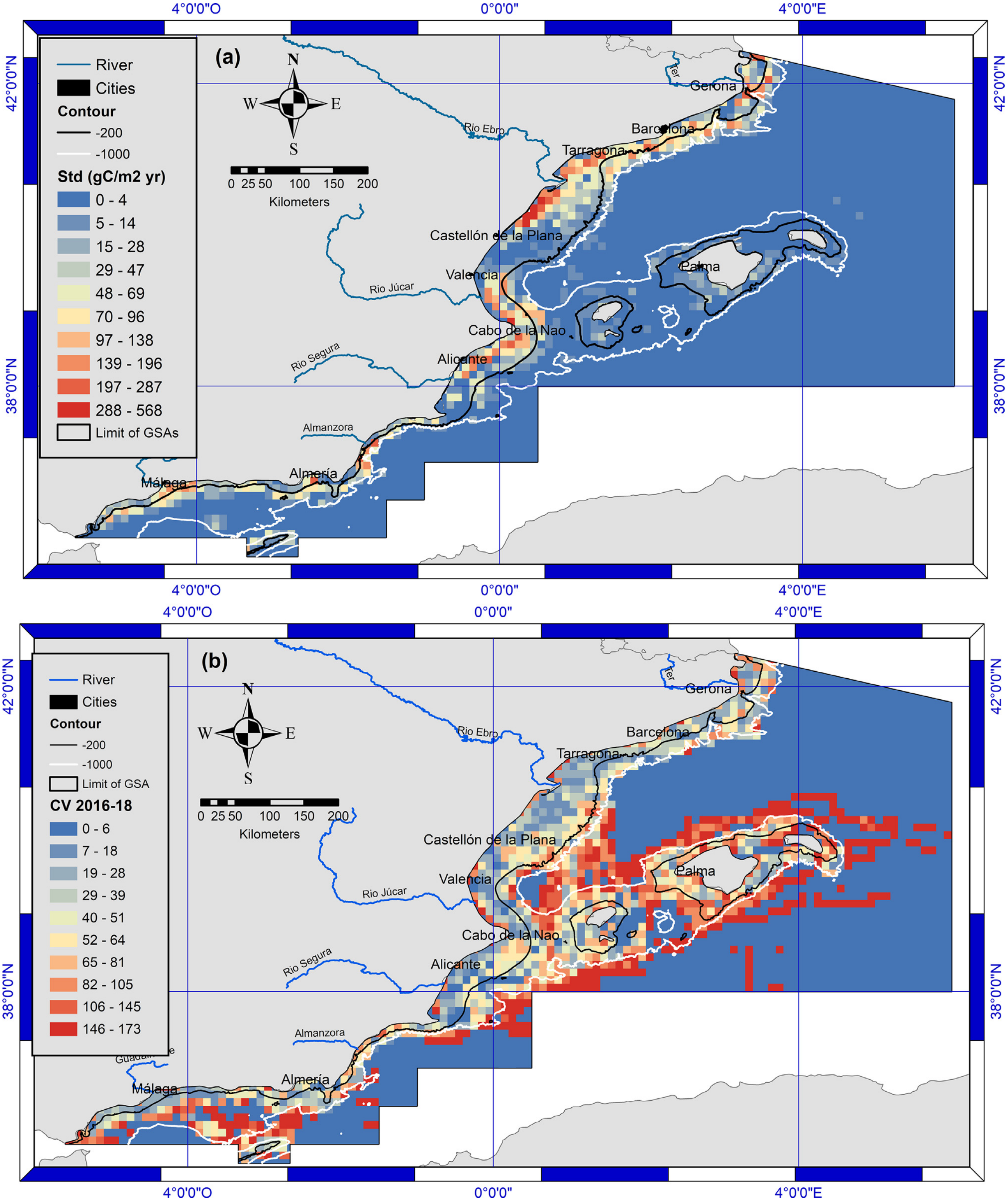
