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Blue carbon accounting as metrics to be taken into account towards the target of GHG emissions mitigation in fisheries

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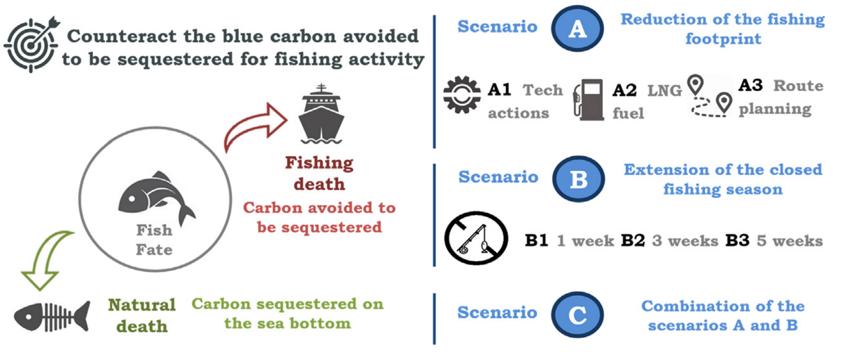
HIGHLIGHTS

- Carbon cycle characterization of a specific species of fish: *Scomber scombrus*.
- Fishing footprint is the main carbon outflow of the whole carbon cycle.
- Corrective measures for counteracting the avoided blue carbon sequestration.
- Vessel improvements and closure periods reported significant carbon reductions.
- More fishing databases are vital to extend the analysis to other case studies.

GRAPHICAL ABSTRACT



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ABSTRACT

The adoption of the 2030 Agenda for Sustainable Development must address the balance between sustainable growth and tackling climate change. In this context, forests can help to reduce greenhouse gas (GHG) emissions, unfortunately, equivalent solutions in the ocean are often overlooked. Moreover, the complexity in determining the real impact of fishing on the environment is not a trivial issue. Thus, the aim of this study is to broaden the scope and analyse, for the first time, the entire carbon cycle associated with the life cycle of a fish: *Scomber scombrus* from a fishery located in the Cantabrian Sea (Spain). From this carbon cycle assessment, it is estimated that fishing activity has prevented 871.7 t of carbon (in terms of blue carbon) from being sequestered each year. This value comes from the fraction of fish that would have died of natural causes if they had not been caught, reaching the seabed, and undergoing remineralisation processes of the carbon content of their bodies. Beyond these results, it is vital to implement a series of actions with the aim of counteracting the amount of carbon that could have been sequestered on the seabed by the natural death of the fishes if they had not been caught. To this end, it is shown that the implementation of technical improvements to the vessels, the replacement of the current fuel used and the rearrangement of shipping routes in combination with an extension in the closed fishing season and a commitment to an omnivorous diet, allows for a reduction in carbon flow of almost 90 % of the blue carbon that has been prevented from being sequestered by fisheries. A consequential approach can then identify the influence of the proposed changes on their corresponding carbon flows for use as decision criteria in regulating fisheries and environmental management policies.

1. Introduction

Recently, the situation caused by COVID-19 indirectly generated remarkable changes in the fisheries sector (Campbell et al., 2021). The different activities necessary to supply fish products from production to the final consumer have been affected not only by new sanitary measures but also by

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a change in consumption habits. On the positive side, the reduction in extractive fishing activity have led to improvements in marine ecosystems. However, this circumstance cannot last over time as dietary patterns are affected by the lack of one of the main sources of protein and micronutrients (FAO, 2021). Therefore, the environmental protection of marine ecosystems must be balanced with its sustainable exploitation.

On a broader horizon, extractive fishing activities have continued to increase over the last half century, which could be related to the current depletion of marine stocks, although gaps in data availability prevent draw clear conclusions (Anticamara et al., 2011). On the other hand, environmental impacts associated with human activities, have an adverse effect on the viability of stocks (Dawson et al., 2011).

To reverse this trend, it is necessary to examine the current challenges in quantifying the environmental profile of fisheries activities, as well as to propose measures to protect fish production and maintain the supply chain. For that, different CO_2 sequestration techniques are currently being investigated as a climate change mitigation strategy. In the case of terrestrial ecosystems, CO_2 is removed from the air and stored as organic matter through photosynthesis of the plant mass (Falkowski et al., 2000), this is the case for forests (Jandl et al., 2007), although there are others such as mangrove forests, tidal marshes or seagrass meadows (Alongi, 2012), which imply almost two orders of magnitude greater in terms of carbon sequestration (Wedding et al., 2021). Despite their importance, coastal ecosystems suffer from a high rate of human disturbance (around 40 % in the 20th century) to such an extent that they may constitute a source of their long-term carbon capture and storage (Irving et al., 2011). All of these involve ecological damages that can translate into monetary units equivalent to billions of dollars per year (Pendleton et al., 2012).

This type of organic carbon sequestered and retained in both plant mass and sediments beneath coastal and marine ecosystems is commonly referred to as "blue carbon" (Macreadie et al., 2019). Within this conceptual framework, different projects have emerged. One of them is the "International Blue Carbon Initiative", composed of governments, research institutions and other organizations that work together for both the protection and restoration of these types of ecosystems with the aim of reducing the impacts caused by global climate change (The blue carbon initiative, 2018).

In terms of the carbon sequestration potential provided by the ocean, more than 80 % of global carbon circulates in its waters, and half of this is sequestered in ocean sediments (IUCN, 2017). In recent years, the considerable contribution of inland waters has become increasingly evident, making them suitable for inclusion in climate change strategies (Battin et al., 2009). Indeed, this gaseous exchange could be considered as the most important ecosystem service provided by marine ecosystems (Hori et al., 2019). Moreover, beyond the role of water in carbon cycling, its biota also come into play in controlling carbon exchanges between ecosystems through different chemical processes (Schmitz et al., 2018). For example, in terms of flora, the combination of seagrasses and a low amount of herbivore predation leads to the accumulation of high amounts of carbonaceous organic matter that is stored in marine sediments through detritus (Howard et al., 2018).

With reference to fauna, fish produce carbon in form of carbonates during their lifetime, which are then excreted by osmoregulatory reactions (Wilson et al., 1996). This flow has a remarkable impact on the inorganic carbon cycle, constituting up to 15 % of all ocean carbonate produced.

However, fish not only contribute to the carbon cycle during their lifetime, but also after their death. This is, in fact, one of the most underestimated carbon streams in the sea, which comes from the natural decomposition of fish carcasses once they reach the seabed. Its importance lies in the moderately easy way to control it, as it is directly related to fishing through two different pathways: modifications of fishing seasons with respect to reducing fishing effort would reduce the carbon footprint (CF) and, at the same time, increasing fish stocks would improve ocean biomass and thus the blue carbon sequestered on the seabed (Mariani et al., 2020).

In view of the above, due to both the current situation of depleting fish stocks and increasing pollution, it is important to change the management of the fisheries sector aiming to increase its sustainability in accordance with restrictive environmental legislation. To this end, this study presents a novel methodology based on the identification of the whole carbon cycle of a specific species (*Scomber scombrus*) integrating the approaches of blue carbon and life cycle assessment. This could prove to be a useful tool to identify the greenhouse gas (GHG) hotspots of the fishing activity, in addition to being used to propose mitigation measures for environmental policies.

