

Cross-vessel eco-efficiency analysis. A case study for purse seining fishing from North Portugal targeting European pilchard

Sara González-García^{1,2} · Pedro Villanueva-Rey² · Sara Belo¹ · Ian Vázquez-Rowe^{2,3} · María Teresa Moreira² · Gumersindo Feijoo² · Luis Arroja¹

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Abstract

Purpose European pilchard captures constitute an important source of income for the Portuguese fishing sector. This raw material is used for a varied range of final seafood products, such as canning, fresh seafood consumption or bait for other fisheries. The Portuguese purse seining fleet, which concentrates most of the pilchard landings, has recently obtained the Marine Stewardship Council certification scheme, demonstrating the effort of the fleet to comply with sustainable fishing practices. However, this scheme does not consider the human inputs to the fishery, such as fuel consumption or the use of other materials and resources. Consequently, life-cycle methods, such as Life Cycle Assessment (LCA), have arisen to provide a thorough assessment of the environmental profile of fishing fleets. In the current study, LCA is combined with Data Envelopment Analysis (DEA), a management tool, in order to understand the eco-efficiency of the individual vessels that compose this fleet.

Methods A 5-step LCA+DEA method, previously used to assess resembling vessel samples, was used to examine the efficiency of 20 purse seiners in the northern Portugal for years 2011 and 2012. Individual Life Cycle Inventories (LCIs) were gathered for each vessel to perform, thereafter, the Life Cycle Impact Assessment (LCIA). DEA matrices were generated based on the LCI in order to obtain the efficiency values for each unit. Finally, based on the efficiency projections provided by the DEA model, a new LCIA was performed for inefficient vessels in order to calculate the potential environmental benefits of operating at higher levels of efficiency.

Results and discussion The average efficiency of the fleet in the two different years of assessment was slightly above 60%. Moreover, individual vessels showed a fairly low standard deviation across the 2 years of assessment, demonstrating that units with higher levels of efficiency tend to maintain these values through the analysed window. In fact, this result, given its strong correlation with fuel use, appears to have relation with the existence of a certain level of “skipper effect”. Important environmental benefits, mainly linked to the optimisation of fuel resources, could be attained if inefficient vessels were to operate efficiently, especially in terms of two main impact categories: climate change and fossil depletion.

Conclusions The results in this study confirm that fishing small-pelagic fish shows low energy intensity as compared to other fisheries. However, despite this worldwide tendency, the use of LCA+DEA confirms that substantial improvements in terms of optimising energy and material inputs, as well as in reducing environmental impacts, can be attained in these fishing fleets.

Keywords LCA+DEA method · Life cycle assessment · *Sardina pilchardus* · Skipper effect

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✉ Ian Vázquez-Rowe
ian.vasquez@pucp.pe

- ¹ CESAM and Department of Environment and Planning, University of Aveiro, Campus Universitário de Aveiro, 3810-193 Aveiro, Portugal
- ² Department of Chemical Engineering, Institute of Technology, University of Santiago de Compostela, Rúa Lope Gómez de Marzoa s/n, 15782 Santiago de Compostela, Spain
- ³ Red Peruana de Ciclo de Vida (RPCV) – Department of Engineering, Pontificia Universidad Católica del Perú, Av. Universitaria 1801, San Miguel, Lima 32, Peru

1 Introduction

European pilchard (*Sardina pilchardus*), commonly referred to as sardine, is an important seafood product in the Iberian Peninsula, constituting one of the main sources of marine protein for human communities (Martín-Cerdeño 2010; INE 2011). In fact, Portugal is the country with highest sardine landings in the European Union (EU; Almeida et al. 2014), with this species representing 34 % of total national landings in 2011 (INE 2012). Most sardines landed along the Iberian Atlantic coast are destined to direct human consumption (DHC) or bait for other fisheries (Vázquez-Rowe et al. 2014), while the production of feed (i.e. indirect human consumption (IHC)) is irrelevant. However, different trends in sardine consumption are observed throughout the year, highlighting the relevance of fresh consumption in the summer months. In contrast, during the rest of the year, most of the Portuguese landings are used, together with imports arriving from Morocco, for the production of canned products (Ernest 2009). This situation implies that sardine landings constitute the most relevant fish supply for the Portuguese canning sector (ICES 2012). In addition, it should be noted that its nutritional importance has increased in recent decades due to its high content in omega-3 fatty acids and its contribution to reducing the incidence of heart diseases (Silva et al. 2009).

This small-pelagic species forms large schools that are distributed along the continental shelf off the Spanish and Portuguese Atlantic coast (divisions VIIIc and IXa) in depths that range from 10 to 100 m (Carrera and Porteiro 2003). The Portuguese purse seining fleet, which is the most socioeconomically important fleet in Portugal, accounts for approximately 98 % of sardine landings (Tacon and Metian 2009; ICES 2012; INE 2012; Almeida et al. 2014), while the remaining landings are linked to small-scale fleets. However, it is important to highlight that the purse seining fleet is also responsible for the landing of other important small-pelagic species, such as Atlantic chub mackerel (*Scomber colias*), horse mackerel (*Trachurus trachurus*) or anchovy (*Engraulis encrasicolus*).

Given the importance of sardine landings in the national context, the Portuguese fishing sector pursued the Marine Stewardship Certification (MSC) for this fishery in 2008, obtaining the sustainability certificate in January 2010 (MSC 2014). Therefore, the Portuguese sardine fishery is, together with the Cornish and South Brittany fisheries, the only sardine fishery with this prestigious certificate in Europe (MSC 2014). However, the certification suffered a short period in which it was suspended in 2012, although it was reinstated in January 2013 (MSC 2014). The main reasons behind this temporal suspension were linked to a series of factors, including the fact that (i) the harvest strategy was not responsive to the state of the stock and (ii) the fishery failed to comply with the ICES recommendations for mortality rates (MSC 2014).

Despite the wide range of advantages that fisheries earn by applying for MSC certification or other fishery certification

schemes, these schemes have systematically focused on the sustainability of the stock, rather than on integrating also abiotic environmental burdens linked to the human activities associated with fishing, such as ozone layer depletion, greenhouse gas (GHG) emissions, toxicity and acidification, among others (Ziegler et al. 2014). In this context, Life Cycle Assessment (LCA) is used as an environmental management methodology that aims at evaluating the life cycle environmental burdens linked to a specific process, product or service (ISO 2006a, b). The use of LCA in the fishing sector has shown to be not only of utter importance in quantifying and evaluating the role of fuel consumption in propelling fishing vessels (Vázquez-Rowe et al. 2012; Ziegler et al. 2014) but also a key in spotting other sources of environmental concern, such as cooling agent leakage from cooling systems (Iribarren et al. 2010a), the role of anti-fouling paints in toxic emissions or, if the entire supply chain of seafood products is examined, the role of post-landing phases on the overall environmental profile (Vázquez-Rowe et al. 2013; 2014).