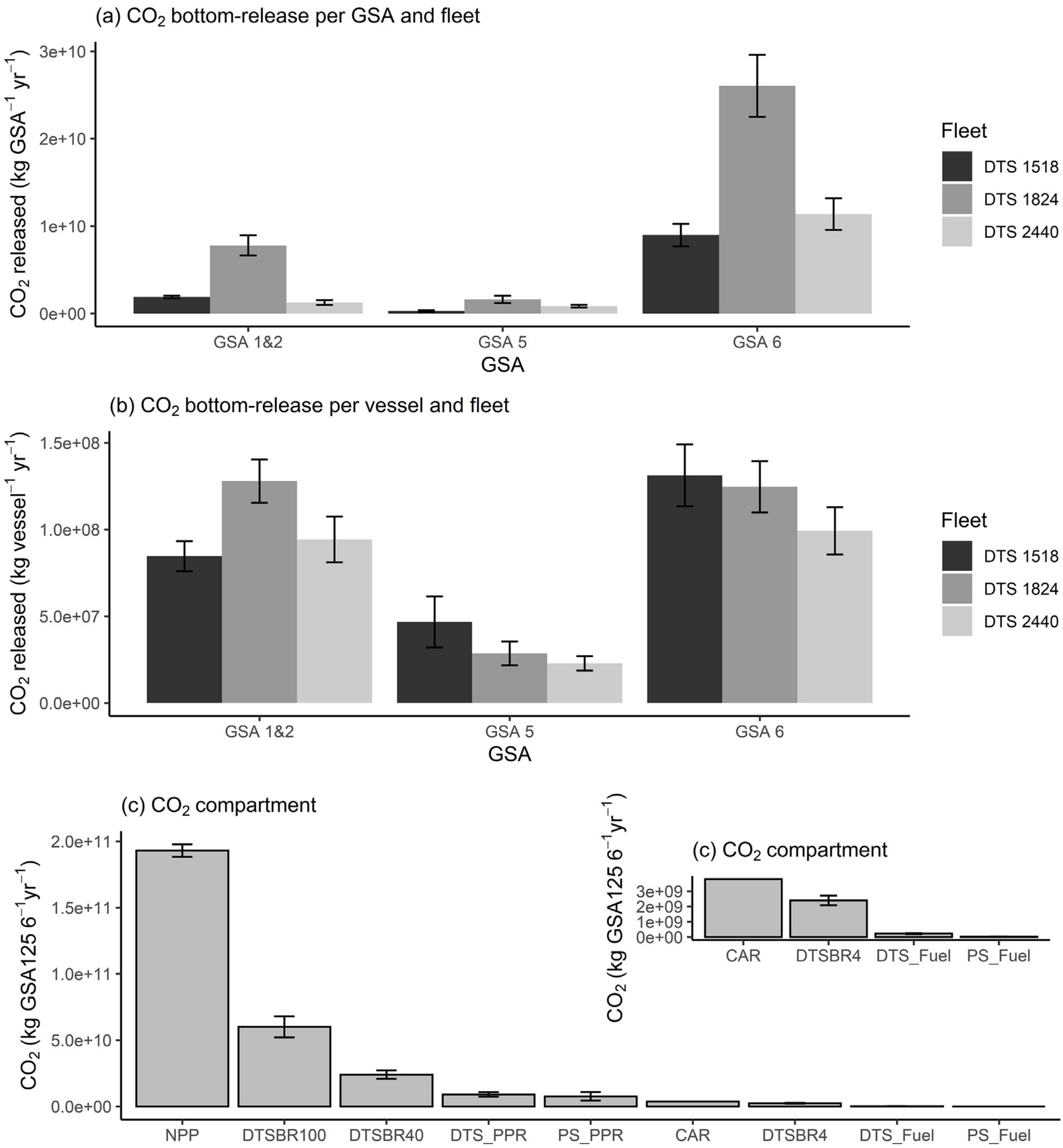