2. Materials and methods

2.1. Purpose of the study

The main objective of this study is to characterize the carbon cycle associated with the life cycle of a specific species of fish: *Scomber scombrus*, as a representative example of a Spanish fishery species abundant in the Atlantic Ocean and the Mediterranean Sea.

Therefore, this study proposes a methodological framework that aims to establish a tool to estimate, in a relatively simple way, the impacts of the fishing sector on the environment beyond its direct consequences (its CF). This has been made possible through the quantification of the blue carbon contained in the body of the fish that has been prevented from being sequestered on the seabed by natural death, having been captured during the development of the fishing activity (death by fishing).

To do this, it is necessary to establish the different subsystems involved in the global carbon cycle, identifying and evaluating various carbon flows associated with it in order to estimate a final value according to the main inputs and outputs.

Once the whole carbon cycle has been characterized, the next goal will be to modify the carbon flows by assuming different fisheries management scenarios to try to mitigate the amount of carbon that has been avoided to be sequestered for fisheries in terms of blue carbon.

The ultimate goal is to have a working tool that broadens the approach to carbon flows that have been considered so far in the LCA literature.

2.2. Scope definition

The species chosen for the carbon cycle approach was Atlantic mackerel (*Scomber scombrus*) due to its considerable importance in the overall fish stocks of Iberian waters, as well as the availability of year-round consumption in a relatively cost-effective way, representing a healthy and protein-rich source option at an affordable cost in the markets (Mercasa, 2020).

To define the total life cycle of this specimen, data on natural and fishery mortality rates have been compiled from previous studies carried out in the area of the Bay of Biscay (NE Spain) (Sánchez and Olaso, 2004). Catch data correspond to records collected for a fleet located in the NW Cantabrian Sea for the 2018–2019 season. Once the fish was landed at the ports, processing (freezing), management of discards from the processing factory (including anaerobic co-digestion of waste and energy recovery in a cogeneration plant) and final human consumption were considered to identify the different carbon streams of the carbon cycle. Any other carbon streams corresponding to the logistics of transporting fish from the port to the processing plant and from there to the different points of sale, as well as other contributions related to the cooking of fish for human consumption are outside the scope of this study.

2.3. Methodological framework

Different subsystems have been proposed as the most influential in the whole fish carbon cycle, as shown in Fig. 1: fish fate, fishing activity, food processing, waste management and food intake. In this sense, the carbon flows of each subsystem, as well as their interactions, have been considered.

The methodology followed for estimating the carbon flows associated with each of the subsystems is described below. The data and the equations used for their calculation are collected in the supplementary material (SM) file.

Carbon stream	Acronym
Blue carbon flow	CBC
Fish catching carbon flow	CFC
Fishing footprint carbon flow	CFF
Process emissions carbon flow	CPE
Food waste carbon flow	CFW
Waste treatment carbon flow	CWT
Avoided emissions carbon flow	CAE
Food processed carbon flow	CFP
Human metabolism carbon flow	CHM

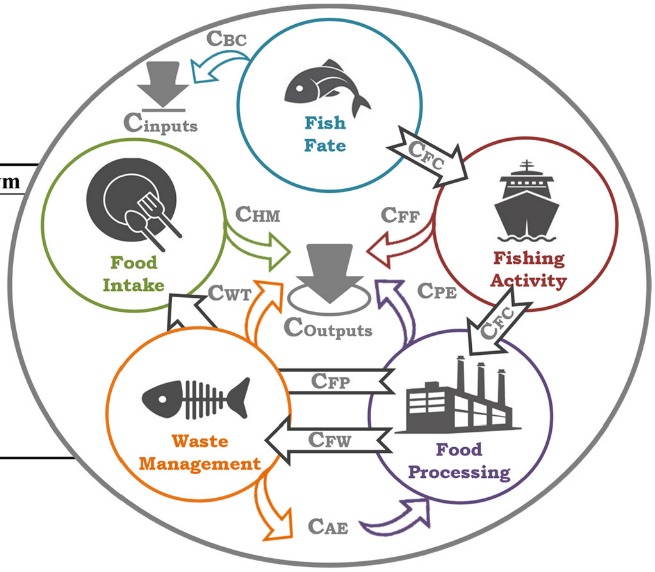

Fig. 1. Carbon cycle of a fish. Each circle illustrates a subsystem: fish fate, fishing activity, food processing, waste management and food intake. The grey circle represents the entire carbon cycle, with its inputs (C_{BC}, C_{AE}), and its outputs (C_{FF}, C_{PE}, C_{WT}, C_{HM}).

2.3.1. Fish fate subsystem

This subsystem considers two carbon flows: one input (blue carbon flow), and other, the fish catching carbon flow which is transferred to the second subsystem (fishing activity).

On the one hand, the fish catching carbon flow was calculated taking into account the whole-body carbon content of the Atlantic mackerel which were removed by fishing from the ocean. Czamanski et al. (2011) estimated a carbon content for this specimen of around 46.8 % in a study where the elemental characterization of several species from the Bay of Biscay was conducted in terms of C, N and P. Although this is a value from a different region to the current case study, very low elemental differences have been identified in fish species regardless of their location, time of capture or nutritional value (Tanner et al., 2000). Therefore, using data collected from a fishing fleet located in the Cantabrian Sea in relation to annual fish catch of *Scomber scombrus* (2019 season), the amount of carbon extracted from the fishing activity was calculated (Eq SM1) in units of tons of carbon per year (tC·year^{-1}).

On the other hand, the blue carbon flow is based on natural and fishery mortality rates. Hence, when fish die of natural causes (no predation), if the carcasses are of a certain size (lengths greater than 30 cm), they are more likely to tend to sink rapidly and reach the seabed, leaving insufficient time to decompose along the water column. They constitute an input in the carbon cycle, then assigning it a negative sign (-tC·year^{-1}), as their biological carbon content will be sequestered on the seabed for long periods of up to millions of years through a remineralisation process, known as "blue carbon" (Macreadie et al., 2019). Its calculation (Eq SM2) is derived from the procedure followed by Mariani et al. (2020), who assume an equilibrium in the stock, as well as that it is fished at a maximum sustainable yield level, which is the highest catch that can be removed from a population by fishing over an indefinite period under average environmental conditions (Froese et al., 2019). For this study, fisheries data and mortality rates were collected from Ecopath with Ecosim trophic modelling in the Cantabrian Sea. This tool uses a trophic mass balance approach that reports values of 0.14 and 0.29, for the fishery and natural mortality rates of Atlantic mackerel, respectively (Sánchez and Olaso, 2004).

2.3.2. Fishing activity subsystem

The fishing footprint carbon flow was calculated thanks to the employment of an attributional LCA methodology (ISO, 2006a, 2006b). The goal was the estimation of the CF associated with the Atlantic mackerel captured by a fleet of trawlers in the Cantabrian Sea relative to one year of fishing campaign (2019). For that, the system boundaries of the fishing activities (Figure SM1) were defined following a cradle-to-boat gate approach, considering all the inputs and outputs from the production of the raw materials, transport and consumption phases until the fish caught are returned to port. The functional unit (FU) selected was 1 t of Atlantic mackerel in perfect conditions to be processed.