The use of LCA has been increasingly applied to small-pelagic fisheries in recent years (Vázquez-Rowe et al. 2010a; Almeida et al. 2014; Avadí et al. 2014). In fact, European pilchard has been analysed from an LCA perspective in Portugal (Almeida et al. 2014) and Galicia—NW Spain (Vázquez-Rowe et al. 2014). Even though pilchard caught in both areas all belong to the same stock, important differences have been observed when cross-checking the results for both fisheries. The reasons behind these discrepancies are linked to a set of legal (fishing quota systems), geographic, stock dynamics and operational issues (Ziegler et al. 2014).

Nevertheless, it is also important to bear in mind that cross-fleet variability may also be strongly influenced by the individual performance of fishing vessels (Almeida et al. 2014; Vázquez-Rowe et al. 2013). Therefore, the use of LCA in combination with Data Envelopment Analysis (LCA+DEA methods), a management tool to evaluate the relative efficiency of multiple entities, has proven to be of special use when production systems are analysed, such as fishing fleets, with multiple units targeting one single purpose (Vázquez-Rowe et al. 2010b; Vázquez-Rowe and Iribarren 2014) as a way to provide a computation of the eco-efficiency of these units (ISO 2012). DEA arose initially as a performance measurement methodology to empirically quantify the relative productive efficiency among a certain number of units that share a resembling functionality (Cooper et al. 2007). In the past decade, its use in environmentally oriented studies as a single methodology was pushed forward to evaluate the environmental performance or the eco-efficiency assessment of multi-entity production systems (Kuusmanen and Kortelainen 2005, 2007; Kortelainen 2008; Vázquez-Rowe et al. 2010b). However, the use of the combined LCA+DEA method allows obtaining a series of synergistic advantages, with the aim of performing the computation of benchmarks of each individual

unit. This joint assessment permits calculation simultaneously the technical inefficiencies as well as the environmental savings that could be performed if the units (in this case fishing vessels) are operating efficiently (Vázquez-Rowe et al. 2011; Vázquez-Rowe and Iribarren 2014).

In this study, the LCA+DEA method has been applied to the Portuguese sardine fishery considering a purse seining fishing fleet sample constituted by 20 vessels with similar characteristics in terms of operational patterns, fishing technology, fishing incentives and seasonal restrictions. The main aim of this study is to estimate the environmental loads linked to operational inefficiency, as well as to define target performance values for inefficient vessels if these were to proceed in an efficient way. In addition, a secondary objective, given the use of data for two operating years (2011 and 2012), was to evaluate the existence of the so-called “skipper effect”, i.e. the role of the fishermen’s skills as a determining factor when assessing vessel efficiency (Ruttan and Tyedmers 2007). Thus, the results from this study are expected to be of great interest for stakeholders in the Portuguese fishing sector, as well as for researchers interested in the primary inventory data collected.

2 Materials and methods

2.1 Definition of the case study

2.1.1 Contextualisation of the case study

According to the MSC (2013), the Portuguese purse seining fishing fleet that targets small-pelagic fish is made up of 99 vessels (MSC 2013) characterised by an average length of 20 m and a mesh size of the seine nets of 16 mm (MSC 2013; MADRP 2010). The raw resource landed by these vessels, European pilchard, constitutes the most important fishery product in Portugal in terms of live weight landings (52,828 t in 2011) and economic turnout (41.1 M€) (Anderson et al. 2012; INE 2012). Moreover, the entire fleet presents the same function: landing pilchards for sale in Portuguese port auctions.

However, it is important to bear in mind that the stock of European pilchard off the coast of Portugal and NW Spain presents important fluctuations in abundance on an annual basis, triggering relevant consequences on the economic viability of the fleet when abundance is at its lowest (Mendes and Borges 2006). Similarly, it should be noted that this fishing stock is also targeted by smaller artisanal vessels in Portugal, as well as by the small-scale and seining fleets in Galicia, Spain (Vázquez-Rowe et al. 2010a, 2014). In this study, however, a sample of 20 vessels belonging to the most important purse seiner producers’ organisation in the northern Portugal (fishing area—ICES division IXa) was considered for analysis. This selection of seiners, the registered in the port of Matosinhos (41° 11' N/08° 42' W) and representing on

average 35 to 40 % of the total annual Portuguese pilchard landings, presents a fairly consistent pattern across vessels, with low standard deviations in terms of vessel length, seine net characteristics or the way in which the fishing operations are carried out (INE 2011, 2012; Belo et al. 2013).

This LCA+DEA study is framed in the context of an increasing interest in the environmental profile of small-pelagic fish captures off the coast of the Iberian Peninsula, mainly on the Atlantic side. For instance, an LCA study in Galicia (NW Spain) identified best gear practices to target small-pelagic fish from an environmental perspective (Vázquez-Rowe et al. 2010a), and a more recent study identified the environmental profile of purse seiners targeting pilchard in Portuguese national waters (Almeida et al. 2014). While these two studies focused on the fishing stage of small-pelagic fish, Vázquez-Rowe et al. (2014) went a step further by analysing the entire supply and consumption chain of pilchards, by comparing three different consumption routes of the same biotic resource (i.e. European pilchard). Despite the fact that fishing fleets that target small-pelagic fish, especially those that use seine nets as the fishing gear, show a relatively low fuel use intensity (FUI) in most fisheries worldwide (Vázquez-Rowe et al. 2012; Fréon et al. 2014; Parker and Tyedmers 2014), the fishing stage still represents an important percentage of environmental impacts when the entire supply chain is considered (Ziegler et al. 2013; Vázquez-Rowe et al. 2014). Moreover, previous studies have delved into the variability in environmental impacts between individual vessels within a single fleet from a seasonal (Almeida et al. 2014) or behavioural (Vázquez-Rowe and Tyedmers 2013) perspective. However, variability among individual vessels remains highly unexplored given the difficulty to obtain high-quality data for large samples of vessels. Nevertheless, previous LCA+DEA studies in the fishing sector have identified strong variation in environmental impacts within a single fishery depending on the vessel that is performing the landing (Vázquez-Rowe et al. 2010b, 2011; Ramos et al. 2014) or on the segment size (Avadí et al. 2014). The current study aims at identifying this variability between vessels in two different years of operation, in order to detect whether vessels tend to operate in similar terms of efficiency in different fishing campaigns.