Fig. 6. (a) Standard deviation (2016–2018) of carbon released from the seafloor (gC m^{-2} yr^{-1}). (b) Coefficient of Variation referred to the mean carbon release ($CV = \left(\frac{std}{mean}\right) * 100$) at each grid cell.

GSA1&2 bottom trawler between 18 and 24 m remained the main contributors to CO_2 release from the seafloor (Fig. 7b). The CO_2 release per vessel in GSA 1&2 and GSA 6 was similar for vessels between 18 and 24 m and 24–40 m while the smallest size class (15–18 m) in GSA 1&2 showed a significantly lower CO_2 release per vessel than in GSA 6. The CO_2 release per vessel in GSA 5 was for all fleet sections significantly lower than those found in GSA 1&2 and GSA 6. (Fig. 7b, and confirmed by two-way ANOVA $p < 0.00$, results not shown).

Comparing different carbon compartments, CO_2 fixation (NPP) of the Spanish Mediterranean GSAs reaches 19.3 × 10^{10} kg CO_2 yr^{-1}. Released CO_2 by bottom trawling if the area is trawled for the first time (DTS_BR$_{\_100\%}$) reaches 60.1 × 10^9 ± 79.7 × 10^8 kg CO_2 yr^{-1}, that is


(a) CO_2 bottom-release per GSA and fleet

(b) CO_2 bottom-release per vessel and fleet

(c) CO_2 compartment

Fig. 7. (a). $CO_{2\_100\%}$ equivalent released per GSA and year by the three bottom trawling fleets (15–18 m, 18–24 m and 24-40 m). (b) $CO_{2\_100\%}$ release from the seafloor per vessel and year. (c) Comparison of carbon fixation (NPP), Bottom Trawling (DTS) bottom released Carbon 100 %, 40 % and 4 % (DTSBR100, DTSBR40, DTSBR4), Primary Production Required to sustain landed fish biomass (DTS_PPR and PS_PPR), Carbon Accumulation Rate and CO_2 emission per gear due to fuel consumption (DTS_Fuel and PS_Fuel). NPP = Net Primary Production. DTS_Fuel = CO_2 emission by trawlers through fuel combustion, PS_Fuel = CO_2 emission by purse seine through fuel combustion. The values and standard deviations are referred to the 2008–2018 time interval. Mean and standard deviation of bottom released CO_2 refers to 2016–2018 time period.

31 % of the fixed CO_2. Considering more than eight sweeps of bottom trawling ($DTS\_BR_{\_40\%}$) the released CO_2 accounts for 24.0 × 10^9 ± 31.9 × 10^8 kg CO_2 yr^{-1}, that is 12.5 % of the CO_2 fixed by NPP, and if the minimum scenario is considered, CO_2 release ($DTS\_BR_{\_4\%}$) is 2.4 × 10^9 ± 3.19 × 10^8 kg CO_2 yr^{-1}, that is 1.25 % of the CO_2 fixed by NPP (Fig. 7c).

PPR required to sustain landed fish biomass extracted by bottom trawling (DTS_PPR) and purse seine (PS_PPR) is 90.5 × 10^8 ± 17.2 × 10^8 kg CO_2 yr^{-1} and 76.3 × 10^8 ± 32.4 × 10^8 kg CO_2 yr^{-1} respectively, accounting for 4.7 % and 4 % of NPP (Fig. 7c). Comparing fuel derived CO_2 emission with bottom trawling CO_2 released from the seafloor we observe that the fuel derived emission of 22.9 × 10^7 ± 31.2 × 10^6 kgCO_2 yr^{-1} by bottom trawler account only between 0.3 % ($CO_{2\_100\%}$) and 9.5 % ($CO_{2\_4\%}$) of the bottom released CO_2. The purse seine fuel derived CO_2 emission (3.2 × 10^7 ± 5.0 × 10^6 kgCO_2 yr^{-1}) is one order of magnitude lower than the bottom trawling fuel derived CO_2 emission (Fig. 7c).

Considering the highest Carbon Settling Rate (CAR) over the continental shelf (19.6 gC m^{-2} yr^{-1} Wilkinson et al., 2018) and the trawled area over the continental shelf (5.29 × 10^{10} m^2) annual CAR along the Spanish Mediterranean shelf is about 3.8 × 10^{10} kgCO_2 yr^{-1} a value close to the lower limit ($CO_{2\_4\%}$) of bottom released carbon (2.4 × 10^{10} kgCO_2 yr^{-1}). If only 10 % of the CAR is buried in the seafloor (Muller-Karger et al., 2005) bottom released carbon overrides the biological pump by almost one order of magnitude.

4. Discussion

Sustainability of fishery and CO_2 footprint are of major concern for the EU-Green Deal (EU-Green Deal, 2021), blue growth and food provision strategy of the EU (European Parliament, 2020). However, with >60 % of the stocks exploited above the Maximum Sustainable Yield (MSY), the Mediterranean and Black Sea is the most overexploited FAO fishery statistical area in the world (FAO, 2018). Comparing continents, only North America and Europe have a negative economic balance (FAO, 2018), indicating net import of fish proteins from Asia (without China), Latin America and Caribbean, China and Oceania. In order to reduce external dependence of fishery proteins, achieve sustainable exploitation, mitigate CO_2 emissions and improve economic benefits the following aspects are discussed below: fuel derived CO_2 footprint and net profit (Section 4.1), fishery impact at ecosystem level (Section 4.2), carbon release from the seafloor (Section 4.3) and CO_2 footprint of food production (Section 4.4).

