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Integrating the water-energy-food nexus and LCA + DEA methodology for sustainable fisheries management: A case study of Cantabrian fishing fleets

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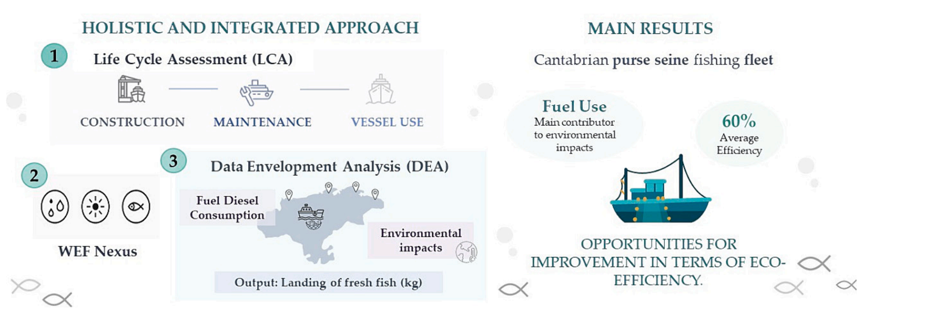
HIGHLIGHTS

- The LCA + DEA methodology combined with WEF Nexus assesses eco-efficiency in Cantabrian fisheries.
- The Cantabrian purse seine fleet presented a 60 % average eco-efficiency value.
- The average efficiency showed a notable increase between 2015 and 2019.
- This novel methodology demonstrated high utility for assessing the sustainability of other fishing fleets

GRAPHICAL ABSTRACT



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ABSTRACT

The fishing sector constitutes an important source of economic revenue in northern Spain. In this context, various research studies have focused on the application of the five-step Life Cycle Assessment (LCA) and Data Envelopment Analysis (DEA) methodology to quantify environmental impacts of fishing systems. However, some of them have used environmental indicators that focus on individual environmental issues, hindering the goal of achieving integrated resource management. Therefore, in this study, the Water-Energy-Food (WEF) Nexus is employed as an integrative perspective that considers the synergies and trade-offs between carbon footprint, energy requirements, and water demand.

The main objective of this study is to evaluate the operational efficiency and environmental impacts of Cantabrian fishing fleets. To this end, the combined use of LCA and DEA, along with the WEF Nexus, was applied to the Cantabrian purse seine fleet. DEA matrices were generated using the LCA-derived WEF nexus values as inputs to calculate efficiency scores for each vessel. Subsequently, based on the efficiency projections provided by the DEA model, a new impact assessment was performed to understand the eco-efficiency and potential environmental benefits of operating at higher levels of efficiency within this fleet.

The average efficiency of the fleet was above 60 %. Inefficient units demonstrated a greater potential to reduce their environmental impacts (up to 65 %) by operating according to efficiency projections. Furthermore, the results revealed a strong dependence of environmental impacts on one of the operational inputs, i.e., fuel consumption. These findings highlight the significance of embracing holistic approaches that combine technical,

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economic, and social factors to achieve a sustainable balance in fisheries systems. In this regard, the five-step LCA + DEA method applied in conjunction with the WEF Nexus emerged as a suitable tool for measuring operational and environmental objectives.

1. Introduction

In the context of a growing world population, the search for food that guarantees optimal nutritional requirements and encourages healthy eating patterns is on the rise (Martínez et al., 2024). Fish and seafood products rank first among high-nutrient foods (Chen et al., 2022). Consequently, due to their beneficial effects on human health, the annual consumption per capita of fish in the EU was approximately 24 kg in 2022 (EUMOFA, 2022).

Despite being one of the largest economic sectors, fishing activities cause several direct environmental impacts including visible pollution, like microplastic litter or oil spills in oceans, as well as invisible pollution, such as microplastics, underwater noise, and releases of chemicals or nutrients (Ruiz-Salmón et al., 2021). Traditionally, the sustainability of seafood products had focused only on direct or biological impacts (Ziegler et al., 2016). However, indirect and off-site effects of fishing activities associated with the extraction and transformation of natural material and fossil fuels used for the construction, maintenance and use of the vessels must be considered. These impacts include emissions that are mainly related to fuel combustion (Parker et al., 2018), but also other activities, such as lubricant oil production, steel production, ice production, release of antifouling substances, cooling and cleaning agents, or wastewater and water discharge (Avadí and Freón, 2013). The fishing sector contributes to 1.2 % of global oil consumption, which results in approximately 134 million metric tons of CO_2 eq. emitted into the atmosphere (Korican et al., 2022). Therefore, optimized fuel consumption and energy efficiency are crucial to reduce operational costs and derived environmental impacts (Fan et al., 2022).

Considering the growing global demand for fishery products, as well as the environmental impacts of fishing (Cortés et al., 2021a), it is crucial to increase the sustainability of the fisheries sector according to environmental legislation (Entrena-Barbero et al., 2022), employing the concept of life cycle thinking to increase production efficiency and minimize its environmental impacts (Cooney et al., 2023). Life cycle assessment (LCA) constitutes a widely accepted methodology used to quantify the environmental impacts of seafood production throughout the entire life cycle (Sandison et al., 2021). However, this approach has proven to have limitations when monitoring the environmental performance of multiple complex units representing the same function (Lozano et al., 2010), such as airports, banks, or fishing vessels. In this context, the complementary application of other management tools is useful. For instance, when it comes to measuring the efficiency of fisheries and fishing fleets, an increasingly used management method applied is Data Envelopment Analysis (DEA) (Laso et al., 2022).

DEA is a linear programming model used to determinate the operational efficiency parameters of multiple similar entities (Rebolledo-Leiva et al., 2017), named decision-making units (DMUs), when the process involves several inputs and outputs (Gennitsaris et al., 2023). The result for each DMU is an efficiency score and targets efficient operating points for those units that is deemed inefficient (Vázquez-Rowe et al., 2011). Therefore, the combination of LCA and DEA enrich operational efficiency optimization with environmental performance indicators of multiple units (Iribarren and Vázquez-Rowe, 2013). This approach avoids the use of average inventory data and enhances the interpretation of results through eco-efficiency verification (Torregrossa et al., 2018).

In recent decades, DEA has been combined with LCA to assess eco-efficiency in fisheries and, particularly, in fishing fleets. Hence, several studies can be found in the literature applying the LCA + DEA approach to fishing fleets in Peru (Avadí et al., 2014), northern Spain (Laso et al., 2018b; Ramos et al., 2014; Vázquez-Rowe et al., 2010, 2011), or northern Portugal (González-García et al., 2015), as well as focusing on fisheries (Lozano et al., 2010; Cortés et al., 2021b). However, all of them have used environmental indicators that focus on individual environmental issues, hindering the goal of achieving integrated resource management. In this study, a modified Water-Energy-Food (WEF) nexus approach was used jointly with the LCA + DEA methodology with the aim of providing a holistic approach aggregating a set of indicators (i.e., water demand, energy demand, and carbon footprint) into a single value in order to address the impacts of the fisheries sector as a whole. For this purpose, an LCA is conducted for each of the vessels in the sample considered within the purse seine Cantabrian fishing fleet, considering the inputs required in the construction, maintenance, and use of each DMU (i.e., fishing vessel) analyzed in a previous study conducted by Ceballos-Santos et al. (2023). Once the impacts of each unit are extracted, the WEF nexus approach is employed to calculate the carbon, water, and energy footprints, which will serve as inputs to the DEA matrix. In addition, a secondary objective was to evaluate the existence of any trends in the operational efficiency of the Cantabrian purse seine fleet over the years 2015 and 2019, comparing the results obtained in this study with those from the study conducted by Laso et al. (2018b) for earlier years.