2.1.2 Definition of the unit of assessment

This study originates from the availability of primary inventory data for a reasonable amount of vessels. Consequently, it is necessary to fix a unit of assessment to measure the eco-efficiency of the fishery under analysis through the DEA matrix. This unit, whose performance will be computed through the use of a specific DEA model, is named decision making unit (DMU; Cooper et al. 2007). For this particular case study, and in accordance with previous LCA+DEA studies in the fishing sector (Vázquez-Rowe et al. 2010b; Vázquez-Rowe

and Iribarren 2014), the unit of assessment selected was each individual fishing vessel. The rationale behind this selection is justified based on the fact that the vessels constitute independent and fairly homogeneous entities within the production system, to which all major inputs and outputs can be linked to. In addition, vessels, even if they are under a similar quota and economic regime, and even if they are operated by the same producers' organisation, will always present a unique managerial behaviour, based on the skippers' and on the rest of the crews' skills (Ruttan and Tyedmers 2007).

The computation of the different DMUs in the DEA matrix is performed through the absorption of their individual data regarding input and output flows of materials and energy, which in this case are obtained from the Life Cycle Inventory (LCI). Thereafter, the DEA model selected for the assessment will non-parametrically calculate the relative efficiency of each DMU (i.e. purse seining vessels). Consequently, a production efficient frontier will be created by the model in which all those DMUs deemed efficient are situated, whereas the remaining entities, which will have different levels of inefficiency, will be located throughout the production possibility set (PPS). Finally, once the DEA model selected has been computed, the practitioners will have a final efficiency score for each DMU, which is calculated based on the individual reduction potentials that were computed for each input/output (Cooper et al. 2007). For those DMUs that have full relative efficiency, no reduction potentials are calculated, whereas for inefficient units, the reduction potentials translate into target operating points (see Section 2.2.1).

The system boundaries for the production system include all life cycle operations from the production of the supply materials up to the landing operations done on board for sale at Portuguese ports (mainly Matosinhos). The construction and maintenance of vessels were also included within the systems' boundaries. However, other operations such as on-land operations at port, distribution by retailers, sale at markets, sardine-processing-related activities and consumption in Portuguese households were excluded due to the fact that these could no longer be attributable to the unit of assessment that was selected (Avadí et al. 2014), i.e. the individual fishing vessels. Figure 1 summarises the input and output flows subject to quantification for each of the DMUs (i.e. each individual purse seiner). Moreover, since DEA computation only involves a selection of the inputs and outputs included in the LCA, DEA and LCA elements are differentiated in the figure.

2.2 LCA+DEA framework

2.2.1 Selection of the LCA+DEA method

Within the wide range of LC (life cycle)+DEA methods available (Vázquez-Rowe and Iribarren 2014), a 5-step LCA+DEA method was selected due to its holistic approach,

including numerous environmental dimensions, as well as the detailed benchmarking process it provides, by basing environmental improvements in the LCIA on actual minimisation of operational inputs. Nevertheless, it should be noted that a modified version of the 5-step LCA+DEA method was considered in this case study, based on the approach adopted by Avadí et al. (2014), in which the DEA matrix is composed of a mixture of inputs of different origins (see Fig. 2). On the one hand, some of the inputs correspond to regular operational inputs obtained from the LCI. Nevertheless, these inputs have to meet free disposability criteria, that is, double counting of resembling traits of the production system should be avoided (Iribarren et al. 2010b). However, this perspective, while regular in LCA+DEA studies, was not fully applicable in this particular case study. Hence, on the other hand, other inputs, which are not directly comparable between DMUs due to their heterogeneous nature, were included as inputs in the matrix using the ReCiPe endpoint Life Cycle Impact Assessment (LCIA) method as a way to homogenise activities within the production system (Avadí et al. 2014).

2.2.2 Selection of the DEA model

The DEA model selected for this study was the slack-based measure of efficiency (SBM). Its use is commonly applied in LCA+DEA studies due to its flexibility in terms of the estimation of the efficiency of the individual DMUs regardless of the units of measure (Cooper et al. 2007; Thrall 1996). In accordance with previous LCA+DEA studies in the fishing sector, non-radial metrics¹ were used in the model to account for independent minimisation of operational inputs within the DEA matrix. Moreover, an input-oriented perspective was assumed in the model. In other words, a minimisation of the inputs while maintaining the final output was assumed, rather than seeking the maximisation of outputs. This perspective was selected given the fact that the sardine fishery in Portugal, despite lacking a total allowable catch (TAC) policy enforced by the European Union (EU), has regulatory schemes through daily and weekly quotas for individual vessels, limiting the capacity of these to land sardine and other small-pelagic fish. Finally, for the production possibility set (PPS) of the DEA calculation, a constant returns-to-scale (CRS) approach was implemented based on the fact that the vessels operate in a competitive market in the same fishing area (Cooper et al. 2007), as well as the fact that the analysed vessels in the sample all constitute a relatively homogeneous cluster, with

¹ One of the main features of DEA matrices is the metrics that are assumed. These can either be radial, in which collective improvement calculations among inputs and outputs are considered, or non-radial, when individual improvement calculations within each input and output dimension are taken into consideration (Cooper et al. 2007).