4.1. Fuel derived CO_2 footprint and net profit

On a global scale, 50 billion L fuel are burnt to land 80 million tons of fish and invertebrates, resulting in an average use of 650 L t^{-1} and an average rate of 1.7 t of CO_2 per ton of landed live weight (Tyedmers et al., 2005). However, this overwhelming mean value changes in space (Tyedmers et al., 2005) and time (Ziegler and Hansson, 2003). Furthermore, it depends greatly on the vessel gear (Schau et al., 2009; Parker and Tyedmers, 2015; Sala et al., 2022) and target species (Ziegler and Hansson, 2003; Ziegler and Valentinsson, 2008; Schau et al., 2009; Parker and Tyedmers, 2015; Sala et al., 2022). The median fuel intensity of bottom trawler reported by Parker and Tyedmers (2015) is about 2000 L t^{-1}, which, changing units and applying a diesel to CO_2 conversion factor of 2.61 KG_{co2}/L_{fuel} correspond to 5.2 $kgCO_2$ kg $fish^{-1}$. This is similar to the CO_2 footprint of bottom trawler obtained in our study for vessel size between 6 and 12 m (4 $kgCO_2$ kg $fish^{-1}$) and between 12 and 18 m (6 $kgCO_2$ $kgfish^{-1}$). Although Mediterranean trawlers are characterized by one day trips, larger sized trawlers in this work reach considerably higher CO_2 footprints, which might be due to longer trawling trips to the fishing grounds, trawling at greater depth and the use of more powerful engines, as larger boats have the capacity of using larger gear. Indeed, real power is sometimes even higher than officially registered by the authorities (Guijarro et al., 2010a, b; Coll et al., 2014). Purse seine CO_2 footprint is for all vessel sizes below 1 $kgCO_2$ kg $fish^{-1}$, coinciding again with results of other studies (Schau et al., 2009). The purse seine fleet did not show significant differences between the fleet segments. The fact that greater sized bottom trawling vessels have a higher fuel derived CO_2 footprint can be considered in strategies for CO_2 footprint mitigation giving more support to policies and measures that foster smaller vessel fishery.

Interestingly, net profit per CO_2 emission was significantly lower for the three greater sized fleets of bottom trawler than for the remaining fleets. This means that the higher CO_2 footprint of bottom trawler with vessel size >12 m is not compensated by increasing net profit. In contrast, purse seine net profit per emitted CO_2 is higher than for bottom trawler, a fact which should be considered in climate change mitigation and economic strategies. However, it is known that the suitable habitat for small pelagic fish targeted by purse seiners will be contracted in the future (Ramírez et al., 2021), which will increase the concentration of purse seiners in smaller areas challenging the future design of spatial management measures under a likely and uncertain decrease of small pelagic fish production. It is also remarkable that net profit per kg CO_2 emission due to fuel consumption is for all fleets smaller than 1 €. According to the Equivalent Transfer System the price of tonnes of CO_2 equivalent emitted to the atmosphere (CO_2e) in the EU in 2018 was 16 US\$/tCO_2e (World Bank Group, 2018) which corresponds to 0.014 € $kgCO_2e^{-1}$ according to currency change for 2018. Taking into account that the median value of net profit per CO_2 emission (€ $kgCO_2e^{-1}$) of the bottom trawler fleet with vessel sizes of 18-24 m and 24-40 m is 0.022 € $kgCO_2e^{-1}$ and 0.024 € $kgCO_2e^{-1}$ respectively, bottom trawlers net profit could be reduced to half if CO_2 taxes are applied. In fact, subtracting a carbon tax of 0.014 € $kgCO_2e^{-1}$ the net profit per CO_2 emission of the greater sized bottom trawler fleets is only 0.008 € $kgCO_2^{-1}$ and 0.01 € $kgCO_2^{-1}$ for bottom trawler fleets with vessel sizes of 18-24 m and 24-40 m, respectively. If bottom released CO_2 is considered, net profit (€) per CO_2 release ranges between $0.0003 \pm 1.3 \times 10^{-7}$ € $kgCO_2^{-1}$ for DTS 3 and DTS 4 in low CO_2 release scenario and $0.0007 \pm 1.3 \times 10^{-7}$ € $kgCO_2^{-1}$ for DTS 3 and DTS 4 in high CO_2 release scenario. This is a very low economic net profit per CO_2 emission. As net profit is very low and governmentally subsidised (Sumaila et al., 2019), economic benefit of bottom trawler fishing is becoming more compromised beyond its still important role of providing food supply for human mankind. Purse seine fleets in contrast provide net profit and have a much lower CO_2 footprint, which could be beneficial in future international CO_2 markets, while not enough to fulfil need food supply.