The main novel contribution of the current study is the combination of two well established analysis tools, LCA and DEA, using a composite index (WEF) as input for the DEA matrix, thus providing an integrated view of the process. To the best of the authors' knowledge, this study is the first to include a nexus approach together with the LCA + DEA methodology. The results of the study are intended to be of utility for fish managers, allowing them to identify the environmental hotspots of the system and the operational efficiency of fishing vessels.

2. Materials and methods

2.1. Definition of the case of study

2.1.1. Contextualization of the study

Spain is one of the leading countries in Europe in terms of fishing activity, and together with other countries in Atlantic Europe, it is recognized as one of the leading producers (FAO, 2024) and exporters (Sanchez-Matos et al., 2024) of seafood. In fact, the high production levels, reaching millions of metric tons annually, underscore the region's critical role in the global seafood supply chain (FAO, 2024). The Spanish fishing sector comprises 8600 fishing vessels (MAPA, 2023) and captured approximately 7.51×10^5 metric tons of live fish in 2022 (EUROSTAT, 2022). The Cantabrian coast is particularly significant, accounting for approximately 50 % of the nation's fishing vessel capacity (MAPA, 2023). In this context, the economy of Cantabria, a coastal region in northern Spain, has traditionally been based on the primary sector, including fishing products due to its extensive coastline (Fernández-Ríos et al., 2022). However, the Cantabrian fishing fleet has experienced a steady decline over recent decades from approximately 380 vessels to a total of 128 vessels that make up the current fleet, distributed throughout 7 fishing ports (MAPA, 2023). In 2023, landings along the Cantabrian coast reached 30,000 metric tons, translating into an economic revenue of approximately 26 million euros (ICANE, 2022). In terms of the fishing gear used, vessels are distributed among small-scale vessels (72) and purse seiners (33). The remaining vessels are a variety of bottom trawlers, long liners, dredgers and gillnetters (Ceballos-Santos et al., 2023). According to national statistics, the Cantabrian fishing fleet had an average age of 28 years in 2023, with a capacity of 6700 GT, and a total power of 17,052 KW (MAPA, 2023).

In the current study a sample of 17 purse seine vessels belonging to the most important purse seining companies in northern Spain was considered for the analysis. The selection of this fleet was performed primarily due to the availability of detailed and reliable inventory data. The vessels represent approximately 60 % of the total purse seine fleet in Cantabria, exhibiting a consistent pattern across vessels (i.e., low standard deviations in terms of vessel length, or seine net characteristics), and similar fishing operations. This consistency facilitates the comparison of operational efficiency among the vessels.

The current LCA + DEA study is framed in the context of a previous LCA study analyzing the environmental performance associated with purse seine fishing in Cantabria under a "cradle-to-port" LCA approach, carried out by Ceballos-Santos et al. (2023). While the former paper dealt with the environmental analysis of this fleet, in our study the eco-efficiency of the different fishing segments within the fleet is evaluated to understand the operational inefficiencies of each vessel. Thereafter, these benchmarks are used to provide target operational values to estimate improvements in environmental impact that can be of utility for both producers and policymakers in the fishing sector. Hence, the study includes another dimension in the environmental assessment through the evaluation of the operational efficiency of vessels. Despite the focus on the fishing fleet of the region of Cantabria, it must be noted that the methodology and approach applied can be easily adapted and extrapolated to other geographical regions to assess the sustainability and enhance the eco-efficiency of other fishing fleets.

2.1.2. Definition of the unit of assessment

The main objective of the DEA methodology is to quantify the relative efficiency of multiple homogeneous units (i.e., DMUs) (Laso et al., 2018a). In the fishing sector, these units of assessment usually correspond to each single fishing vessel (Avadí et al., 2014). The rationale behind this choice is the fact that individual vessels constitute independent and relatively homogeneous units within the production system (Ramos et al., 2014), to which the different inputs and outputs can be related to. Furthermore, for computation in DEA, a detailed and reliable amount of data is required regarding the input and output flows of materials and energy for each DMU (Lorenzo-Toja et al., 2015), which are obtained from the Life Cycle Inventory (LCI). To obtain the individual data for each purse seining vessel that make up the DEA matrix, the LCI extracted from the study by Ceballos-Santos et al. (2023) was used. More specifically, fishing activity data for the year 2019 were collected from a sample of 17 purse seine belonging to the Cantabrian fleet. Fig. 1 shows the input and output flows subject to quantification for each of the DMUs. Moreover, since the DEA computation only involves a selection of the inputs and outputs included in the LCA, in Fig. 1 DEA and LCA limits are differentiated.

As shown in Fig. 1, the inputs of the LCA correspond to all the input and output flows of both materials and energy for the vessel's construction, maintenance and use stages. The system boundaries include all the stages of the vessel's life cycle in a so-called 'cradle-to-port' approach, i.e., from capture to landing fish, and excluding port operations. In contrast, DEA encompasses only those inputs and/or outputs that are expected to generate a significant environmental and/or economic impact.

2.2. LCA + DEA method

Once purse seine fishing vessels have been selected as DMUs, the methodological framework to be followed must be chosen, as shown in Fig. 2.

2.2.1. Selection of LCA + DEA method

In this study, the "five- step LCA+DEA method" developed by Vázquez-Rowe et al. (2010) and refined by Avadí et al. (2014) was applied. This approach has been recommended in past literature as appropriate for conducting eco-efficiency validation analyses by assessing the environmental impacts of operational inefficiencies through quantification (Iribarren et al., 2010). The main steps of this method, which can be seen in Fig. 2, are the: i) collection of input and output data for each DMU to build the LCI using a mass-based functional