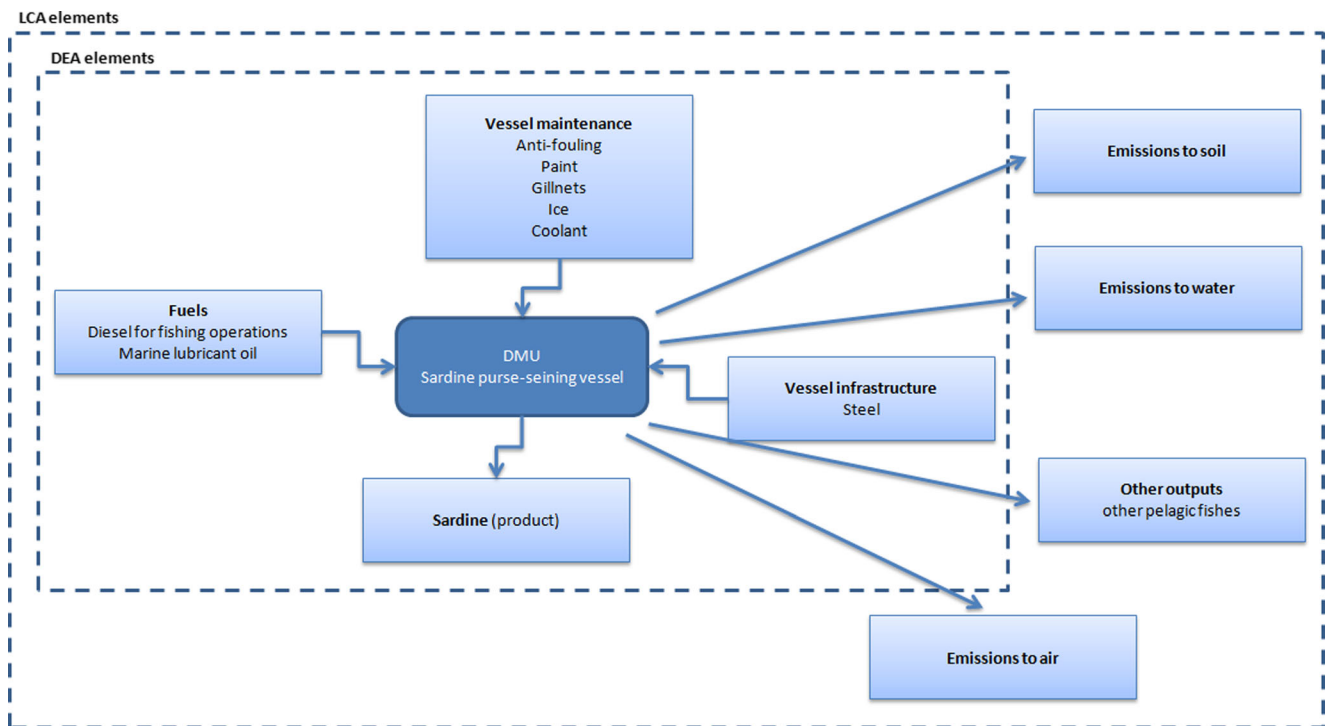


Fig. 1 LCA and DEA items considered in each DMU

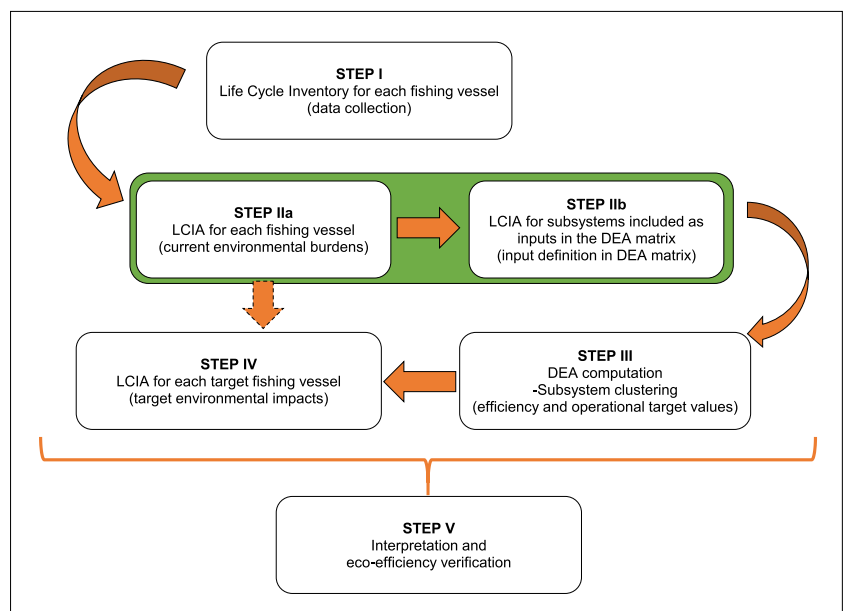
low standard deviations in terms of vessel size, which suggests that no scale factor should be assumed (Banker et al. 1984).

2.2.3 Input and output selection for the DEA matrices

A total of three inputs were computed in the DEA matrix. On the one hand, the amount of fuel used for propulsion by the seiners was inserted in the matrix as input 1, constituting the

only conventional inventory-based input included in the assessment (Iribarren et al. 2010b). On the other hand, inputs 2 (vessel construction) and 3 (maintenance) constitute a cluster of operational activities and, therefore, inventory processes from an LCI perspective, that are inserted in the DEA matrices in terms of their aggregated environmental profile using the ReCiPe single-score endpoint assessment method (Goedkoop et al. 2009). The latter perspective allowed integrating operational items with a similar function in one single input.

Fig. 2 Schematic representation of the 5-step LCA+DEA method (adapted from Avadi et al. 2014)



Finally, the output selected was the amount of pilchard landed in 1 year of operation. Despite the fact that other untargeted species were landed, these represented only 2.2 % of landings in 2011 and 1.4 % in 2012. Moreover, these species only represented 0.1 % of the total economic value in both years (Belo et al. 2013). Hence, their computation in the DEA matrix was disregarded.

3 Results

3.1 Inventory data

The data included in the LCI are mainly of primary origin and were retrieved from the most important cluster of purse seining vessels in the northern Portugal. Table 1 presents the main average characteristics for the selected sample. Data were collected for two different years of assessment, 2011 and 2012. These data included total annual capture, the use of fuel to propel the vessels, the consumption of ice as well as the technical characteristics of the vessels. Furthermore, the inventory was completed with data from bibliographical sources in order to account for the construction and certain maintenance aspects of the vessel (Vázquez-Rowe et al. 2010; Ramos et al. 2011). For instance, the amount of steel used in the construction of the vessels was calculated based on the lightship weight (LSW) equation (Fréon et al. 2014). Thereafter, the use of steel was allocated during the entire life span of the vessels, which in all cases was assumed to be 40 years (Fréon et al. 2014). Similarly, the use of anti-fouling paint was estimated based on the dimensions of the vessel (Ramos et al. 2014). Emission factors from fuel combustion were obtained from the EMEP-Corinair standards (EMEP-Corinair 2009), and those linked to the emissions of anti-fouling agents were retrieved from Hospido and Tyedmers (2005). Finally, background data to support the primary data were obtained from the ecoinvent[®] database, using version 2.2 (Frischknecht et al. 2007).

3.2 Environmental characterisation of the current vessels

The assessment method to convert the inventory processes in environmental impacts was ReCiPe using the SimaPro v8.01 as the selected computational software (Goedkoop et al. 2009;

Table 1 Characteristics of the Portuguese purse seining fleet. Source: Anderson et al. (2012) and MCS (2013)

	2008–2011
Total Portuguese fleet	4978 vessels
Purse seining fleet	200 vessels
Pelagic purse seining fleet ^a	54 vessels

^a Vessel 18–24 m in ICES division IXa

PRè Consultants 2014). This method choice was based on the fact that it covers a wide range of midpoint impact categories (18), and provides the possibility to calculate also the endpoint damage categories. In addition, as pointed out by Hauschild et al. (2013), this assessment method has a high compliance rate with a series of quality indicators, such as certainty, scientific robustness, transparency or completeness of scope. Therefore, fishery-specific impact categories, which are not included in the ReCiPe assessment method, were excluded from the analysis (Avadí et al. 2014).