4.2. Fishery impact at ecosystem level

According to the quantitative ecosystem index considering spatial GSA reference (Fig. 4b) or trawlable area (0 - 1000 m, supplementary material Fig. S4), GSA 1&2 and GSA 6 are at risk for overexploitation although the situation has improved in recent years. GSA 5 in contrast is exploited sustainably. Besides, it has to be taken into account that our study only considers bottom trawling and purse seine. Including other gear and bycatch can lift the points even more above the 50 % probability function. Therefore, ecosystem overfishing scenario at GSA1&2 and GSA 6 should be considered seriously compared to GSA 5. These results agree with those obtained with monospecific stock assessment methods for demersal species, which show that the level of exploitation of the stocks exploited in GSA 6 is higher than in GSA 5 (Quetglas et al., 2012). Recent stock assessment shows that, except for the specific target species *Nephrops norvegicus,* the F/F_{MSY} ratio of exploited stocks in GSA 5 is equal or lower than those of GSA 1 or GSA 6 (FAO, 2020b).

Total PPR and %PPR can be achieved by different combinations of fishing gear and vessel size, affecting different marine ecosystems, such as the pelagic ecosystem (purse seine) or demersal-benthic ecosystem (bottom trawling). Thus, the difference between GSAs and the contribution of gear and fleet sections to total PPR and %PPR among GSAs can provide important information where fishery measures should focus, in our case, the PPR in GSA1&2 > GSA6 > GSA5. In GSA1&2, the main contributor to total PPR is purse seine fishery (69 %), which affects the pelagic food-web, while bottom trawling is the main contributor in GSA 5 (84 %) and GSA 6 (70 %), affecting demersal-benthic food-web and ecosystem. This proves that fishing activity is impacting the transfer of energy in the food web at different levels across GSAs. Thus, from the trophic point of view in GSA 1&2, fishery measures should pay special attention to the purse seine fleet. In contrast in GSA 6, bottom trawling should be regulated first. Also at GSA 5 bottom trawling dominates the PPR but relatively low values do not require urgent and in any case more moderate measures.

Comparing the time evolution of TLc of bottom trawling and purse seine, it is remarkable that in all the GSAs, the TLc of purse seine decreases, while the TLc of bottom trawling remains constant or increases. This can indicate that the pelagic target species are objective of down fishing, as has been described for extractive fishery at global scale, where the mean trophic level decreased from 3.3 in 1950 to 3.1 in 1994 (Pauly et al., 1998). Combined climate change and fishing pressure led the small pelagic fish community in the study area close to collapse, and reducing fishing pressure at sites where cumulative climate change is highest has been suggested (Ramírez et al., 2021). Furthermore, middle sized pelagic fish could have declined respect to small pelagic fish, lowering TLc. On the other hand, it is also possible that the landings of high trophic level species remain constant, but in order to increase food availability, additional species with lower trophic level are increasingly landed (Essington et al., 2006). Another factor could be that vessel power reduction between 2008 and 2018 was greater for bottom trawler (from 2008 to 2018 from 156024kw to 93493kw, 40 %) than for purse seine (from 47479kw to 35,609 kw, 25 %) in the study area (STECF, 2020) or deepening in the trawling depth down to −1000 m. A progressive displacement of fleet in the last decade towards deeper strata with species of higher TL have been suggested in other studies (Ramírez et al., 2021; Veloy et al., 2022), which is also consistent with patterns obtained in the present study. In any case, purse seine fishery target species are small pelagic fish and might depend more on large scale phenomena and could be affected by overexploitation at basin scale or large scale fluctuations beyond the Spanish GSAs.