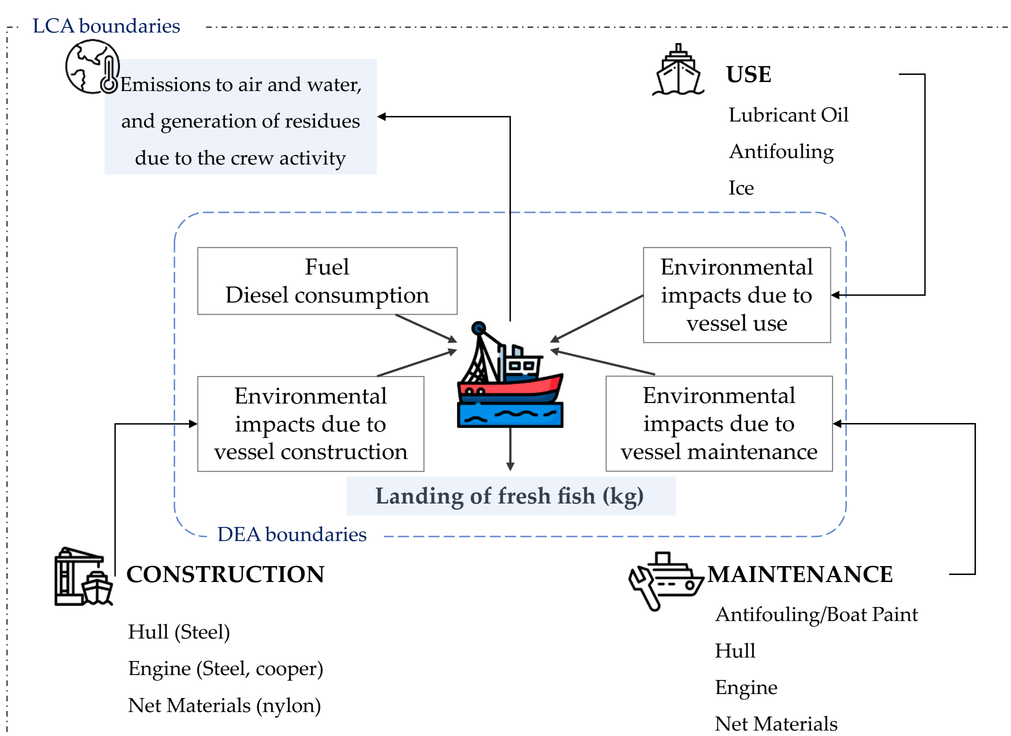

Fig. 1. Life Cycle Assessment (LCA) and Data Envelopment Analysis (DEA) system boundaries for each Decision-Making Unit (DMU). The inner dotted line represents the system boundaries for the DEA matrix, whereas the outer dotted line represents the system boundaries in the LCA modelling.

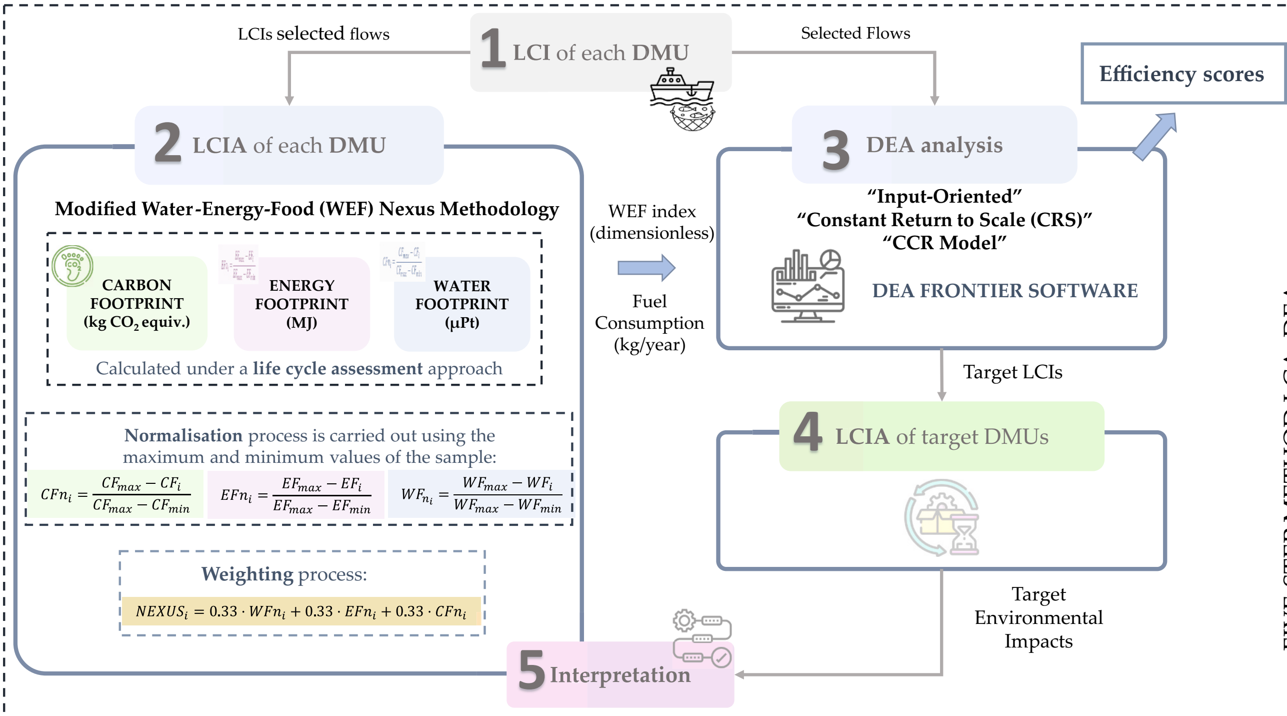

Fig. 2. Inclusion of the water-energy-food (WEF) nexus methodology in the five-step LCA + DEA method (adapted from Vázquez-Rowe et al., 2010).

unit (FU), which was set as the total amount of fresh fish captured per year for each DMU; ii) Life Cycle Impact Assessment (LCIA) computation of each DMU to obtain environmental impacts for various impact categories, hereafter referred to as current environmental impacts; and the definition of the subsystems, which are included as inputs within the DEA matrix; iii) determination of the operational efficiency of each DMU from the DEA matrix using the "DEA frontier software"; iv) LCIA of target DMUs (i.e., virtual units) based on the new LCI data obtained from step three; and, v) quantification of the environmental impacts to compare between the potential environmental impacts for the virtual DMUs and those for the current DMUs in order to quantify the impacts associated with inadequate operational practices. For those DMUs that turn out to have full operational efficiency, no reduction potentials are calculated, while for those units that have turned out to be inefficient, reduction potentials are calculated which are called objective operating points (Rebolledo-Leiva et al., 2017).

Some LCA + DEA studies utilizing the 5-step approach included specific operational inputs in the DEA analysis. For example, Vázquez-Rowe et al. (2010) included operational inputs such as fuel consumption, lubricant consumption, paint consumption, and the amount of steel for ship construction, among others. This approach was also implemented in the study conducted by Ramos et al. (2014), among other authors. However, in this study it is difficult to select an individual operational input because it comprises a fleet of vessels with differing technical characteristics. For instance, including hull material or fishing tools as operational inputs was not possible due to the existence of three different types of vessels (i.e., wooden, polyester or steel vessels) and different fishing tools. Therefore, as explained in depth in Section 2.2.2, a set of subsystems were constructed to group together operational elements that share similar functions within vessel operations.

2.2.2. *Input and output selection for the DEA matrices*

The methodological aspects to be defined in order to perform a DEA analysis are: i) construction of the DEA matrix (this section); ii) choice of model orientation; iii) determination of the returns to scale; and, iv) selection of the DEA model (Laso et al., 2022). The current study, uses the Water-Energy-Food Nexus Methodology (WEF) index that grouped three individual indicators rather than including specific operational inputs in the DEA matrix (e.g., steel production, ice production, etc.).

To construct the DEA matrix, the first step consists of the collection of data for the computation of results. In this study, primary data collected by Ceballos-Santos et al. (2023) for the fishing activity for the year 2019 were used. The background system was constructed based on secondary data, i.e., background datasets related to energy or raw materials production, which were collected from the Ecoinvent v3.7. (Moreno-Ruiz et al., 2018) and Agribalyse v3.0.1. (Auberger et al., 2022) databases.

Three subsystems have been designed as shown in Fig. 1: the construction phase (steel production, seine, purse seine engine), vessel maintenance (alkyd paint, antifouling paint, steel production and maintenance of the seine and purse seine engine), and use of materials (ice production, lubricant oil production and fuel consumption). The main objective of this grouping is to encompass the full depth of the LCI within the DEA matrix by adding all operational elements with similar functions but heterogeneous characteristics. Once the subsystems were defined, the environmental impacts were calculated by introducing the WEF methodology proposed by Entrena-Barbero et al. (2023) and later implemented by Ceballos-Santos et al. (2024). In the current study, the methodology developed by these authors was slightly modified, as only the three environmental footprints are considered, omitting the nutritional footprint. The nutritional dimension was excluded because the nutritional value of the fish landings and their contribution to the human diet were considered out of scope of the study. Thereafter, footprints were normalized by scoring the vessel with the lowest WF, EF, and CF at 100, and the highest footprint at 0. Each footprint was then equally weighted at 33 %, resulting in a final nexus value for each vessel within the 0–1 range.