All the necessary data for the life cycle inventory (LCI) were collected directly through interviews with fishermen who were provided with a set of questionnaires, which were filled in with relevant information corresponding to the annual consumption of marine diesel oil, marine lubricating oil, refrigerant gas (R507), ice, paint, antifouling, trawl nets and water intake, as well as the infrastructure materials required for the construction of the vessel. Additionally, for certain flows consumed during the fishing vessel operations, it was necessary to consider certain assumptions and carry out the modelling of their impacts (see Section 2.1 of the SM).

For sharing the environmental burdens between the target specimen and other secondary species, a mass allocation was performed: *Scomber scombrus* with 930 t of captures (94.51 %) and *Merluccius merluccius* with 54 t (5.49 %). Inventory data (Table SM3) was implemented in the SimaPro v9.0 software and the characterization factors from the ReCiPe v1.1 2016 Midpoint method (Huijbregts et al., 2017) were used to estimate the score. In addition, the Ecoinvent v3.5 database (Wernet et al., 2016) was used for the modelling of the background processes involved in the production of the required inputs.

Once the CF was obtained having selected the global warming impact category per FU (t CO_2 eq·t fish^{-1}), the carbon flow associated to the fishing footprint was calculated using the Eq SM3 having considered the annual catch of the 2019 season (930 t).

2.3.3. Food processing subsystem

Primarily, this subsystem has a carbon flow output (process emissions carbon flow) that derives from the processing of the Atlantic mackerel fished. This basically consists of freezing (individual quick freezing method) and packaging (plastic wrapping and cardboard box) the fish to be put subsequent marketing.

For its estimation, an analogous calculation methodology of the fishing activity subsystem was followed. Then, after the system boundaries definition (Figure SM2) and electricity modelling (Table SM4), primary data at factory scale was compiled to elaborate an LCI of all material and energy inputs required for the processing of frozen fish (Table SM5), as well as to calculate the CF associated with the industrial process (Eq SM4).

Secondly, from the factory two different carbon flows emerge depending on the comestible content of the Atlantic mackerel: the edible portion will be the input (food processed carbon flow) for the food intake subsystem (Eq SM5), while the uneatable part will be the input (food waste carbon flow) of the waste management system (Eq SM6).

2.3.4. Waste management subsystem

The discard fraction has been processed in an anaerobic digester in order to valorise biogas production (Ivanovs et al., 2018). In addition, this waste management process will be coupled to a combined heat and power (CHP) plant, while at the same time reducing GHG emissions by supplying electricity to the processing plant, making it an ideal candidate as an input (-tC·year^{-1}) to the fish carbon cycle (avoided emissions carbon flow).

First, the digester input mass flow (Eq SM7) was characterized in terms of volatile solids content to estimate the theoretical biogas production yield (Eq SM8). For this purpose, standard temperature and pressure conditions were assumed, as well as the use of sewage sludge as inoculum (Eiroa et al., 2012). On the other hand, 60 % of methane in the biogas was considered for the calculations (Anukam et al., 2019).

Once the output composition was defined, the amount of potential electricity from the biogas was calculated using Eq SM9 (Arias et al., 2020; McAllister et al., 2011).

After this, two carbon flows associated with this subsystem were estimated. On the one side, there is an input: the carbon flow related to the electricity produced in the CHP plant (Eq SM10), as well as an output of the carbon flow related to the waste treatment emissions derived from the activities carried out in the industrial facility (Eq SM11). The CHP plant was implemented in the food processing factory, so the electricity production derived from anaerobic digestion is used to supply the energy demand of the processing industry. Thus, the negative value of the avoided emissions carbon flow was used to offset the process emissions carbon flow from the food processing subsystem.

2.3.5. Food intake subsystem

The carbon content of the edible portion will be emitted as CO_2 after its consumption in the diet (human metabolism carbon flow). For its calculation (Eq SM12), a specific catabolic reaction (Muñoz et al., 2008) was taken into account together with an average nutritional content of degradable constituents: carbohydrates, fats and proteins (BEDCA, 2006) to obtain a human emission factor (Table SM6).

2.4. Carbon cycle

Once the carbon cycle was characterized, the objective was to modify the values considered in the search to determine the robustness of the proposed method, as well as to find the best options to achieve a full offset of the avoided blue carbon sequestration. Therefore, to counteract the current imbalance of the entire cycle for the Atlantic mackerel fishery, three different scenarios were proposed: A (reduction of the fishing footprint), B (extension of the closed fishing season) and C (a combination of both).

2.4.1. Scenario A: Reduction of the fishing footprint

Regarding Scenario A, the principles of the measures aimed at reducing the fish footprint are related to minimizing the impact caused by fuel, as it has been shown to involve the main environmental burden in fishing activity (Avadí and Fréon, 2013). Consequently, the implementation of three different corrective measures was proposed: technological improvements in the vessel infrastructure (scenario A1), use of an alternative fuel (scenario A2) and optimization of the navigation route (scenario A3), as well as all possible combinations between them (scenarios A1–2, A1–3, A2–3 and A1–2–3).

For the first option (A1), there are procedures to minimize fuel consumption related to the shape of the vessel hull and drive systems. However, those based on optimizing the propeller design as well as its rotational speed stand out, as they have proven to be the most promising improvement opportunities, achieving ranges of 10 % to 20 % more energy efficiency (Schau et al., 2009). In this case, considering that the different design improvements described above are implemented in the fleet under study, it was assumed that it would be possible to achieve a 15 % reduction in fuel consumption.

In scenario A2, liquefied natural gas (LNG) was selected as a potential short-term alternative to traditional fuel (diesel) due to the long-standing interest in using it in shipping for both economic and environmental reasons, as well as its suitable implementation in some currently operating fleets (Burel et al., 2013). This alternative can reduce the CO_2 emission factor by 20 % (Herdzik, 2011).

Scenario A3 implies the implementation of a new sea route planning that reduces fuel consumption through moderation of vessel speed, even if it means longer fishing days. Consequently, more efficient driving translates into both lower energy demand and lower GHG emissions (Mesquita et al., 2017). In fact, a modelling study of a trip following these assumptions from Portugal to Norway reports up to 15 % less fuel used and 16 % lower CO_2 emission factor (Vettor et al., 2016). In this case study, it was assumed the reduction of 10 % for both fuel consumption and CO_2 emissions.

2.4.2. Scenario B: extension of the closed fishing season

The total catches used in this study were estimated considering 141 working days per year, whereby the reduction in catches has been made possible by extending the closed fishing season. This option is increasingly being used due to social awareness of the overexploitation of many fishing grounds despite its unquestionable negative economic impacts (Cohen et al., 2013).

The closed fishing season was increased by three different time periods of one (scenario B1), three (scenario B2) and five (scenario B3) weeks, respectively, considering that one week includes six working days. Therefore, it is necessary to re-estimate all carbon flows of the carbon cycle, reporting a less avoided blue carbon flow as well as lower carbon flow outflows. However, it will also lead to a shortage of protein intake resulting from a lower fish supply. To this end, according to the main diets recommended in Spain: Mediterranean, South Atlantic European and Spanish dietary guidelines (González-García et al., 2020), several dietary habits (vegetarian, carnivorous and omnivorous) have been proposed as being able to readjust this protein shortage through other potential sources: legumes and meat (Tharanathan and Mahadevamma, 2003).