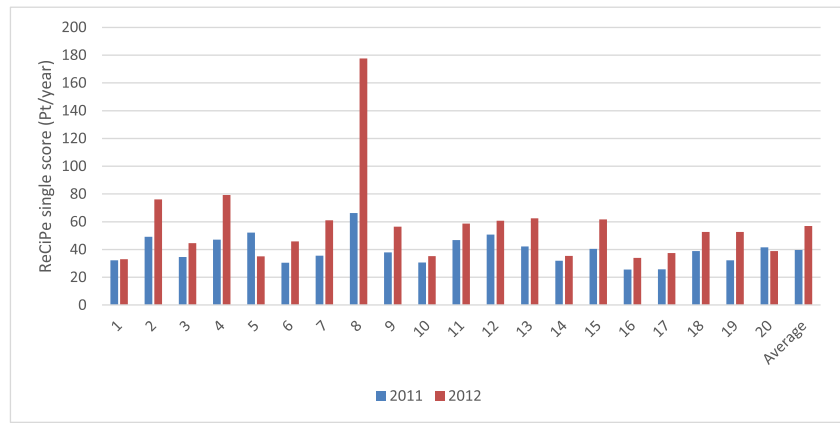
The selected functional unit (FU) to refer the environmental impacts to was 1 t of landed pilchard in a Portuguese port in one of the two years of operation. The main reason for this bulk FU selection is related to the fact that the system boundaries were limited to the fishing stage of pilchard supply chains. Hence, the FU chosen reflects the characteristics of the raw material once it is landed at port. Allocation was used in the Life Cycle Inventory (LCI) in order to assign 100 % of the environmental impact to pilchard, rather than using mass, economic or any other type of allocation strategy, due to the minimal economic value of the untargeted species, as well as the fact that these species imply a very low level of incidental catch (below 2.5 %). Figure 3 shows the current endpoint single-score environmental impacts that have computed for each individual vessel.

3.3 DEA performance

Using the LCI as the initial framework, two different DEA matrices (see Tables 2 and 3), corresponding to the two different years of operation, were created with a total of three operational inputs and one single output to which the inputs are referred to (see Section 2.2.3). An SBM-I (i.e. input oriented) model was chosen, as mentioned in Section 2.2.2, with constant returns to scale (CRS) in order to compute the results using the DEA-solver Pro software (Tone 2001; Saitech-inc 2014). The selection of an input-oriented model perspective is justified, in a similar way to other LCA+DEA studies in the fishing sector (Avadí et al. 2014; Ramos et al. 2014), on the basis that the aim of any environmental sustainability assessment is intimately linked to the minimisation in the use of resources, following the concept of eco-efficiency, rather than on the maximisation of the output (Fréon et al. 2008; Avadí et al. 2014).

The results are shown in Tables 4 (year 2011) and 5 (year 2012), with the quantification of the estimated reduction that is feasible for the individual operational inputs, as well as the average efficiency value (Φ) for each DMU. One single vessel was deemed efficient in 2011, while in 2012, the number of vessels operating at full relative efficiency rose to three. However, the average efficiency for the entire sample was practically identical for the 2 years of operation, being slightly higher in 2012 (63 %) than in 2011 (62 %). In contrast, the range of scores for inefficient DMUs was smaller in 2011 (32

Fig. 3 Current environmental endpoint single-score results for the individual fishing vessels selected (results reported per functional unit: 1 tonne of landed fish)



to 87 %) than in 2012 (16 to 86 %). Interestingly, despite these minor differences, the examined vessels showed similar trends when analysed individually from 1 year to the next, as discussed in depth in Section 4.

3.4 Target environmental characterisation; eco-efficiency verification

The individual reduction targets for each DMU computed in the DEA matrix (step 3) were utilised in a further step to perform a second LCIA of those vessels that were deemed

inefficient in the first iteration. Hence, a modified LCI for these vessels was constructed, in which the reduction values for the different operational inputs substituted the original data. Thereafter, a new environmental characterisation was computed for inefficient DMUs, with the main objective of identifying their environmental benchmarking. Figure 4 shows the potential environmental gains for the inefficient vessels for a selected mid-point impact category, whereas Fig. 5 presents these gains aggregated in the single-score weighted endpoint indicator.

Based on this second iteration of the LCIA, step 5 of the LCA + DEA method intends to confront the real

Table 2 Input/output data envelopment analysis (DEA) matrices for the sample of 20 vessels from the Portuguese purse seining fleet (year 2011)

DMU	Inputs			Output
	Fuel consumption (L/year)	Construction phase (Pt/year)	Maintenance phase (Pt/year)	Landed pilchard (tonnes/year)
1	92,890	452	9701	1194
2	95,890	378	9609	802
3	85,350	350	9574	1031
4	89,250	428	9671	786
5	89,250	472	9725	711
6	90,750	372	9602	1231
7	135,250	564	9840	1512
8	90,750	423	9665	568
9	99,750	358	9584	1077
10	115,000	408	9646	1511
11	99,750	275	9481	869
12	98,750	484	9740	798
13	112,500	402	9639	1075
14	125,350	445	9797	1586
15	92,550	380	9611	945
16	99,750	275	9481	1595
17	100,500	440	9686	1603
18	121,500	458	9709	1251
19	96,750	420	9661	1232
20	95,550	394	9629	944

DMU decision making unit

Table 3 Input/output data envelopment analysis (DEA) matrices for the sample of 20 vessels from the Portuguese purse seining fleet (year 2012)

DMU	Inputs			Output
	Fuel consumption (L/year)	Construction phase (Pt/year)	Maintenance phase (Pt/year)	Landed pilchard (tonnes/year)
1	88,650	452	9873	1120
2	105,037	452	9873	563
3	83,810	350	9746	789
4	86,550	428	9843	457
5	64,280	472	9897	807
6	92,290	372	9774	834
7	129,000	564	10,012	845
8	92,165	423	9837	215
9	97,750	358	9756	710
10	117,250	408	9818	1342
11	97,555	275	9653	682
12	112,150	484	9912	748
13	103,000	402	9811	673
14	111,500	440	9858	1279
15	95,250	380	9783	636
16	106,580	275	9653	1273
17	115,000	440	9858	1238
18	124,960	580	13,583	1101
19	102,500	420	9833	797
20	101,500	394	9801	1068

DMU decision making unit

environmental performance of the vessels with the virtual environmental impacts calculated in step 4. As can be observed in Fig. 5, similar levels of potential reduction in terms of the environmental profile of the different vessels are observed in both years of assessment. In Fig. 4, one single impact category, climate change, computed with ReCiPe, demonstrates that reductions in the use of operational inputs have an unequal impact on individual categories, which is probably linked to the weight of fuel use in the optimisation through DEA and, hence, making the environmental gains more evident in those categories with a higher affinity to this energy carrier.