The LCIA assessment methods applied were the Environmental Footprint (EF) 3.0 method and the Cumulative Energy Demand (CED) v1.11 method, is the latter being the sum of the energy demand of all the inputs required to produce a certain product (Zarei et al., 2019). The impact categories considered in this study were climate change reported in kg CO_2 eq. in order to calculate carbon footprint (CF); and water use, freshwater eutrophication and marine eutrophication expressed as a single score to quantify water footprint (WF). Moreover, the CED, which is reported in MJ indicator was also included and used for the calculation of the energy footprint (EF). In order to obtain the nexus, weighting factors of 33 % were included for each of the environmental footprints. Thereafter, to meet the secondary objective of comparing the operational efficiency of the Cantabrian purse seine fleet, results obtained in this study were compared to those studied by Laso et al. (2018b). For the sake of comparison, the individualist (I) endpoint perspective of the ReCiPe LCIA method was computed. The value of the endpoint single score obtained was employed as the input.

A total of four inputs were included in the DEA matrices: i) fuel Consumption, reported in kg of fuel per year; ii) WEF Construction Phase (dimensionless); iii) WEF Maintenance Phase (dimensionless); and iv) WEF Use Phase (dimensionless). The annual amount of diesel consumed by the fishing vessels was computed (input 1). Since this flow is considered individually as an input of the DEA matrix, it was decided to remove it from the use phase subsystem. Therefore, this input involves the direct use of inventory data from the LCI, a regular practice in 5-step LCA + DEA studies (Vázquez-Rowe et al., 2012). Finally, the output selected was the amount of fish landed by each vessel in 1 year of operation, obtained directly from the data reported by the vessels included in the sample.

2.2.3. Selection of the DEA model

Once the input and output data are collected for each DMU, the next step consists of choosing the appropriate DEA model to meet the objectives of the analysis (Lozano et al., 2009). This study applies the slacks-based measure efficiency (SBM) model due to its flexibility for individual DMU calculations regardless of the units of measure that are used for the different inputs/outputs (Laso et al., 2022). The SBM model is noted for its ability to identify slacks (i.e., it deals with input excesses and output shortfalls simultaneously), allowing a detailed assessment of how each DMU can improve its efficiency (Tone, 2001). Therefore, this model is suitable for situations where the data are heterogeneous, as is the case in this study.

Furthermore, to perform a DEA analysis, it is necessary to consider other factors, such as model orientation and the display of the production possibility set (PPS). In this case, an input-oriented perspective was selected to reduce inputs while fixing the output values, i.e. the level of fish captures. This is often the most commonly used orientation for LCA + DEA studies in the fishing sector (Laso et al., 2018b), given that fishing fleets typically operate under regulation regimes with daily and weekly quotas for individual vessels, which limit their capacity to land fish (BOC, 2024).

Finally, the type of production technology assumed for the production possibility set must be selected, which can be with constant returns to scale (CRS) or variable returns to scale (VRS). In this study, a CRS approach was selected since the three common assumptions of DEA analysis were attained, which are convexity, scalability, and free disposability of inputs and outputs (Vázquez-Rowe and Tyedmers, 2013). Hence, it was assumed that the purse seiners under study have similar technical characteristics, target the same types of fishing species, and operate under the same regulations in a single fishing ground. This means that the ratio of inputs (such as fuel, and other items like lubricants or paint) to outputs (fish catch) remains consistent regardless of the scale of operation. This choice ensures a consistent evaluation of the relative efficiency of vessels under standardized operational conditions.

3. Results and discussion

3.1. Environmental characterization of current vessels

Annual environmental impacts are shown in Fig. 4 per vessel (i.e., DMU) for CF, WF and EF and aggregated by stages, considering fuel consumption as a separate item. For CF, the fleet showed an average impact of 632 t CO_2 eq per vessel. The maximum value corresponded to DMU16 (1560 t CO_2 eq.) due to its high diesel consumption, while the minimum value was found in DMU1 (246 t CO_2 eq.). It was observed that some high-capacity vessels, such as DMU16 (402 m^3) and DMU3 (363 m^3), exhibit higher CF values, which may seem contradictory. However, this observation is reasonable because vessels with greater catch capacities tend to require more fuel to operate. In parallel, fisheries authorities establish fishing quotas that limit the total amount of species that can be caught within a specific time period, leading to overcapacity (Villasante, 2010).

Therefore, it is evident that the CF levels observed for each individual vessel are influenced by both vessel size and fishing regulations, among other parameters. It was found that vessels with smaller capacities, such as DMU2 (134 m^3) and DMU15 (141 m^3), show lower carbon emission values despite having similar catch levels compared to larger vessels.

It was observed that fuel consumption was the main contributor in all the categories analyzed, exceeding 90 % of total impacts. With the predominance of fuel combustion on CF results is linked to the distance from the port to the fishing grounds, as well as the operational and technical conditions of the vessel. The skill and experience of the skipper, and consequently the crew, also influence the environmental profile of the vessels (Laso et al., 2018c). This behavior, usually referred to in the literature as the "Skipper Effect" (Vázquez-Rowe and Tyedmers, 2013), indicates that more experienced and skilled skippers can locate fish more quickly and accurately, which reduces the time and distance required to catch the same amount of fish, decreasing fuel use intensity.

The production of purse seine nets, the purse seine net engine, and steel used in the construction of the vessels contributed 4.2 % to the CF, while the maintenance stage related to the steel of the boat and nets, as well as paint production and its emissions, contributed 1.1 %. Finally, the production of ice and the production of lubricating oil and its emissions showed contributions below 2 %. For EF, the trend was found to follow those discussed in the CF, leading to the conclusion that the primary focus for improving the overall environmental performance of fisheries should be on fuel efficiency, as numerous LCA studies focused on the fishing sector have confirmed that fuel use in vessels is the primary factor responsible for environmental impacts (Weidema et al., 2008). The contribution of the usage stage (i.e., production of ice and lubricants) to the EF increased to approximately 4 %. In terms of WF, diesel production and consumption had a significant contribution (98 %), so the remaining stages barely contributed to the total environmental impact.

The values obtained are consistent with results reported in previous studies that studied fisheries with similar characteristics. Hence, the average CF value of 1.03 kg CO_2 eq. per kg of fish landed was obtained in the current study shows slightly lower emissions than the European anchovy purse seine fleet analyzed in Cantabria with data from 2015 (1.44 kg CO_2 eq. per kg of fish landed) (Laso et al., 2018c). In contrast, the sardine purse seining fishery in Portugal analyzed by Almeida et al. (2014) presented one of the lowest values in the literature (0.36 kg CO_2 eq.), together with those reported for Peruvian anchoveta, at 77 g CO_2eq. per kg of landed anchoveta (Avadí et al., 2014). A study by Parker et al. (2015) reported an average value for the global tuna purse seine fleet of 1.10 kg CO_2 eq. per kg of tuna caught. All of these studies, included the current one, converge in terms of being some of the lowest carbon industrial fishing fleets in the world (Parker et al., 2018), although variability between them is expected to prevail due to distance to fisheries (Vázquez-Rowe et al., 2011), skipper-effect (Vázquez-Rowe and Tyedmers, 2013), or inefficiencies of certain vessels (Laso et al., 2018c), among other factors. For EF, the fleet's average impact was 1.63 $\times 10^8$ MJ, with vessel 16 showing the highest energy consumption (154 % more compared to the average value of the fleet). Finally, for WF the fleet showed an average value of 32.4 $\times 10^1$ μPt.