Therefore, the modus operandi followed was to estimate the amount of protein lost from fish that will not be caught due to the extension of the closed fishing season and replace it in an equitable manner with three other sources of protein based on different dietary patterns: vegetarian diet (chickpeas, beans and lentils), carnivorous diet (beef, chicken and pork) and omnivorous diet (chicken and chickpeas, pork and beans and lentils). For example, in the case of the carnivorous diet, if it is assumed a protein shortage due to the extension of the closed fishing season of 75 kg, this amount of protein will be replaced equally for beef, chicken and pork, which means 25 kg of protein from each of them.

Subsequently, the environmental impact of all feeds was calculated in terms of kg of CO_2 eq per kg of protein provided (González-García et al., 2020), obtaining a final value for each of the diet plans considered by summing them up. These results will be taken into account to obtain the carbon balance of the different B scenarios, with the possibility of obtaining better or worse results depending on the environmental profile of the proposed diet plan compared to that previously established (carbon flow of the fishery footprint).

2.4.3. Scenario C: combination of the scenarios A and B

Finally, the combination of scenarios A and B has been considered as feasible in pursuit of reducing as much as possible the outputs of the carbon flows from the entire carbon cycle in order to compensate the blue carbon that has been avoided to be sequestered on the seabed. With such aim, the results of the reduction obtained (in percentage) of each scenario (A + B) will be aggregated to try covering even more the goal set. For that, two main criteria: the amount of carbon that are able to reduce, as well as the viability for developing it; will be the determining factors applied to every scenario (A and B) for choosing which ones will appear in the final scenario (C).

3. Results and discussion

3.1. Carbon cycle balance

The results obtained following the methodology detailed above are summarized in Fig. 2 in units of tons of carbon (tC) per year. The first subsystem, fish fate, is composed of two streams: fish catch and blue carbon, which imply carbon flows of 435.2 and 901.6 t/year, respectively. These values derive from the carbon content of the species (46.8 %) (Czamanski et al., 2011) according to the catches corresponding to the 2019 fishing year which was 930 tons of Atlantic mackerel, as well as the individual contribution of fishery (0.14) and natural (0.29) mortality rates with respect to the total mortality rate (0.43). These scores lead to a carbon sink subsystem, as the carbon flow from sunk biomass is higher (as a cause of the natural mortality rate) than the carbon flow from fish catch due to the lower fishery mortality rate. However, this is a common finding in other species, such as horse mackerel, blue whiting, anchovy, sardine or squid where the natural rate is higher (Sánchez and Olaso, 2004).

The second subsystem, fishing activity, involves a transition carbon flow in relation to the carbon content of the fish that are caught (fish catch) to the food processing subsystem. On the other hand, during the fishing activity there is another carbon flow from the emissions of the fishing activity, its score (1227 tC) comes from an emission of approximately 1.32 t of CO_2 eq·t fish^{-1}, similar in comparison to that reported by Iribarren et al. (2011) for a Galician fleet with the same target species and fishing gear (0.88 CO_2eq per ton of fish).

Considering the third subsystem (food processing), the carbon flow related to the fish catch of the previous subsystem is disaggregated into two flows that are associated with the food portion of the fish caught (food processed carbon flow: 309 tC) and the one linked to the fraction considered as waste (food waste carbon flow: 126.2 tC). In addition, this subsystem has an impact through process emissions of 166.5 tC annually.

However, this is associated with the waste management subsystem, which contributes to the whole carbon cycle with a carbon flow equal to −29.9 tC, thanks to the higher amount of avoided emissions (53 tC) compared to the on-site emissions of the waste treatment plant (23.1 tC). These values are better understood under the focus of the methane production rate (0.35 l/g SV) compared to other fish species, such as tuna, sardine or marlin, with methane production yields of 0.28, 0.25 and 0.26 l/g SV, respectively (Eiroa et al., 2012). Unlike other food waste, it is at an intermediate point between the values obtained with cauliflower stems (0.33 l) and mango (0.37 l), although there are other wastes with considerably higher methanogenic potentials such as onion peel (0.40 l) or lemon peel waste (0.47 l) (Ji et al., 2017).

The last subsystem (food intake) is associated with CO_2 released by human metabolism through digestion of processed food, this constitutes an immutable carbon flow of the cycle reporting 253 tC per year (approximately 15 % of the total outputs).

Finally, the entire carbon system encompasses all five subsystems, differentiating between inputs and outputs. In terms of inputs, the reduction target in relation to avoided input is −871.7 tC, as thanks to the contribution of the waste management subsystem it can been achieved an additional carbon flow contribution of −29.9 tC. Despite the above, this is only a small amount, so in order to reverse the dominance of outputs over inputs the most viable solution is to reduce the identified outputs. Given that the fisheries footprint is the predominant

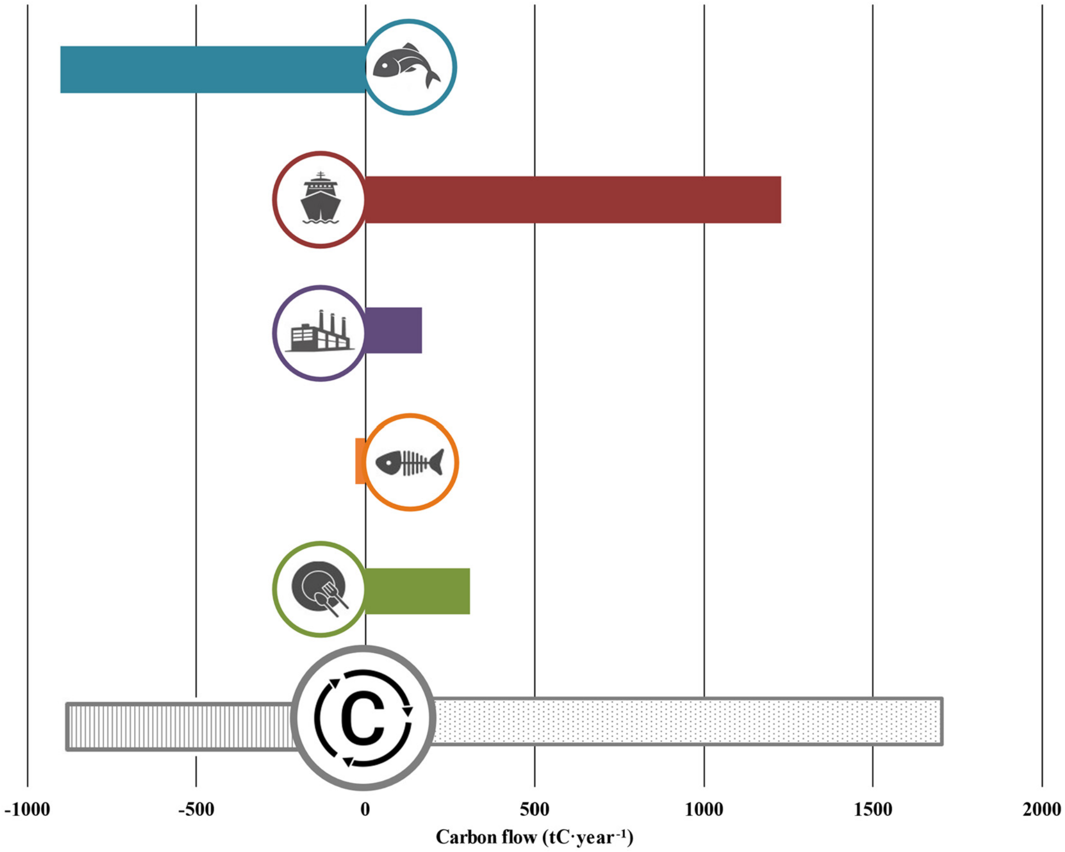

Fig. 2. Carbon flows for each subsystem: fish fate (blue), fishing activity (red), food processing (purple) waste management (orange) and food intake (green), included the total inputs (vertical stripes) and outputs (dotted) of the whole carbon cycle (grey) of the Atlantic mackerel fishing per year.

quantified output (more than 73 % of the total output contribution), it is reasonable to combine efforts for reducing this carbon flow.