4.3. Carbon release from the seafloor

Continental shelves are the most fertile, productive and dynamic marine ecosystems and are important for carbon cycle models as they are involved in the exchanges of energy and matter between land, atmosphere and ocean (Muller-Karger et al., 2005). Carbon Accumulation Rates (CAR) on the seafloor of the continental shelf is between 5 gC m^{-2} yr^{-1} (Muller-Karger et al., 2005) and 19.6 gC m^{-2} yr^{-1}(Wilkinson et al., 2018) and at least one order of magnitude lower than the highest (CO2$_{\_100\%}$) released carbon rate by bottom trawling on the shelf (134 gC m^{-2} yr^{-1}). Considering the lowest CO_2 release, (CO2$_{\_4\%}$ = 5.36 gC m^{-2} yr^{-1}) and that only 10 % of CAR over the continental shelf is buried in the seafloor (CAR_{buried} = 0.5–1.96 gC m^{-2} yr^{-1}), CO_2 release by bottom trawling is 2.7–10 times greater than the CO_2 buried in the seafloor by the biological pump. This means that in trawlabel areas the trawling released carbon not only equals the sequestered carbon through the biological pump in the present, but also releases additional carbon settled and buried in the past.

According to the CO_2 release by vessel size, the bottom trawler between 18 and 24 m of GSA1&2 and GSA6 would be the most important fleet segments where mitigation measurements for CO_2 bottom release should be focused on. Another mitigation measure could be avoiding fishing areas with high labile CO_2 concentration, such as fine sediment areas around river mouths and deltas. This is the case of the Ebro delta in the GSA 6 with an elevated fishing activity. However, the main goal should be the reduction of bottom trawling damage on the seafloor in order to avoid carbon release from the seafloor. Gear modification could be a promising approach and should reduce bycatch, benthic habitat impact and energy consumption (Guijarro et al., 2017; McHugh et al., 2017). For example, mid-water or flying doors, originally developed to save fuel consumption in order to increase net-profit of trawling fishery and mitigate CO_2 emission by burning fossil fuels (Guijarro et al., 2017), could also reduce contact with the seafloor which is the cause of bottom CO_2 release. In that sense, McHugh et al. (2017) mention several gear modifications and references that reduce contact with the substrate by an average of 75 % (Sterling and Eayrs, 2008; Broadhurst et al., 2012; Broadhurst et al., 2015a; Broadhurst et al., 2015b; McHugh et al., 2015). In light of the elevated carbon release from the seafloor by conventional bottom trawling gears, a triple strategy comprising Restriction, Modernisation and Innovation (RMI) is world widely recommended. Restriction of harmful fishing gears and reservation of coastal zones for selective fishing gears (EC, 2006, measures 14 and 18) should be applied to carbon rich river influenced areas which usually act as a nursery ground; as for example in the case of the Ebro Delta in the GSA 6 (Druon et al., 2015; Tugores et al., 2019; Paradinas et al., 2022). The final goal in critical areas due to their ecological importance and/or the high probability to release carbon might be to eliminate bottom contact completely by bottom trawling restriction or shifting to midwater trawling gears.

4.4. CO_2 footprint of food production

Climate change and feeding of the growing human population are two of the biggest challenges of mankind right now, calling for novel adaptation measures that consider all the complexity in socio-ecological systems and important trade-offs (Hidalgo et al., 2022b). Protein supply by extractive fishery increases CO_2 emissions due to fuel powered fishing vessels. The importance of carbon footprint of food production increases as the global population growth increases, and the human diet towards more plant-based food with less CO_2 footprint is suggested (Sandström et al., 2018). Specially the elevated CO_2 footprint of farmed animals is criticized and reduction in the diary diet proposed (Aleksandrowicz et al., 2016).