3.2. DEA performance and eco-efficiencies scores

Based on the LCI data available, a DEA matrix was created (See Section 2.2), as shown in Table 1. The DEA-Solver Pro, the selected software to compute the results, is specialized in analyzing the efficiency of different DMUs using DEA (Zhu, 2022). The specific steps to use this software begin with preparing the data in a spreadsheet, where each row represents a DMU and each column represents an input or output (see Table 1). Thereafter, these data must be imported to the software and the DEA model applied is selected. For this particular case study, the SBM-I model was used, and the model options, such as orientation (input-oriented), are configured. Finally, the DEA analysis is executed, and the relative efficiency of each DMU is calculated (Cooper et al., 2007).

The results, shown in Table 2, include the efficiency score for each DMU (ϕ), together with the estimated reduction percentages for each operational input. These results constitute the operational benchmark of each individual vessel. A vessel is considered inefficient when efficiency score $\phi < 1$, whereas when the efficiency of the vessel is equal to 1.00, it is an efficient vessel (Vázquez-Rowe and Iribarren, 2015). In our case study, 11 units were identified as operating inefficiently, ranging from 34 % to 99 %, and representing approximately 65 % of the sample of vessels analyzed, whereas only 6 units operated at full efficient (i.e., efficiency score of 100 %). The average efficiency for the entire sample was 0.69. It should be noted that efficient vessels do not exhibit identical behaviors, as efficiency with the model applied implies that based on the real data computed and the three basic assumptions (i.e, convexity, scalability, and free disposability of inputs and outputs) it is not possible to increase production without an increase in resource consumption.

The average efficiency obtained for Cantabrian seiners (69 %) was found to be higher than for the purse seining fleet in NW Portugal (above 60 %), as discussed in González-García et al. (2015). When compared to purse seiners from northern Spain, the average efficiency obtained in the current study is higher than that obtained for purse seiners in Galicia (44 %), as discussed by Vázquez-Rowe et al. (2011). While the inputs included in the studies are not completely identical and the number of vessels considered from the total fleet is not the same, the higher average efficiency in the Cantabrian fleet in comparison with the findings obtained by other authors for the fleet of northern Portugal and for the Galician purse seiner fleet, is remarkable. However, Avadí et al. (2014) demonstrated that the average efficiency obtained when applying the LCA + DEA method to the largest single species fishery in the world (i.e., Peruvian anchoveta) exceeded 85 %. Therefore, it should be noted that the efficiency of the Peruvian purse seiner fleet is significantly higher than that of the purse seiner fleets from northern Spain or Portugal. Higher reliance on fossil fuels in Spain and Portugal may magnify operational differences between skippers, explaining this difference.

The assessment of environmental impacts as independent indicators may lead to limited interpretations, although a combination of them taking their synergies into account can add subjectivity and uncertainty to the system (Entrena-Barbero et al., 2023). The double weighting that comes with aggregating multiple impact categories into a single indicator (WEF nexus) introduces a certain degree of uncertainty to the study (Fang and Heijungd, 2015). Thus, a potential advantage is that the results of individual efficiency values for each vessel are more robust when considering multiple environmental impacts in an integrated manner. In summary, although the integration of aggregated environmental indicators can offer a more holistic view, it can also introduce challenges in interpreting the results and in decision-making based on them.

Original input values of the different DMUs and the estimated target or virtual values are presented in Fig. 4. Furthermore, target reduction percentages were represented for these units operating inefficiently. Reduction targets represent potential input savings to be achieved by the (estimated) inefficient DMUs, if they were to operate under the conditions of the DEA calculated efficiency matrix. It is interesting to note that a reduction between 28 % and 66 % could be achieved in terms of fuel consumption. However, the highest reduction percentages correspond to the construction phase (24.7 %–90.3 %), which may be due to the high impacts in this stage and to a certain overcapacity of the fleet (Villasante, 2010). Other authors (González-García et al., 2015) have obtained similar results for the Portuguese purse seine fleet, with reduction percentages for fuel consumption ranging between approximately 20 % and 50 %. Given that fuel consumption constitutes the largest contribution to a vessel's total impact, and considering that the amount consumed and the reduction target achieved for both studies are similar, one might expect the overall efficiency of both fleets to be similar. However, the inclusion of the WEF Nexus results in a higher overall efficiency. Hence, the integration of environmental footprints can reveal synergies between different impact categories, which can lead to strategies that improve operational efficiency and reduce

Table 1
Inventory data selected per decision making unit (DMU) for inclusion in the Data Envelopment Analysis (DEA) matrix for the sample of 17 vessels from the Cantabrian purse seining fleet (year 2019).

DMUs	Inputs				Output
	Fuel consumption (ton fuel/year)	WEF Maintenance phase	WEF Construction phase	WEF Use phase	catch value (ton/year)
1	614	0.290	0.0400	0.100	228
2	161	0.460	0.520	0.510	682
3	25.0	0.680	0.750	0.210	677
4	21.4	0.350	0.420	0.330	744
5	17.8	0.170	0.190	0.230	579
6	17.8	0.390	0.360	0.290	409
7	137	0.120	0.140	0.210	873
8	178	0.180	0.200	0.430	544
9	192	0.750	0.700	0.320	466
10	110	0.440	0.570	0.00	766
11	80.1	0.200	0.180	0.100	527
12	187	0.0700	0.00	0.220	992
13	89.0	0.350	0.240	1.00	856
14	107	0.430	0.350	0.330	604
15	80.1	0.220	0.150	0.110	425
16	399	1.00	1.00	0.290	842
17	101	0.00	0.150	0.110	529

DMU = decision making unit; WEF=Water-Energy-Food Nexus.

Table 2
Input-Oriented CRS efficiency scores and operational reduction for the purse seine fleet units studied.

DMUs	Input-Oriented CRS efficiency (ϕ)	Reduction Target (%)			
		Fuel consumption	WEF Maintenance phase	WEF Cosntruction phase	WEF Use phase
1	0.62	37.6	90.3	37.6	37.6
2	0.58	42.4	42.4	44.0	42.4
3	0.41	59.4	65.2	59.4	59.4
4	0.53	47.3	48.2	47.3	47.3
5	0.54	46.5	46.5	46.5	46.5
6	0.35	65.5	72.6	65.5	65.5
7	1.00	0.00	0.00	0.00	0.00
8	0.47	52.9	52.9	55.3	62.5
9	0.34	65.7	73.4	65.7	65.7
10	1.00	0.00	0.00	0.00	0.00
11	0.99	0.58	24.7	0.58	0.6
12	1.00	0.00	0.00	0.00	0.00
13	1.00	0.00	0.00	0.00	0.00
14	0.77	23.5	43.0	23.5	23.5
15	0.81	18.7	53.2	18.7	18.7
16	0.34	66.3	0.00	0.00	0.00
17	1.00	0.00	0.00	0.00	0.00

DMU = decision making unit; WEF=Water-Energy-Food Nexus.

environmental impact simultaneously.