3.2. Scenario A: reduction of the fishing footprint

The reported results of the reduction achieved (in %) for the different proposed A-scenarios in relation to the carbon target set (−871.7 tC) are shown in Fig. 3.

Scenario A-1 reports an imperceptible result, with only a 2.5 % reduction above the previously set target. The reason behind this result may be due to the fact that although fuel consumption has been reduced by 15 %, trawling, the fishing gear used to catch Atlantic mackerel, has proven to be one of the most energy efficient, reporting values of 0.354 kg of fuel per kg of fish captured (Jafarzadeh et al., 2016). The same is true for this case study, where the energy efficiency was calculated: 0.337 kg fuel·kg fish^{-1}, obtaining similar values in relation to the previous study.

Fuel substitution by LNG (scenario A2) is the proposal with the best result achieved among the three alternatives with a 22.8 % reduction, however, this has some drawbacks. Among them, it involves an investment for configuration costs, prior training courses for fishermen are required, as well as having to maintain stricter safety conditions (Jafarzadeh et al., 2017). Despite this, in a comparative study against other suitable alternatives, LNG has reported the most promising results in terms of particulate matter production, photochemical ozone, acidification, eutrophication and total energy extracted (Brynolf et al., 2014).

Regarding the scenario A3 (route planning), this is where the worst results are obtained, with only a 2.4 % reduction. The implementation of this scenario, which reports a 10 % reduction in both fuel consumption and CO_2 emissions, is based on the modification of the navigation route through the weather forecast at sea, as storms with high wind and waves will result in higher fuel consumption for the ship. Despite that, fish prices is still the main reason to go fishing (Bastardie et al., 2013).

Having studied the different A-scenarios individually, it is now time to explore all possible combinations between them. As expected, the common action of all of them is the one that achieves a significant percentage of reduction (38.5 %), but it is also the one that implies the highest number of obstacles for its implementation. To this end, it might be more interesting from a feasibility point of view to compare the different scenarios that combine only two alternatives. Among them, scenario A2–3 stands out above the rest with a reduction of 36 %, while scenario A1–3 only achieves a 15 % reduction, achieving worse results than other scenarios that implement individual actions (scenario A2). On the other hand, scenario A1–2 exceeds the results reported for scenario A2, but only by a little (25.4 %).

3.3. Scenario B: extension of the closed fishing season

Scenario B involves different implications due to the prolongation of the closed fishing period. Among them, on the one hand, there is the immediate consequence of fishing less amount of fish per year, consequently, there will be less amount of protein in human diets. Therefore, three diets of a vegetarian, carnivorous and omnivorous nature (including other protein sources), have been proposed for counteracting the shortage of fish protein. Each of them is composed of three main meals that would be consumed equally so that their nutritional values satisfy the protein gap produced. This is why the CF of each meal has been calculated in terms of tC. After that, the sum of the three meals integrates the environmental loads of the diets (diet footprint). Finally, this final value will be balanced with the fishing footprint, allowing to know whether the transition in dietary patterns can be more (reduction) or less (increase) environmentally sustainable (Fig. 4). For more information about the calculation procedures followed, see Section 2 of the SM.

According to scenario B1, it can be seen little differences between the vegetarian and omnivorous diets, as both achieve similar reduction results (15.2 % and 11 %, respectively). In contrast, in the case of the carnivorous diet, an increase of more than 25 % is shown, demonstrating that a meat-based diet leads to a more significant environmental impact rather than a fish-based one. The above has been the subject of discussion in other scientific publications available in the literature, where meat consumption has been shown to have a greater impact on the environment in terms of GHG emissions (up to 53 % higher) compared to fish eaters (Scarborough et al., 2014).

On the other hand, the scenario B2 shows greater differences in the results obtained for the two potential alternatives that remain: the vegetarian and omnivorous diets, with reduction percentages of 44.1 % and 31.5 %, respectively. This remarkable value of the vegetarian diet can be explained by the low environmental impacts reported for beans, chickpeas and lentils. This is in line with the study by Reijnders and Soret (2003), in which they calculate that for each gram of fish protein about 14 times more fossil fuel consumption is required compared to vegetable protein.

As expected, a five-week longer closed fishing season (scenario B3) achieves the best results. However, this would mean reducing the current fishing season in place (141 days) by almost 18 %, unleashing significant economic and social barriers, although it is a difficult task to estimate, in monetary terms, all the costs (loss of employment, instability of the fishing sector) and revenues (ecological conservation, improvement of ecosystem services provided) involved (Failler and Pan, 2007).

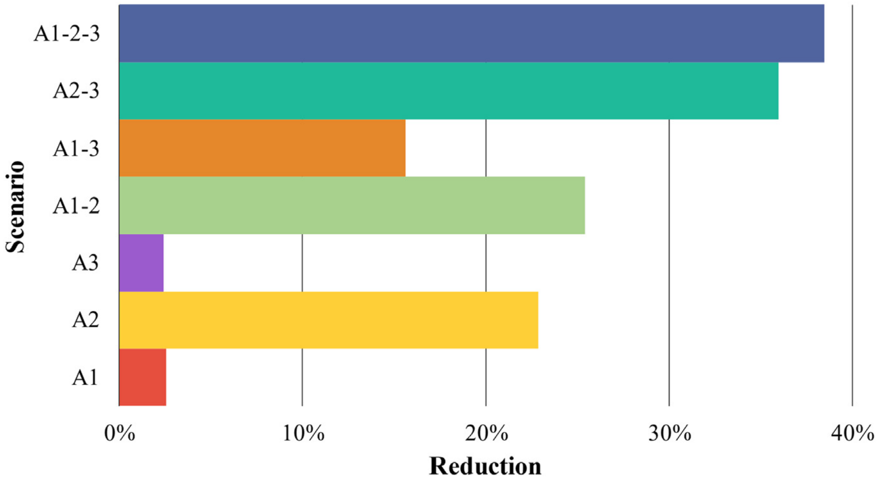

Fig. 3. Contributions of A-scenarios in the reduction of the target set (−871.7 tC).

