Operational Efficiency and Environmental Impact Fluctuations of the Basque Trawling Fleet Using LCA+DEA Methodology

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Abstract

A recent study, using Life Cycle Assessment (LCA), suggests that natural fluctuations in stock abundance in fisheries may cause high variability in environmental impacts related to the Atlantic mackerel fishery in the Basque Country. The aim of this study is to analyze environmental fluctuations through time of a demersal species, European hake (*Merluccius merluccius*), caught by Basque bottom trawlers in European waters. The three-step LCA+DEA method, which combines LCA with data envelopment analysis (DEA), a linear programming tool, was implemented to assess annual variability of the environmental impacts in the period 2001-2006. The identification of the varying operational efficiency levels between vessels and the potential environmental gains of input minimization were explored. Results showed variations of up to 25% in the environmental impacts between years, although minimal environmental gains were identified through operational benchmarking, given the similar efficiency values between vessels. Hence, it was observed that despite substantial interannual changes in the impacts, there is limited potential for environmental impact reduction for the assessed environmental dimensions. Environmental and operational differences between years impeded setting a particular best-performing target for this production system, attributable to the high variance observed in input/output distribution through time. Finally, results seem to confirm the lower fluctuations in environmental impacts for demersal species fishing in comparison with those of small pelagic fish.

Keywords: Data envelopment analysis, fishing vessels, hake, life cycle assessment, trawling.

Introduction

Protein supply from fishing and aquaculture activities constitutes an outstanding source of economic revenue for coastal communities (Cooley *et al.*, 2009). However, commercial fisheries are currently facing a serious crisis on a worldwide level, due to the overexploitation of fishing stocks (Pauly *et al.*, 2002; Worm *et al.*, 2009). This situation has led to important economic and social effects on local fishing communities (Hamilton, 2007; Hannesson, 2006). In virtue of this complex international context, European nations agreed in the 1970s to set common rules in European waters to regulate fish landings, protect fishing communities from abrupt changes in seafood trade and manage European fisheries with a continental perspective (Song, 1995). This strategy derived in what is now known as the Common Fisheries Policy (CFP).

Spain, the main fishing nation in Europe in terms of gross tonnage, landings and employment, concentrates most of its fishing infrastructure along the Cantabrian and Atlantic coasts, mainly in the Basque Country and Galicia (European Commission, 2012). While Galicia is responsible for nearly 50% of the Spanish fishing vessels and is characterized by mainly artisanal fishing vessels, (MARM, 2011), the Basque Country is noted for its small, specialized, and in many cases, industrial fishing fleets (Freire and García-Allut, 2000; Iriondo *et al.*, 2010; Murua, 2010). Even so, the size of the Basque fleet is comparable to that of important fishing nations, such as Denmark (EUROSTAT, 2009). Given the characteristics of these two regions, shifts in decision making in the CFP can have important consequences on the local communities and on the economy. Consequently, due to the increasing predominance of environmental issues in fisheries management, a spate of scientific research regarding environmental sustainability of fisheries has been observed in research centers throughout NW Spain (Borja *et al.*, 2000, 2011; Carballa-Penela and Domenech, 2010; Vázquez-Rowe *et al.*, 2012a).

While environmental sustainability in fisheries

has usually been limited to the effects that fishing causes in marine ecosystems, a broader interpretation is starting to be applied, in which energy demand and materials used in industrial fishing are evaluated in order to assess their environmental and operational impacts (Hospido and Tyedmers, 2005; Vázquez-Rowe et al., 2012a; Avadí and Fréon, 2013). One of the methodologies commonly used to analyze these environmental impacts is Life Cycle Assessment – LCA, the only internationally standardized environmental assessment tool (ISO, 2006a; Kloepffer, 2008).