It was observed that large vessels with higher catch capacities (i.e., DMU7, DMU12, and DMU13) exhibited higher operational efficiencies, reaching 100 %, while those with lower fishing capacities (e.g., DMU1, DMU6, and DMU9) achieved lower operational efficiencies of 62 %, 35 %, and 81 %, respectively. However, DMU 16, despite having a high level of catches, achieved a low efficiency value (34 %) due to the high reported diesel consumption. Therefore, the percentage reduction for this DMU is 66 % in terms of fuel consumption. In terms of operational efficiency, it could be concluded that larger and technologically advanced fishing vessels are more efficient in terms of fish capture. However, this efficiency may be counterproductive if it leads to overexploitation of fish resources and depletion of fish populations. This highlights that sustainable management of fishing fleets involves finding a balance between operational efficiency and conservation of fish resources.

It was observed that DMU16, despite being the largest in terms of capacity (i.e., 402 m^3) within the studied fleet, maintains a capture level similar to that of other vessels with smaller capacities. This could be attributed to an overcapacity issue with the vessel, likely stemming from its size being disproportionate to the amount of fish that can be caught in accordance with current regulations. Despite some vessels with large capacities (which entail higher resource consumption for their operation) and low catch levels also exhibiting reduced efficiency values (DMU5 and DMU8), a clear correlation between vessel size and efficiency was not established. It should be noted that this variation in technical efficiency could also be due to epistemic uncertainties in data availability and quality, such as misinformation provided by skippers.

The most significant reduction percentages were observed in the construction stage, reaching values of up to 80 %. However, it should be noted that virtual gains that are estimated through the DEA software do not correspond to an effort to make inefficient DMUs efficient through innovations or technological advances. Instead, the LCA + DEA methodology points out environmental inefficiencies through comparison to similar units (i.e., DMUs), without linking the inefficiency with a technological gap.

These results show significant variations in operational efficiency and environmental impact within the Cantabrian purse seiner fleet, thus highlighting the importance of identifying and addressing areas for improvement to maximize efficiency and minimize environmental impact across the entire fleet. Hence, it can be concluded that the integration of LCA and DEA methodologies allows identifying areas for improvement that would not only reduce the environmental impact of their activity but could also lead to a reduction in production costs through a more efficient use of resources.

The results obtained in this study are intended to be of interest for stakeholders to aid in the identification of the operational inputs that should be optimized, as well as in the implementation of cleaner production strategies. Similarly, the results obtained as well as the methodology employed could also be of interest to policymakers when it comes to reviewing current fisheries management strategies, such as fuel consumption minimization and overcapacity.

3.3. Environmental characterization of the target vessels

When the target values were computed with the DEA model for inefficient vessels, these underwent a new environmental impact assessment to calculate the potential environmental impacts of these vessels if they are operated in an efficient way. It should be noted that this second environmental assessment should not be seen as a consequential LCA (Vázquez-Rowe et al., 2010), but as a descriptive analysis of the current fleet if they were to operate with the optimal values obtained in the previous step. The analysis of this section began with the calculation of the new environmental impacts exclusively for units operating inefficiently. These new impacts were evaluated once the percentage of target reduction, obtained as a result of previous stages, was applied to the inputs of the matrix (refer to Table 2).

Once the new values for the categories of climate change, water use, freshwater eutrophication, marine eutrophication, and energy demand were obtained, they were grouped and compared with the current environmental impacts (Fig. 5).

Fig. 5 presents a comparative representation of environmental impacts between current and target vessels. As expected, the environmental impacts for the virtual DMUs were lower than original DMUs, except for those vessels that were found to be efficient, for which target vessels were the same as the current ones. Thus, the units that were completely efficient (i.e., DMUs 7, 10–13, and 17) have not been represented in Fig. 5.

Once the target values are incorporated into the LCI, a reduction in environmental impact is achieved for the impact categories (i.e., climate change, water use, and energy demand) analyzed. The most notable environmental reductions are associated with the most inefficient purse seiner vessels. It is worth noting the contribution of energy use in the total life cycle environmental impacts in all the assessed fleets (see Figs. 3 and 5). Hence, activities related to fuel production, distribution, and combustion were the main contributors for all the assessed fleets; all the other activities analyzed had a secondary role in the environmental impact minimization. As discussed in Avadí et al. (2014), categories with high potential for improvement in impact are closely associated with characterization factors related to fuel consumption and combustion, such as climate change.

3.4. Historical evolution of the Cantabrian fleet efficiency

When comparing the efficiency of the Cantabrian purse seine fleet in 2019 (this study) and that of the same fleet for the year 2015 (Laso et al., 2018b), it should be noted that the fleet considered in the previous study consisted of 33 purse seine vessels from ports along the Cantabrian coast rather than 17 now (out of 32 purse seiners operating at present). Therefore, the comparison has been made with the 14 vessels that have operated during both periods, as it is likely that due to a lack of generational continuity in the fishing profession or to stricter fishing regulations, including restrictions in fleet size, catch quotas, or closed seasons, a number of vessels ceased operations in recent years.

To compare the operational efficiencies of the fishing fleet for the two years, the ReCiPe endpoint single score method was used to calculate the environmental impacts from an individualistic perspective (I), which were then used as inputs to the DEA matrix in both studies.

The average efficiency obtained for the purse seiners in 2019 (above 72 %) turned out to be higher than that of the same vessels in 2015 (approximately 61 %). While the inputs included in both studies are not completely identical, similar ranges of efficiency for each DMU and average efficiency of the fleet for the two periods studied is obtained. However, the average standard deviation (SD) identified for the Cantabrian seiners in 2019 was ±23.6 %, substantially higher than in 2015 (±20.8 %). Similar results were obtained by González-García et al. (2015), who compared the operational efficiency of Portuguese purse seiners for two consecutive years (2011 and 2012). Specifically, they found that the average efficiency values for the entire fleet in the two years of assessed operation were similar (62 % in 2011 versus 63 % in 2012), and similarly, standard deviations (SD) for the Portuguese seiners were similar to those in this study (in 2011 it was ±16.8 %, while in 2012 it was ±23.1 %). While it is impossible to make a direct comparison of the two fleets average efficiency values due to inherent disparities in the studied fleets and the system boundaries considered in each investigation, it is possible to conclude that both studies exhibit a similar trend. Specifically, both investigations suggest that the overall average efficiency of the fleet tends to remain constant over time.