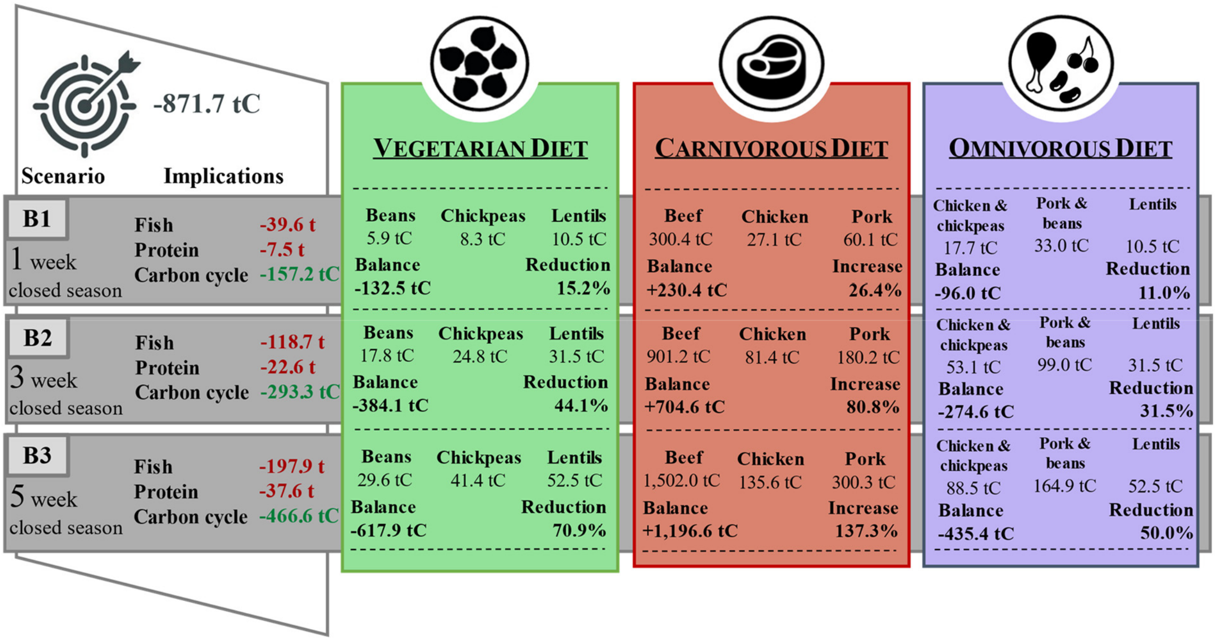

Fig. 4. Implications of the B-scenarios to the fish shortage, protein scarcity and the reduction in the fishing footprint, as well as the balance of each one of the diets proposed: fishing footprints reduction plus the contributions of the diets (summatory of the CFs of the three meals) and their percentage of reduction (or increase) according to the target of reduction set (−871.7 tC).

3.4. Scenario C: combination of the scenarios A and B

Finally, in scenario C (Fig. 5) the main contributors of A-scenarios (A1–2, A2–3 and A1–2–3) have been aligned to the positive implications achieved for the omnivorous diet (scenarios B1, B2 and B3), as it has reported good results in terms of reducing the fish footprint, as well as being more appropriate if people might be willing to make a transition to more environmentally friendly eating habits.

From the aggregation of the first alternative considered in the omnivorous diet of the scenario B (B1) with A-scenarios, it is shown that all three scenarios achieve percentages between 25 and 50 %. Therefore, extending the closed fishing season by only 1 week per year seems insufficient, as it

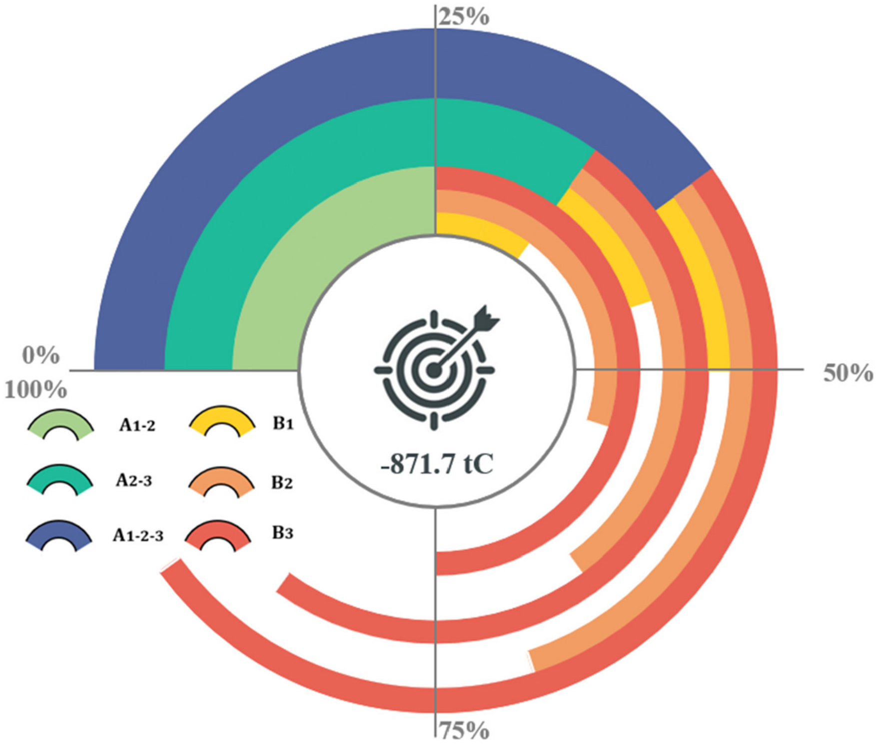

Fig. 5. Results of the combined actions of the main contributions of A-scenarios (A1–2, A2–3 and A1–2–3) and the omnivorous diet of scenario B (B1, B2 and B3) in the reduction of the target set (−871.7 tC).

can only reach half of the target set. When it moves to the combination of A-scenarios with B2, the results are placed in the second quadrant of the circumference, obtaining more relevant results up to 67 % and 70 %, for scenarios A2–3 + B2 and A1–2–3 + B2, respectively. Finally, establishing a five-week extension of the closed fishing season (scenario B3) reports the most promising values, with reductions from 75 % to 88 %. Thus, in view of the results obtained, although the main objective was not achieved with the current proposed measures, it can be avoided to be emitted up to 770 tC into the atmosphere from the Atlantic mackerel fishery.

4. Conclusions

The methodology developed in this study can be used as an indicator for the estimation of the main carbon flows related to the capture, processing, consumption, and waste management of the target fishery. Furthermore, although it has been applied to a specific specimen (*Scomber scombrus*) where catches are consumed after processing, there is the possibility of modifying the carbon cycle through the different subsystems considered to cover other species, fishing gears and farming procedures (aquaculture).

In the carbon cycle balance, it has been shown that reducing fishing effort will reduce the impact of fishing activity (in terms of CF), as well as having a double benefit in terms of carbon sequestration: on the one hand, a fraction of fish not caught will die naturally (more carbon sequestered) and, on the other hand, it will contribute to increasing the population of the target species, which in turn will result in a greater amount of biomass whose carbon will be sequestered in the future.