4 Discussion

4.1 Efficiency analysis through the analysed period

The average efficiency values for the entire fleet in the two different years of operation assessed were surprisingly similar (62 % in 2011 vs 63 % in 2012). The similarity in the pattern plotted in Fig. 6 for DMUs in the two different years of assessment reveals a significant level of correlation in the inefficiencies presented by the individual vessels ($R^2=0.51$). In addition, the average standard deviation (SD) identified for the Portuguese seiners in 2011 was ± 16.8 %, substantially

lower than in 2012 (± 23.1 %). However, when the individual SD of the vessels is analysed based on efficiency ranges, the lowest SD is observed for vessels with efficiency values higher than 75 % in both years of assessment (below ± 10 %). Nonetheless, the difference with the other two ranges (50–75 % and below 50 %) was not significant, being remarkably low for the range below 50 % in 2011 (± 5.5 %). The efficiency values, as well as the SDs observed for individual vessels, suggest that vessels tend to maintain similar levels of efficiency from a temporal perspective. Despite the lack of a longer time period to identify whether this trend is confirmed through time, it should be noted that similar results have been seen in other purse seining fisheries (Vázquez-Rowe and Tyedmers 2013), linking efficiency to the existence of a “skipper effect”. However, the results in the current study should be interpreted with care, since the link between eco-efficiency using LCA+DEA and the existence of a “skipper effect” in this fleet may not be completely linear, as discussed in more details in Section 4.2.

In terms of the environmental profile of the vessels, it was difficult to compare the environmental profile of this fleet with that of others analysed in the literature due to the different methodological assumptions, objectives of the study and, most importantly, the different assessment methods that were used to compute the results. Having said this, GHG emissions

Table 4 Efficiency scores (Φ) and target reduction scores (%) for the sample analysed (year 2011)

DMU	Inputs			Efficiency (Φ)
	Fuel consumption (%)	Construction phase (%)	Maintenance phase (%)	
1	19.6	54.4	26.8	0.66
2	47.7	63.4	50.4	0.46
3	24.5	49.2	36.0	0.63
4	44.9	68.3	51.7	0.45
5	50.2	74.0	56.5	0.40
6	15.2	42.9	23.8	0.73
7	30.1	53.7	8.7	0.69
8	60.9	76.8	65.1	0.32
9	32.5	48.1	33.2	0.62
10	17.8	36.1	6.9	0.80
11	45.5	45.5	45.5	0.54
12	49.5	71.5	51.3	0.43
13	40.2	53.9	33.7	0.57
14	20.9	38.5	3.8	0.79
15	36.1	57.1	41.6	0.55
16	0.0	0.0	0.0	1.00
17	0.3	37.2	1.6	0.87
18	35.6	52.9	23.4	0.63
19	20.4	49.3	24.2	0.69
20	38.2	58.7	41.7	0.54

DMU decision making unit

Table 5 Efficiency scores (Φ) and target reduction scores (%) for the sample analysed (year 2012)

DMU	Inputs			Efficiency (Φ)
	Fuel consumption (%)	Construction phase (%)	Maintenance phase (%)	
1	0.0	0.0	0.0	1.00
2	55.1	73.1	56.8	0.38
3	21.2	51.3	38.6	0.63
4	55.8	76.9	64.8	0.34
5	0.0	34.4	29.2	0.79
6	24.3	51.6	35.3	0.63
7	45.2	67.6	36.0	0.50
8	80.5	89.0	83.4	0.16
9	39.2	57.1	44.8	0.53
10	0.0	0.0	0.0	1.00
11	41.5	46.4	46.4	0.55
12	44.2	66.6	42.8	0.49
13	45.3	63.8	48.0	0.48
14	4.0	37.2	1.6	0.86
15	44.1	63.8	50.7	0.47
16	0.0	0.0	0.0	1.00
17	9.9	39.2	4.8	0.82
18	26.2	58.9	38.5	0.59
19	34.9	58.9	38.5	0.56
20	11.9	41.5	17.4	0.76

DMU decision making unit

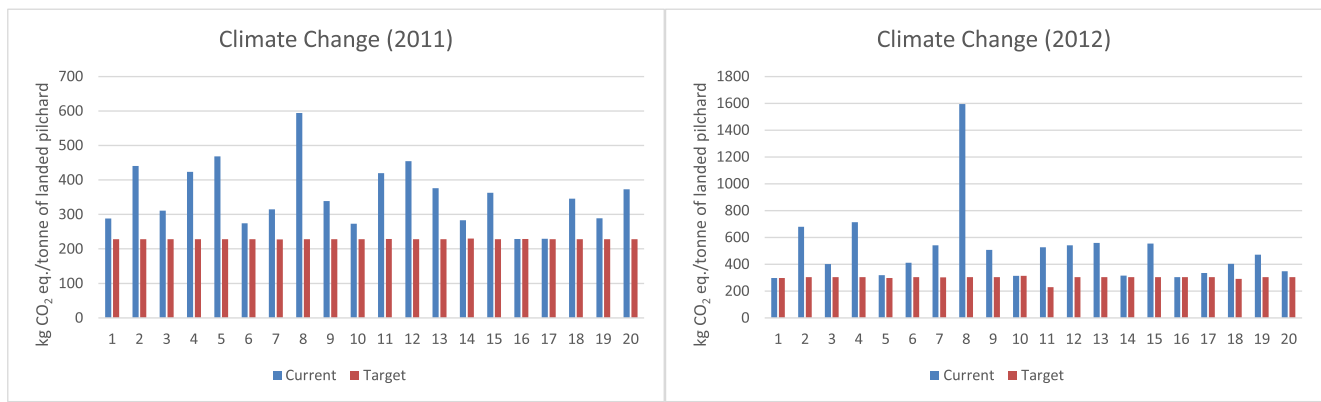
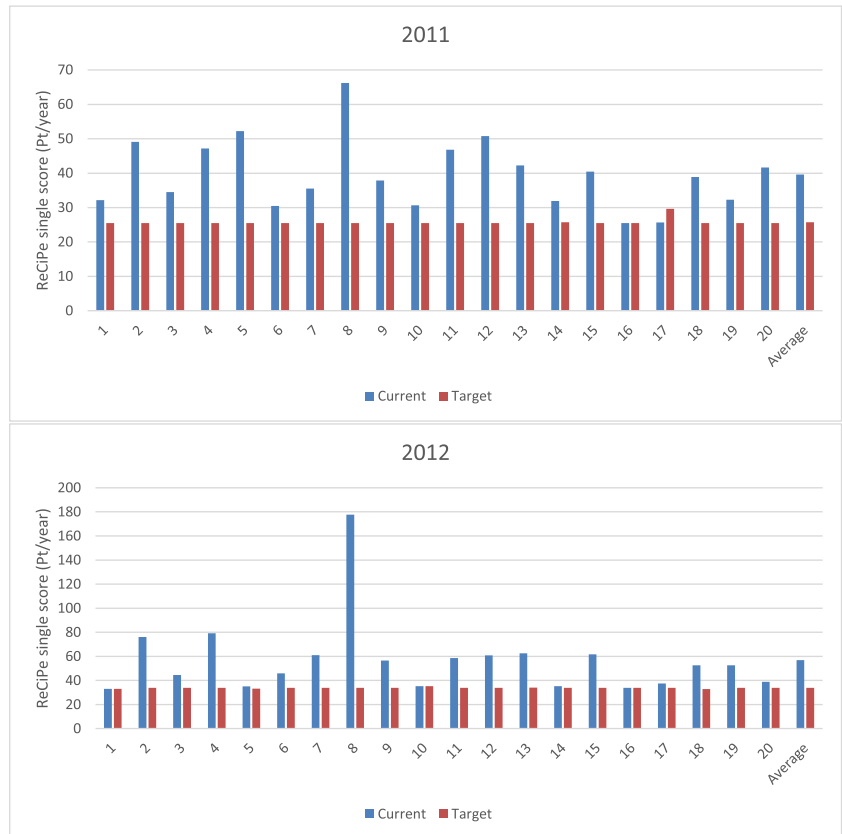