Comparison of Green House Gases (GHG) emission per kg food production among different food productions have been evaluated by Poore and Nemecek (2018), beginning with inputs (the initial effect of producer choice) and ending at retail (the point of consumer choice), considering fertilizer quantity and type, irrigation use, soil, and climatic conditions. Our extractive fishery approach considers CO_2 emission processes of purse seine and bottom trawling until the fish is landed at the harbour but not the processing, packaging and transport on land to the end-user. Most of the landed fish might be consumed without further processing and packaging, but transport to the end-user can be important if the site of consumption is far from the landing harbour. Therefore, our CO_2 footprint has to be considered as a minimum value. Comparison of the carbon footprint of both fishing gears and fleet segments, with those of Poore and Nemecek (2018) show that fuel derived CO_2 footprint of purse seine is among the food with the lowest carbon footprint (from 0.49 to 1.21 (kg_{CO2} kg^{-1}_{Food}) (Fig. 8). As purse seine gears do not affect the seafloor only fuel combustion has to be considered as CO_2 emission process. Accordingly, purse seine fishery provides the animal protein with the lowest CO_2 footprint being even lower than some vegetables. Fuel derived CO_2 footprint of bottom trawler is, however, almost an order of magnitude higher (4.39–12.1 kg_{CO2} kg^{-1}_{Food}), and clearly above 1 kg_{CO2} kg^{-1}_{Food}, but still provides a footprint lower than the other animal proteins such as pig meat, farmed fish, Lamb&Mutton (sheep) and beef. However, the bottom released CO_2 footprint due to sweeping the seafloor makes the fish extracted by bottom trawling to the animal protein with the highest CO_2 footprint on the list. Even when the lowest bottom CO_2 release scenario ($CO_{2\_4\%}$) is considered (Fig. 8), the fleet segment DTS 12_24 m is higher than the CO_2 footprint of the second animal protein on the list (Beef (beef herd) = 99.88 kg_{CO2} kg^{-1}_{Food}). The fleet segment DTS_24–40 (88.00 kg_{CO2} kg^{-1}_{Food}) is in the third position, but climbs to the second rank if fuel consumption (12.1 kg_{CO2} kg^{-1}_{Food}) is added. Thus, considering the lowest CO_2 bottom release scenario ($CO_{2\_4\%}$) and fuel consumption all bottom trawling fleets show the highest CO_2 footprint per kg food. Accordingly, bottom trawling protein production is at least among the protein productions with the highest CO_2 footprint. Therefore, bottom trawling should urgently reduce CO_2 emission, focussing preferably on reduction of bottom released CO_2 footprint by reducing the contact of the fishing gear and/or avoiding it in certain areas. Furthermore, reduction of bottom contact clearly reduces fuel consumption which is more important to guarantee net profit. Thus, investigation on alternative fishing gear with less impact on the seafloor should be encouraged urgently.

5. Conclusions and implications

Our study provides transdisciplinary information that allows identifying key points and strategies for developing plausible mitigation and adaptation actions to facilitate a fast transition towards reduction of Green House Gases emission, economic and ecologic sustainable fishery in the Mediterranean Sea. This will be a key component of the objective stablished in the GFCM 2030 Strategy (FAO, 2021).

Purse seine net profit per CO_2 footprint (€ kg^{-1}_{CO2}) is higher than for bottom trawlers; and within bottom trawler CO_2 footprint is smaller for small trawlers than for bigger ones. Thus, climate change mitigation and economic strategies should focus on favouring purse seine fishery and small bottom trawlers, if reconcilable with local stock resilience studies. From the trophic point of view, downscaling of extractive fishery is required at GSA 1&2 and GSA 6 to reach sustainable exploitation, with measures primarily focused on purse seine in GSA 1&2 and bottom trawling in GSA 6. GSA 5 in contrast does not require special actions at the moment.

The bottom released carbon by trawling not only equals the sequestered carbon through the biological pump in the present, but also releases additional carbon settled and buried in the past. Thus trawled continental shelves turn from areas with CO_2 sequestration by the biological pump into CO_2 source areas due to bottom trawling, a fact that should be included