Fig. 6 shows operational efficiency score of each DMU for the two periods studied. It can be observed that for the majority of the vessels analyzed (72 %), efficiency was higher in 2019, specifically between 18 % and 57 % higher. Only for four purse seiners was efficiency higher in

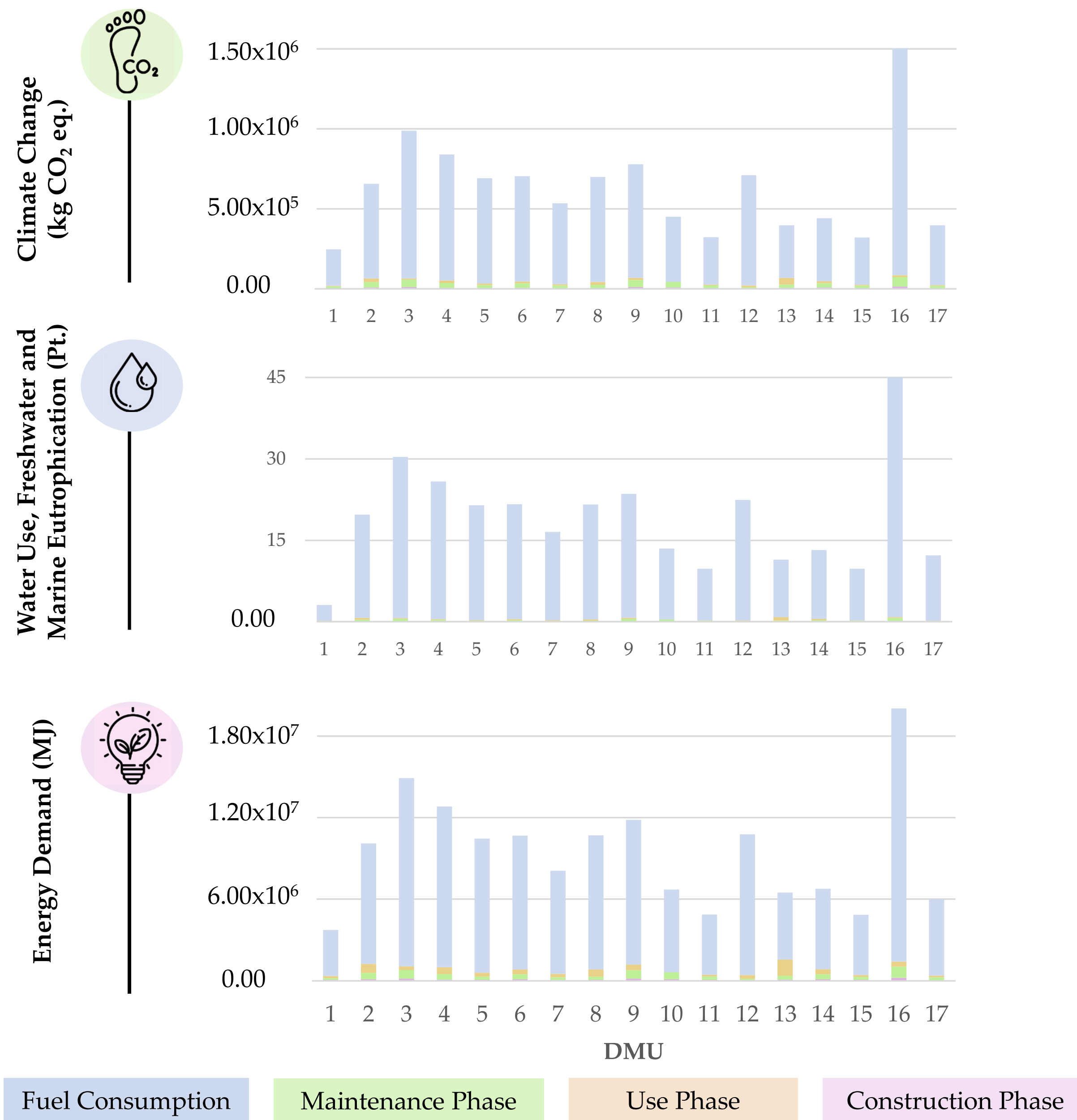

Fig. 3. Current environmental results for each individual fishing vessel grouped by stages (maintenance, construction and use) and for fuel consumption.

2015 than in 2019. To ascertain whether this trend holds over time, data from a longer inventory period would be necessary to understand the environmental profile of these products, an issue that has not yet been clearly addressed in life cycle literature due to a variety of reasons, such as data gaps and/or limitations or the relatively short duration of research projects.

The increase in operational efficiency of vessels over the years can be attributed to some factors such as technological advancements with significant improvements in hull design, more efficient propulsion systems, and the integration of digital technology and automation onboard, which allow vessels to operate more efficiently (Birchenough et al., 2021). Additionally, improvements in fleet management, including the development of real-time tracking and monitoring systems, as well as advanced route planning and scheduling techniques, have contributed to more efficient resource management (Watson et al., 2018). Other factors such as fleet aging, changes in maritime regulations (Avadí and Freón, 2013), or inadequate fleet management, including inefficient resource allocation and lack of long-term planning (Colloca et al., 2017), could contribute to a decrease in operational efficiency over time.

Vessels with better performance in the fleet consistently achieved higher efficiency levels, while units with lower efficiency levels failed to improve efficiency over the years. These results may suggest that differences between vessels were linked to the fact that some skippers were able to maintain high performance standards throughout the season, while others cannot sustain the desired rates (Ruttan and Tyedmers, 2007). Although the “skipper effect” was not directly analyzed in this study, it has been identified by other authors as a critical factor when studying purse seining fisheries behavior (Vázquez-Rowe and Tyedmers, 2013).

4. Conclusions

The joint implementation of the LCA+ DEA method using a composite index (WEF) as input for the DEA matrix has proven to be a

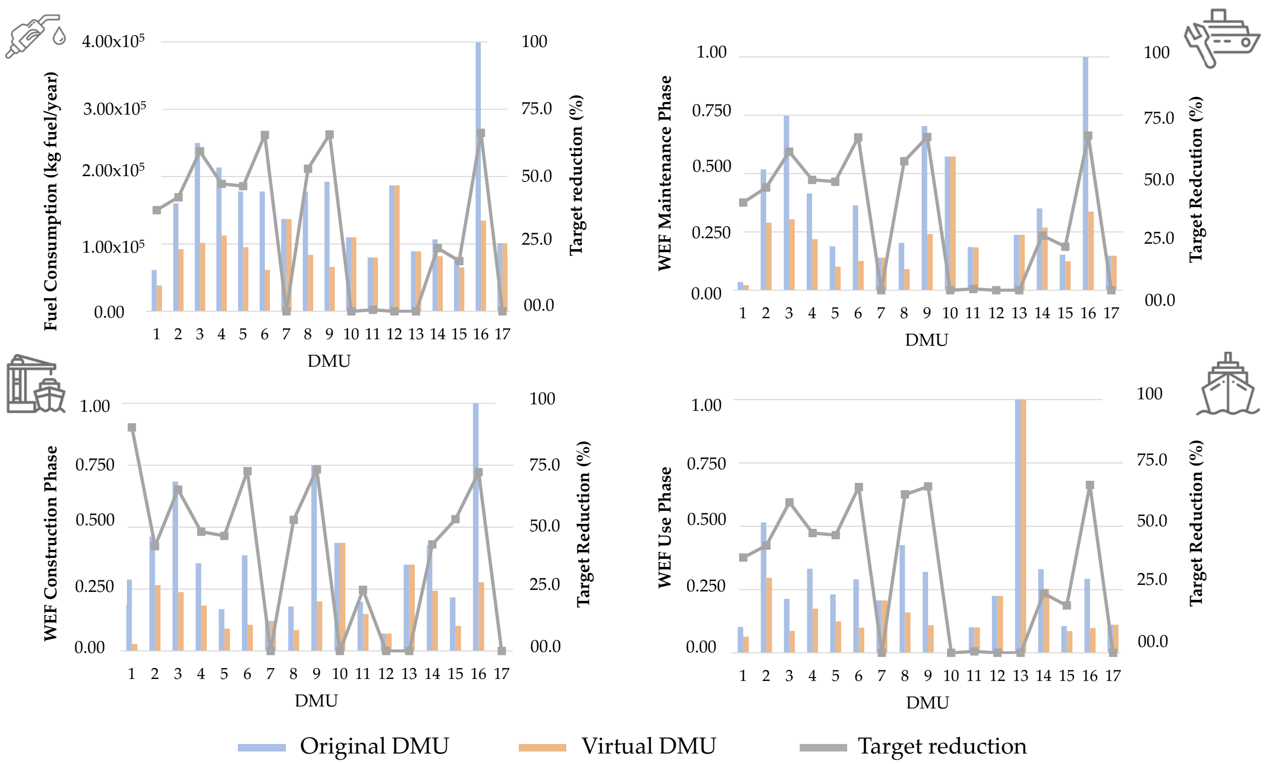

Fig. 4. Process value for the original and virtual decision-making units (DMUs) and the corresponding reduction target, for each of the inputs considered.