Fig. 4 Climate change (CC) environmental impact for original DMUs (blue bar) and virtual targets (red bar) per year of assessment

computed through the ReCiPe method do not present strong methodological differences with respect to other assessment methods, as determined by Hauschild et al. (2013). Therefore, as observed in Table 6, the contributions of 1 t of landed pilchard are compared across different studies. Results for pilchard in this sample appear to be in accordance with another sample of pilchard-targeting seiners in Portugal assessed by Almeida et al. (2014), which determined that pilchard landings roughly accounted for 300–450 kg CO₂eq./t of pilchard in the period 2005–2011. The results for 2011 in the current study are placed on the lower side of the range, while values for 2012 are slightly above the range observed in the previous

study (507 kg CO₂eq./t). Interestingly, the latter value coincides with that of the year with the lowest spawning stock biomass (SSB) ever recorded for the fishery (ICES 2013). Nevertheless, the values obtained in this study are still below the results recorded for this same stock in Galician (NW Spain) waters, 780 kg CO₂eq./t in 2008 (Iribarren et al. 2010a, 2011), although important differences should be considered between the two fleets in terms of accessibility to the pilchard stocks. This is mainly due to the fact that Galician purse seiners are not allowed to operate within the inner fraction of the continental platform, a circumstance that increases FUI considerably (Vázquez-Rowe et al. 2010a).

Fig. 5 Single-score endpoint environmental impact for original DMUs (blue bar) and virtual targets (red bar) per year of assessment



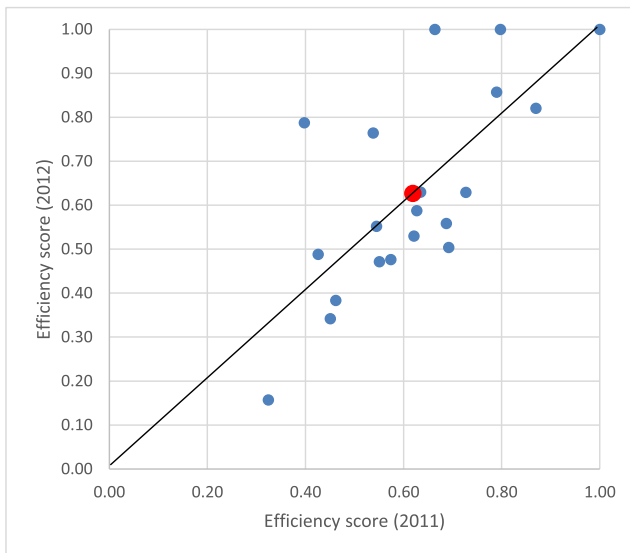


Fig. 6 Comparative efficiency score (Φ) for the 2 years of assessment. The red dot represents the average efficiency of all vessels

The average efficiency obtained for Portuguese seiners (above 60 %) was found to be higher than that for the purse seining fleet targeting European pilchard in NW Spain (approximately 44 %), as discussed in Vázquez-Rowe et al. (2011). While the inputs included in both studies are not completely identical, the lower range of efficiency scores and the higher average efficiency in the Portuguese fleet are remarkable. Linked to what has been previously mentioned, a higher reliance on fossil fuels in NW Spain may magnify operational differences between skippers, explaining this differential. Based on the LCA results obtained, most impact categories would considerably benefit if the entire sample was to be performed efficiently. Moreover, this would translate into a reduction in CO₂ eq. emissions of 2817 t in 2011 and 3550 t in 2012 for the sample of vessels assessed. In a similar way, savings in terms of energy use, water depletion or

emissions of acidifying agents would be attained in similar proportions. In accordance to previous purse seining studies, the main reductions in environmental impact would be attributable to the FUI of the vessels, while other operational activities, such as the construction of the vessel, maintenance or the use of ice, would have a secondary role (Fréon et al. 2014; Vázquez-Rowe et al. 2010).

4.2 Do the results demonstrate the existence of a “skipper effect”?

As observed in Fig. 7, efficiency values for single vessels tend to be somewhat resembling in the two different years of assessment, despite the fact that the available stock in 2012 was much lower as compared to that in 2011 (ICES 2013). These results, although limited by the short timeline that has been taken into consideration, suggest that there is an existence of certain differences between vessels in their capacity to operate at their highest level of efficiency. However, it remains unclear whether this variability is due to a series of technical differences between vessels, or whether the “skipper effect”, which accounts for the skills of the skipper and other members of the crew to sense or know where the catch will be available (Squires and Kirkley 1999), has an important effect on these results.

In the first place, several studies in the literature report the fact that the skills of the crew tend to be more important in seining fleets than in other industrial fleets, such as trawlers or long liners (Gaertner et al. 1999). For instance, strong correlations between the “skipper effect” and vessel efficiency have been identified in several purse seining fleets (Ruttan and Tyedmers 2007; Vázquez-Rowe and Tyedmers 2013). Therefore, at first sight, it may seem plausible to assume that the results presented in this study are, in effect, a consequence of the “skipper effect”.