If current fishing fleets implement different environmental actions, such as technological improvements in vessels, use of alternative fuels or restructuring of shipping routes, their impacts (CF) could have been reduced. The same is true if the annual fishing ban is extended by a few weeks, compensating for the shortage of fish on the market with other sources of protein that are less harmful to the environment by changing eating habits. However, both approaches are needed to achieve more promising results.

Ultimately, the procedure followed could show the way to launch more zero carbon policy decision-making studies focused on fisheries. However, it is essential to foster greater understanding of the natural dynamics of marine community structure, together with assessments of natural and fishing mortality rates and the true potential of blue carbon sequestration processes.

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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Appendix A. Supplementary material

Supplementary material to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.157558.

References

Alongi, D.M., 2012. Carbon sequestration in mangrove forests. Carbon Manag. 3, 313–322. https://doi.org/10.4155/cmt.12.20.

Anticamara, J., Watson, R., Gelchu, A., Pauly, D., 2011. Global fishing effort (1950–2010): trends, gaps, and implications. Fish. Res. 107, 131–136. https://doi.org/10.1016/j.fishres.2010.10.016.

Anukam, A., Mohammadi, A., Naqvi, M., Granström, K., 2019. A review of the chemistry of anaerobic digestion: methods of accelerating and optimizing process efficiency. Processes 7, 1–19. https://doi.org/10.3390/PR7080504.

Arias, A., Feijoo, G., Moreira, M.T., 2020. Linking organic matter removal and biogas yield in the environmental profile of innovative wastewater treatment technologies. J. Clean. Prod. 276, 124292. https://doi.org/10.1016/j.jclepro.2020.124292.

Avadí, A., Fréon, P., 2013. Life cycle assessment of fisheries: a review for fisheries scientists and managers. Fish. Res. 143, 21–38. https://doi.org/10.1016/j.fishres.2013.01.006.

Bastardie, F., Nielsen, J.R., Andersen, B.S., Eigaard, O.R., 2013. Integrating individual trip planning in energy efficiency - building decision tree models for Danish fisheries. Fish. Res. 143, 119–130. https://doi.org/10.1016/j.fishres.2013.01.018.

Battin, T.J., Luyssaert, S., Kaplan, L.A., Aufdenkampe, A.K., Richter, A., Tranvik, L.J., 2009. The boundless carbon cycle. Nat. Geosci. 2, 598–600. https://doi.org/10.1038/ngeo618.

BEDCA, 2006. The Spanish Food Composition Database [WWW Document].

Brynolf, S., Fridell, E., Andersson, K., 2014. Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol. J. Clean. Prod. 74, 86–95. https://doi.org/10.1016/j.jclepro.2014.03.052.

Burel, F., Taccani, R., Zuliani, N., 2013. Improving sustainability of maritime transport through utilization of liquefied natural gas (LNG) for propulsion. Energy 57, 412–420. https://doi.org/10.1016/j.energy.2013.05.002.

Campbell, S.J., Jakub, R., Valdivia, A., Setiawan, H., Setiawan, A., Cox, C., Kiyo, A., Darman, Djafar, Rosa, E.de la, Suherfian, W., Yuliani, A., Kushardanto, H., Muawanah, U., Rukma, A., Alimi, T., Box, S., LF, 2021. Immediate impact of COVID-19 across tropical small-scale fishing communities. Ocean Coast. Manag. 200, 105485. https://doi.org/10.1016/j.ocecoaman.2020.105485.

Cohen, P.J., Cinner, J.E., Foale, S., 2013. Fishing dynamics associated with periodically harvested marine closures. Glob. Environ. Chang. 23, 1702–1713. https://doi.org/10.1016/j.gloenvcha.2013.08.010.

Czamanski, M., Nugraha, A., Pondaven, P., Lasbleiz, M., Masson, A., Caroff, N., Bellail, R., Tréguer, P., 2011. Carbon, nitrogen and phosphorus elemental stoichiometry in aquacultured and wild-caught fish and consequences for pelagic nutrient dynamics. Mar. Biol. 158, 2847–2862. https://doi.org/10.1007/s00227-011-1783-7.

Dawson, T.P., Jackson, S.T., House, J.I., Prentice, I.C., Mace, G.M., 2011. Beyond predictions: biodiversity conservation in a changing climate. Science (80-.) 332, 53–58.

Eiroa, M., Costa, J.C., Alves, M.M., Kennes, C., Veiga, M.C., 2012. Evaluation of the biomethane potential of solid fish waste. Waste Manag. 32, 1347–1352. https://doi.org/10.1016/j.wasman.2012.03.020.

Failler, P., Pan, H., 2007. Global value, full value and societal costs: capturing the true cost of destroying marine ecosystems. Soc. Sci. Inf. 46, 109–134. https://doi.org/10.1177/0539018407073660.

Falkowski, P., Scholes, R.J., Boyle, E., Canadell, J., Canfield, D., Elser, J., Gruber, N., Hibbard, K., 2000. The Global Carbon Cycle: A Test of Our Knowledge of Earth as a System. 290, pp. 291–297.

FAO, 2021. The impact of COVID-19 on fisheries and aquaculture food systems, possible responses. The impact of COVID-19 on fisheries and aquaculture food systems, possible responses https://doi.org/10.4060/cb2537en.

Froese, R., Winker, H., Coro, G., Demirel, N., Tsikliras, A.C., Dimarchopoulou, D., Scarcella, G., Probst, W.N., Dureuil, M., Pauly, D., 2019. On the pile-up effect and priors for Linf and M/K: response to a comment by Hordyk et al. on "a new approach for estimating stock status from length frequency data". ICES J. Mar. Sci. 76, 461–465. https://doi.org/10.1093/icesjms/fsy199.

González-García, S., Green, R.F., Scheelbeek, P.F., Harris, F., Dangour, A.D., 2020. Dietary recommendations in Spain –affordability and environmental sustainability? J. Clean. Prod. 254. https://doi.org/10.1016/j.jclepro.2020.120125.

Herdzik, J., 2011. LNG as a marine fuel - possibilities and problem. J. KONES 18, 169–176.

Hori, M., Bayne, C.J., Kuwae, T., 2019. Blue carbon: characteristics of the ocean's sequestration and storage ability of carbon dioxide. Blue Carbon in Shallow Coastal Ecosystems. Springer, Singapore.

Howard, J.L., Creed, J.C., Aguiar, M.V.P., Fouqurean, J.W., 2018. CO2 released by carbonate sediment production in some coastal areas may offset the benefits of seagrass "Blue carbon" storage. Limnol. Oceanogr. 63, 160–172. https://doi.org/10.1002/lno.10621.

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., van Zelm, R., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22, 138–147. https://doi.org/10.1007/s11367-016-1246-y.

Iribarren, D., Vázquez-Rowe, I., Hospido, A., Moreira, M.T., Feijoo, G., 2011. Updating the carbon footprint of the Galician fishing activity (NW Spain). Sci. Total Environ. 409, 1609–1611. https://doi.org/10.1016/j.scitotenv.2011.01.007.

Irving, A.D., Connell, S.D., Russell, B.D., 2011. Restoring Coastal Plants to Improve Global Carbon Storage: Reaping What We Sow. 6, pp. 1–6. https://doi.org/10.1371/journal.pone.0018311.

ISO, 2006. ISO 14040:2006 - Environmental Management - Life Cycle Assessment - Principles and Framework.