promising methodology to assess the operational and environmental performance of a purse seiner fleet. A set of 17 purse seine vessels belonging to 4 ports along the Cantabrian coast were analyzed using a 5-step LCA + DEA approach jointly with the WEF nexus. Firstly, the average CF result of the fleet was 632 t CO_2 eq per vessel, with the highest impact computed for DMU16 (1560 t CO_2 eq). Larger vessels generally had higher CF values due to greater fuel requirements, despite fishing quotas limiting catch amounts. In terms of EF, the average value was 1.63×10^8 MJ, with DMU16 consuming the most energy (i.e., 154 % above average). The average WF was 32.4×10^1 μPt. The study highlights that fuel consumption is the primary contributor to environmental impacts across all categories, accounting for over 90 % of the total impacts. Furthermore, results showed a relatively high overall efficiency throughout the fleet (>)70 %. Inefficient units showed a higher potential to reduce their environmental impacts (up to 65 %) if operating under efficiency projections calculated within the DEA matrix.

These results highlight significant variations in operational efficiency and environmental impact within the fleet, thus highlighting the importance of identifying and addressing areas for improvement to maximize efficiency and minimize environmental impact across the entire fleet. Furthermore, results demonstrate the strong dependence of environmental impacts on fuel consumption. It is important to note that this analysis is based on the available data and assumptions used in the LCA + DEA model, which may introduce a certain degree of uncertainty into the available data.

When comparing trends across two years (i.e., 2015 and 2019) based on a prior analysis of this same fleet, it was observed that vessels exhibiting high levels of efficiency in a particular year tended to maintain these levels, while those with lower efficiency levels did not demonstrate the capacity to enhance their efficiency to higher standards. However, it would be necessary to analyze a broader time frame to understand the environmental profile of the fleets, as this aspect has not been clearly addressed in the literature.

While some vessels may be operating efficiently in terms of resources, there are still opportunities to improve operational efficiency and associated environmental impacts. This underscores the importance of adopting holistic approaches that integrate considerations of both technical, economic, and social aspects to achieve a sustainable balance between economic profitability and environmental impacts. In this context, the 5-step LCA + DEA method applied in this study proved to be a suitable tool for quantifying operational and environmental targets, enhancing the effectiveness of using LCA or DEA as standalone tools. In order to validate the suitability of incorporating the nexus approach within the LCA + DEA methodology for analyzing eco-efficiency in fishing systems (fishing fleets or fisheries), it is necessary to conduct additional studies covering various fleets and through longer time frames. Having said this, the methodology as applied to the Cantabrian fishing fleet has proven to be robust and flexible, and potentially replicable to any other context regardless of its geographical area and/or fleet characteristics.

Among the limitations of the present study, a major issue was the uncertainty related to the quality of the inventory data. As detailed in the study by Ceballos-Santos et al. (2023), although primary data were obtained directly, a series of assumptions were necessary, including the calculation of combustion emissions through emission factors, introducing a degree of uncertainty into the system. Additionally, the background systems used from the Ecoinvent and Agribalyse databases are also subject to uncertainty, as the processes included may not be representative of the conditions of the system under study. Another significant limitation is that most operational activities, including fuel use, are analyzed on an annual basis. Therefore, it was not possible to break down fuel consumption by landed species and it was not feasible to incorporate the nutritional aspect of the WEF Nexus, as the species were not studied separately.

The limitations identified open avenues for future research, particularly in terms of expanding this methodology to other case studies to verify whether the methodology remains robust, valid, accurate, and effective across various contexts. Additionally, further research into the reasons behind differences in operational efficiency and reduction percentages among fleet vessels is proposed. Incorporating socioeconomic

Fig. 5. Current environmental impacts (color bar) of the different inefficient decision-making units (DMUs), target environmental impacts (striped bar), and the corresponding reduction target percentage (line).

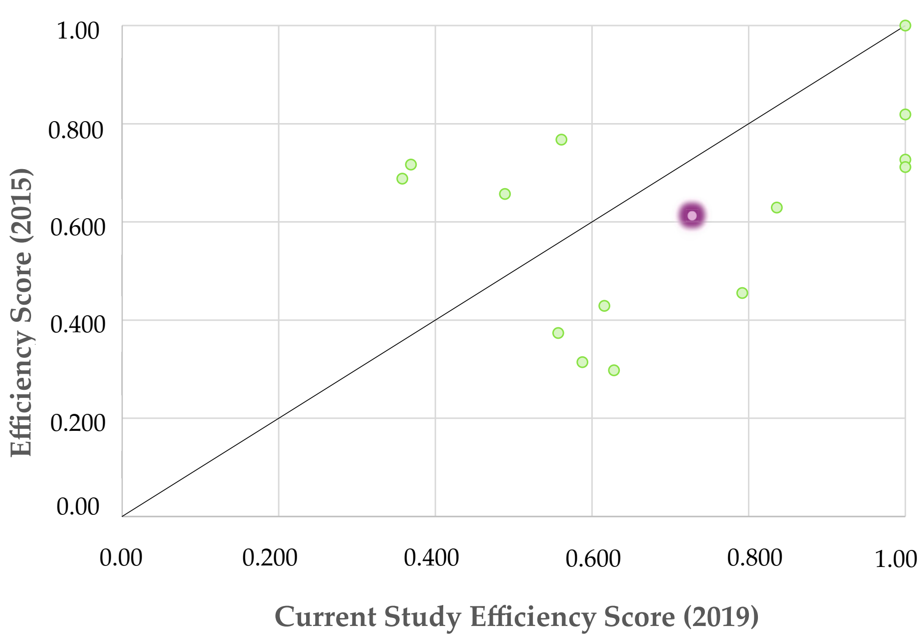

Fig. 6. Comparative efficiency score for the 2 years of assessment. Note: The purple dot represents the average efficiency of all vessels.

indicators could also provide a more comprehensive understanding of the impacts of fishing practices on local communities and regional economies. Furthermore, establishing continuous monitoring programs could help evaluate how efficiencies and environmental impacts evolve over time, allowing for a thorough analysis of the effects of fluctuations in fish populations or the implementation of new regulations, among other factors.

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CRediT authorship contribution statement

Eva Martínez-Ibáñez: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Conceptualization. **Jara Laso:** Writing – review & editing, Visualization, Validation, Formal analysis, Data curation, Conceptualization. **Ian Vázquez-Rowe:** Writing – review & editing, Validation, Software, Investigation, Conceptualization. **Sandra Ceballos-Santos:** Writing – review & editing, Visualization, Validation. **Ana Fernández-Rios:** Writing – review & editing, Visualization, Validation. **María Margallo:** Writing – review & editing, Visualization, Validation, Supervision, Funding acquisition, Conceptualization. **Rubén Aldaco:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization.

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.

Data availability

Data will be made available on request.

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