Table 6 GHG emissions of pilchard landings across published studies

Publication	Product	Inventory year	Functional unit	kg CO ₂ eq./FU
Current study	European pilchard (Portugal)	2011	1 t of landed pilchard	354
		2012		507
Iribarren et al. (2011)	European pilchard (NW Spain)	2008	1 t of landed pilchard ^a	780
Almeida et al. (2014)	European pilchard (Portugal)	2005	1 t of landed pilchard ^b	320
		2006		292
		2007		363
		2008		466
		2009		398
		2010		301
		2011		318

^a The allocation method used in this study was economic, although very similar price values were found across the landed species

^b Mass allocation was used in this study

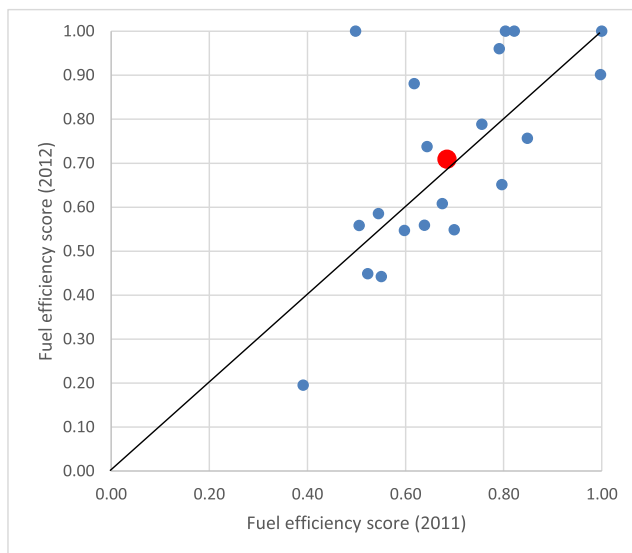


Fig. 7 Comparative fuel efficiency score for the 2 years of assessment. The red dot represents the average fuel efficiency of all vessels

Secondly, the technical differences between the units assessed are assumed to be relatively low, since the range in terms of vessel size and characteristics is low (see Table 1). Moreover, these operate in the same geographical area, targeting the same stock and using the same fishing gear. Data gaps and misreporting are also considered to be minimal, since all vessels belong to the same organisation, and data were supplied directly by the producers' headquarters. Finally, illegal, unreported and unregulated (IUU) fishing were also considered to be low, given the strict controls from authorities and certification agencies.

However, it remains unclear whether the inputs selected in the DEA matrices for this study are the most appropriate to determine whether there is a “skipper effect” in this fleet. On the one hand, the use of two inputs in the DEA matrix that conform a wide range of individual processes contributes to cover a higher proportion of the energy and material inputs of the vessels, but also may shadow potential inefficiencies for individual inputs that have been aggregated. On the other hand, fuel efficiency has repeatedly been associated with the skill of skippers, since its use, especially in coastal fisheries with short distances to port and static gears such as seine nets, is a direct measure of the capability of the crew to perform. Based on this discussion, it seems plausible to assume that the measure of the partial efficiency values in the DEA matrix for fuel use may be a more precise measure of the existence of a “skipper effect” in this fleet than the global DEA efficiency scores analysed above. Hence, these partial scores for fuel, shown in Fig. 7, tend to maintain a similar pattern to those observed for the global efficiency scores, demonstrating that there is a significant correlation between the efficiency scores per individual vessel in both years of operation ($R^2=0.45$). In addition, despite the existence of vessels that do not fit into

this pattern, no major differences were observed between efficiency ranges, suggesting that efficient vessels tend to operate in similar efficiency ranges in the two different seasons.

Despite the fact that the results from this study tend to suggest that the “skipper effect” could have a certain degree of influence on the observed inefficiencies, it is important to highlight that a wider window of analysis would be desirable to confirm the tendencies shown. In addition, while the use of DEA in combination with LCA can help identifying inefficient practices in production systems, together with potential environmental improvements, it does not provide a detailed analysis on what the underlying sources of inefficiency may be (Vázquez-Rowe and Iribarren 2014). Hence, other factors, such as epistemic uncertainties in data quality or the capacity size of the fleet (e.g. the construction phase in the DEA results showed to be the input with highest inefficiency levels), are factors that could also have a considerable effect on the results.

5 Conclusions

The joint LCA+DEA method allowed zooming into the individual environmental profiles of vessels of the same fishery. Although the time frame was limited, results suggest that those vessels that perform at high levels of efficiency in one given year tend to repeat these levels, whereas vessels with lower levels of efficiency did not show the capability of improving their efficiency to higher standards. While these results advocate for the existence of behavioural and operational differences between skippers, future research should delve into the specific motives that lead to this variability.

While different studies across Europe have shown that environmental impacts linked to the fishing of pilchard are usually in a similar range, the use of the LCA+DEA certifies that important reductions in environmental impacts could be attained if most vessels were to operate at higher levels of efficiency, which would seem reachable based on the levels presented by best performing vessels. However, these improvements will be ultimately linked to a wide range of issues that in some cases may seem difficult to identify. In the present study, some of these inefficiencies appear to be linked, at least partially, to what is named the “skipper effect”, while other important parameters, such as the characteristics of the vessels, did not show any correlation to the inefficiency values.

In addition, the results from this study confirm the important variability in the environmental performance between different years of assessment observed in previous studies. While this tendency occurs in most natural ecosystems due to climatic, geographical or operational changes, purse seining activities seem to be affected more than other sectors due to the high oscillation in available biomass attributable to most small-pelagic fish (Fréon et al. 2008). Hence, it seems plausible to

increase the temporal window to understand the environmental profile of these products, an issue that is yet to be tackled clearly in the life cycle literature due to a variety of reasons, such as data gaps and/or limitations or the relatively short period of research projects.

Finally, the results in this case study confirm the low environmental impacts associated with fishing small-pelagic fish worldwide. These species, however, are not those that are typically most consumed in Western societies for DHC, since consumers tend to prefer other species such as tunids or gadoids (e.g. hake or cod) than pilchard, mackerel or anchoveta. From a life cycle perspective, while it would seem consistent to initiate changes in consumer preferences through awareness campaigns, it remains to be seen how the highly variable small-pelagic stocks would react to a higher consumption for DHC of these species. Therefore, the use of consequential LCA perspectives may be a promising proxy to evaluate the environmental changes linked to changing seafood consumer habits, as well as to periodic or climate change-driven variations in fishing stocks (Vázquez-Rowe and Benetto 2014).

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