ISO, 2006. ISO 14044:2006 - Environmental Management - Life Cycle Assessment - Requirements and Guidelines.

IUCN, 2017. International Union for Conservation of Nature. Issues Brief: Blue Carbon. 2.

Ivanovs, K., Spalvins, K., Blumberga, D., 2018. Approach for modelling anaerobic digestion processes of fish waste. Energy Procedia 147, 390–396. https://doi.org/10.1016/j.egypro.2018.07.108.

Jafarzadeh, S., Ellingsen, H., Aanondsen, S.A., 2016. Energy efficiency of Norwegian fisheries from 2003 to 2012. J. Clean. Prod. 112, 3616–3630. https://doi.org/10.1016/j.jclepro.2015.06.114.

Jafarzadeh, S., Paltrinieri, N., Utne, I.B., Ellingsen, H., 2017. LNG-fuelled fishing vessels: a systems engineering approach. Transp. Res. D Transp. Environ. 50, 202–222. https://doi.org/10.1016/j.trd.2016.10.032.

Jandl, R., Lindner, M., Vesterdal, L., Bauwens, B., Baritz, R., Hagedorn, F., Johnson, D.W., Minkkinen, K., Byrne, K.A., 2007. How Strongly can forest management influence soil carbon sequestration?. 137, pp. 253–268. https://doi.org/10.1016/j.geoderma.2006.09.003

Ji, C., Kong, C.X., Mei, Z.L., Li, J., 2017. A review of the anaerobic digestion of fruit and vegetable waste. Appl. Biochem. Biotechnol. 183, 906–922. https://doi.org/10.1007/s12010-017-2472-x.

Macreadie, P.I., Anton, A., Raven, J.A., Beaumont, N., Connolly, R.M., Friess, D.A., Kelleway, J.J., Kennedy, H., Kuwae, T., Lavery, P.S., Lovelock, C.E., Smale, D.A., Apostolaki, E.T., Atwood, T.B., Baldock, J., Bianchi, T.S., Chmura, G.L., Eyre, B.D., Fourqurean, J.W., Hall-Spencer, J.M., Huxham, M., Hendriks, I.E., Krause-Jensen, D., Laffoley, D., Luisetti, T., Marbà, N., Masque, P., McGlathery, K.J., Megonigal, J.P., Murdiyarso, D., Russell, B.D., Santos, R., Serrano, O., Silliman, B.R., Watanabe, K., Duarte, C.M., 2019. The future of blue carbon science. Nat. Commun. 10, 1–13. https://doi.org/10.1038/s41467-019-11693-w.

Mariani, G., Cheung, W.W.L., Lyet, A., Sala, E., Mayorga, J., Velez, L., Gaines, S.D., Dejean, T., Troussellier, M., Mouillot, D., 2020. Let more big fish sink: fisheries prevent blue carbon sequestration-half in unprofitable areas. Sci. Adv. 6, 1–9. https://doi.org/10.1126/sciadv.abb4848.

McAllister, S., Chen, J.-Y., Fernandez-Pello, A.C., 2011. Fundamentals of Combustion Processes. https://doi.org/10.1007/978-1-4419-7943-8.

Mercasa, 2020. Alimentación en España 2020. Producción, industria, distribución y consumo. 23a edición.

Mesquita, M., Murta, A.G., Paias, A., Wise, L., 2017. A metaheuristic approach to fisheries survey route planning. Int. Trans. Oper. Res. 24, 439–464. https://doi.org/10.1111/itor.12252.

Muñoz, I., Canals, L.M.I., Clift, R., 2008. Consider a spherical man: a simple model to include human excretion in life cycle assessment of food products. J. Ind. Ecol. 12, 521–538. https://doi.org/10.1111/j.1530-9290.2008.00060.x.

Pendleton, L., Donato, D.C., Murray, B.C., Crooks, S., Jenkins, W.A., Sifleet, S., Craft, C., Fourqurean, J.W., Kauffman, J.B., Marbà, N., Megonigal, P., Pidgeon, E., Herr, D., Gordon, D., Baldera, A., 2012. Estimating global “Blue carbon” emissions from conversion and degradation of vegetated coastal ecosystems. PLoS One 7. https://doi.org/10.1371/journal.pone.0043542.

Reijnders, L., Soret, S., 2003. Quantification of the environmental impact of different dietary protein choices. Am. J. Clin. Nutr. 78, 664–668. https://doi.org/10.1093/ajcn/78.3.664s.

Sánchez, F., Olaso, I., 2004. Effects of fisheries on the Cantabrian Sea shelf ecosystem. Ecol. Model. 172, 151–174. https://doi.org/10.1016/j.ecolmodel.2003.09.005.

Scarborough, P., Appleby, P.N., Mizdrak, A., Briggs, A.D.M., Travis, R.C., Bradbury, K.E., Key, T.J., 2014. Dietary greenhouse gas emissions of meat-eaters, fish-eaters, vegetarians and vegans in the UK. Clim. Chang. 125, 179–192. https://doi.org/10.1007/s10584-014-1169-1.

Schau, E.M., Ellingsen, H., Endal, A., Aanondsen, S.A., 2009. Energy consumption in the Norwegian fisheries. J. Clean. Prod. 17, 325–334. https://doi.org/10.1016/j.jclepro.2008.08.015.

Schmitz, O.J., Wilmers, C.C., Leroux, S.J., Doughty, C.E., Atwood, T.B., Galetti, M., Davies, A.B., Goetz, S.J., 2018. Animals and the zoogeochemistry of the carbon cycle. Science 80-,). 362. https://doi.org/10.1126/science.aar3213.

Tanner, D.K., Brazner, J.C., Brady, V.J., 2000. Factors influencing carbon, nitrogen, and phosphorus content of fish from a Lake Superior coastal wetland. Can. J. Fish. Aquat. Sci. 57, 1243–1251. https://doi.org/10.1139/f00-062.

Tharanathan, R.N., Mahadevamma, S., 2003. Grain legumes - a boon to human nutrition. Trends Food Sci. Technol. 14, 507–518. https://doi.org/10.1016/j.tifs.2003.07.002.

The blue carbon initiative, 2018. Blue Carbon and Nationally Determined Contributions. Guidelines on Enhanced Action. A Guide on How Countries May Include Blue Carbon in Their Nationally Determined Contributions.

Vettor, R., Tadros, M., Ventura, M., Guedes Soares, C., 2016. Route planning of a fishing vessel in coastal waters with fuel consumption restraint. Proc. 3rd Int. Conf. Marit. Technol. Eng. MARTECH 2016. 1, pp. 167–174. https://doi.org/10.1201/b21890-24.

Wedding, L.M., Moritsch, M., Verutes, G., Arkema, K., Hartge, E., Reiblich, J., 2021. Incorporating blue carbon sequestration benefits into sub-national climate policies. Glob. Environ. Chang. 102206. https://doi.org/10.1016/j.gloenvcha.2020.102206.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycl. Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8.

Wilson, R.W., Gilmour, K.M., Henry, R.P., Wood, C.M., 1996. Intestinal base excretion in the seawater-adapted rainbow trout: a role in acid-base balance? J. Exp. Biol. 199, 2331–2343. https://doi.org/10.1242/jeb.199.10.2331.