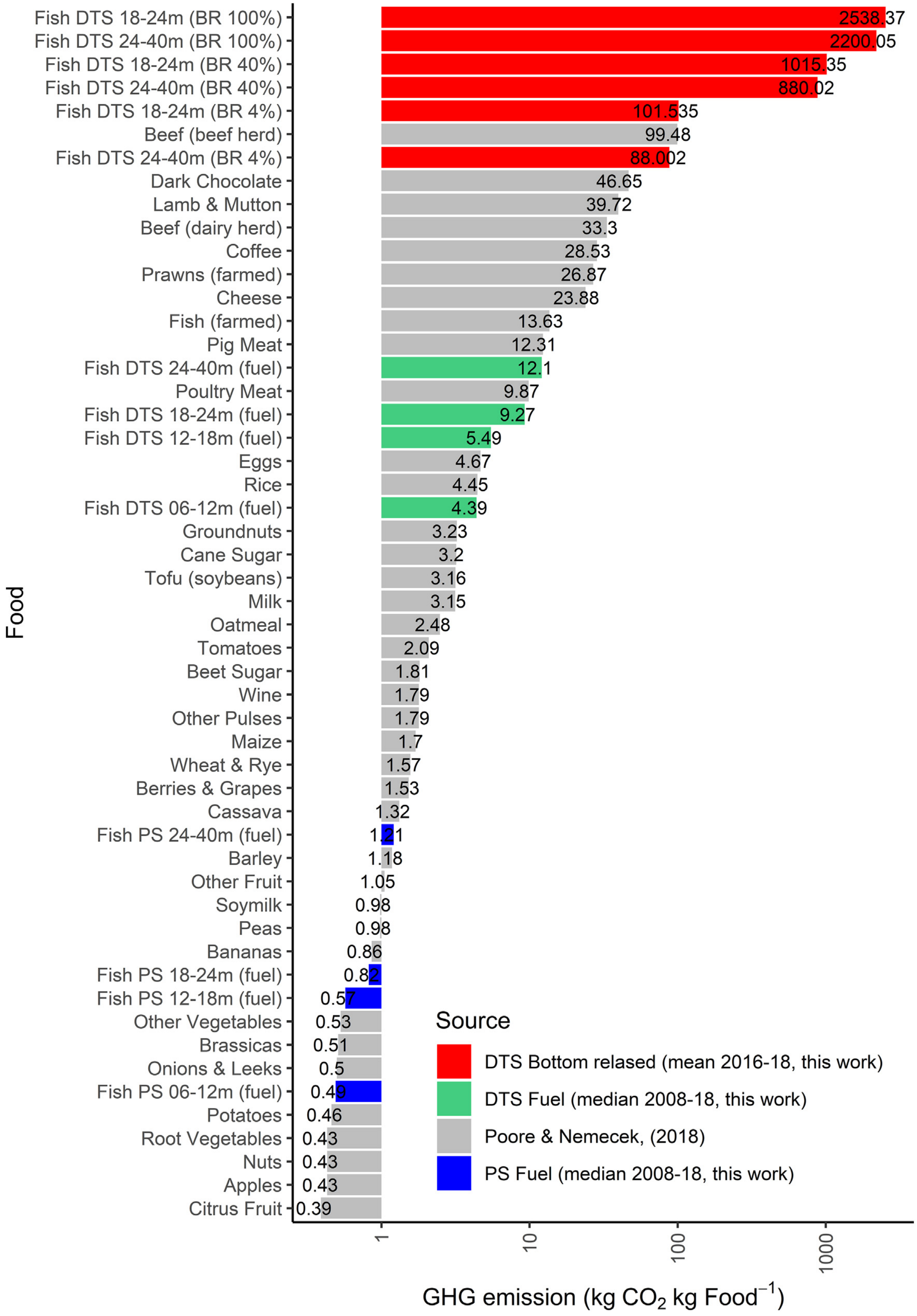


Fig. 8. Carbon footprint of different food categories (source: own data, Poore and Nemecek, 2018). Details about the methodology used by Poore and Nemecek can be found under the subheading "Building the multi-indicator global database" and supplementary material of the article of Poore and Nemecek (2018).

in climate models and requires urgent measures to reduce carbon release from the seafloor by trawling, such as: (i) modernisation of the traditional gear to gear with less contact to the seafloor which reduces both, fuel and sweep derived CO_2 footprint and (ii) restriction of harmful fishing gear and reservation of coastal zones for selective fishing gear should be mainly applied to carbon rich river influenced areas which usually act as a nursery ground.

The sweep derived CO_2 footprint makes food production (extraction) by bottom trawling to one of the proteins with the highest CO_2 footprint, while purse seine fishery provides the protein with the lowest CO_2 footprint. Recommendation for low carbon footprint food, requires detailed analyses of the fishing gear used before classifying the CO_2 footprint of extracted fish and suggest diets with low carbon footprint. Given the likely uncertainties (more than one order of magnitude!) of CO_2 bottom release, field measurements in adjacent trawled and untrawled areas are urgently needed. Nonetheless, including bottom released CO_2 estimation in carbon budget of extractive fishery is crucial for climate change adaptation even if the lowest carbon release is applied.

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CRediT authorship contribution statement

M.M.: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, original draft writing, Writing - review & editing.

R.A.: Data curation, Methodology, Writing - review & editing.

G.B.: Writing - review & editing.

M.H.: Supervision, Project administration, Writing - review & editing.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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