LCA allows compiling and analyzing the inputs and the outputs, as well as the potential environmental impacts of a production system throughout its entire life cycle (ISO, 2006a; 2006b). Its use for the environmental assessment of food systems has shown a strong development in the past two decades (Roy et al., 2009; De Vries and De Boer, 2010). More specifically, its application to fishery and seafood systems first appeared in Scandinavian countries (Eyjolfsdottir et al., 2003; Ziegler et al., 2003), as a tool to measure environmental impacts, such as global warming, toxicity or eutrophication, generated by operational activities in fisheries and fish processing systems (Hospido and Tyedmers, 2005). However, triggered by the holistic approach of LCA, a series of methodological innovations have been developed which take into consideration a series of fishery-specific impacts, such as the computation of discards, seafloor impacts or biotic resource use –BRU (Ziegler et al., 2003; Pelletier et al., 2007; Vázquez-Rowe et al., 2012a).

The use of LCA in the Spanish seafood sector has undergone substantial development, with studies analyzing the environmental profile of a wide range of coastal and offshore fisheries (Vázquez-Rowe et al., 2012a), as well as aquaculture (Iribarren et al., 2012). These studies have centered mainly on hake fisheries worldwide (Vázquez-Rowe et al., 2011b; 2013), since hake is the most consumed seafood product in Spanish households (Martín-Cerdeño, 2010; Asche and Guillen, 2012).

The integrated perspective of evaluating a wide range of environmental studies is definitely one of the main advantages of the LCA methodology. However, certain constraints can be linked to the applicability of regular LCA studies, such as temporal details of the case studies, or the way in which multiple datasets are handled (Weidema and Wesnaes, 1996; Reap et al., 2008; Udo de Haes et al., 2004). Together with methodological innovation within the tool, LCA practitioners have taken advantage of other existing methodologies in order to obtain suitable combined methods to solve the specific methodological barriers in a particular case study. One of these tools is the Data Envelopment Analysis (DEA), which has been combined with LCA in a wide range of publications under the name of the LCA+DEA method (Vázquez-Rowe et al., 2010; 2011a; 2012b; Iribarren et al.,

2010; 2011; Jan et al., 2012).

DEA is a linear programming methodology that provides a comparative empirical efficiency of multiple similar units (Cooper et al., 2007). DEA has been applied to fisheries and other primary sector activities as an independent methodology in several studies (Kao et al., 1993; Idda et al., 2009; Griffin and Woodward, 2011; Picazo-Tadeo et al., 2011). In fact, DEA, thanks to its ability to discriminate between different units within multiple datasets, has been used in the fishing sector to analyze the technical efficiency (TE) or the capacity utilization (CU) of a wide range of different fishing fleets (Tingley et al., 2003; 2005; Färe et al., 2006; Maravelias and Tsitsika, 2008), as a tool to evaluate the degree of overcapacity of fishing fleets worldwide (namely European fleets) while proposing strategies to improve and homogenize their efficiency (Herrero and Pascoe, 2003; Griffin and Woodward, 2011).

The use of DEA with LCA aims at linking the environmental impacts with operational benchmarking, as a way of attaining eco-efficiency verification through the theoretical optimization of inputs and outputs (Lozano et al., 2009). Having said this, it should be noted that these theoretical optimization standards do not suggest specific improvement actions to attain eco-efficiency standards, even though some studies (Vázquez-Rowe and Tyedmers, 2013) do explore the specific sources of environmental inefficiencies. Furthermore, it also makes it possible to avoid the use of average data in multiple unit systems, reducing common sources of uncertainty in LCA studies (Vázquez-Rowe et al., 2010), which enhances the delivery of best-performing targets for individual units (e.g. fishing vessels). Despite the fact that this method has only been developed quite recently, it has been successfully applied to a range of production systems in the primary sector, including fisheries, viticulture or dairy farms (Iribarren et al., 2011; Vázquez-Rowe et al., 2011a; 2012b). However, a series of unexploited potentials of this joint methodology remain unexplored (Iribarren et al., 2010). One of these is the use of a timeframe methodological option for DEA, window analysis, to determine the environmental impact efficiency of production systems on a time frame basis (Charnes et al., 1985).

Previous studies have highlighted the strong variations in stock abundance in small pelagic fisheries which have occurred long before human exploitation of marine resources and, therefore, cannot be associated with fishing activities (Holmgren-Urba et al., 1993; Schwartzlose et al., 1999; Fréon et al., 2008). Furthermore, a study conducted by Ramos et al. (2011a) suggested strong changes in environmental impacts on a seasonal basis in the Basque Atlantic mackerel (Scomber scombrus) fishery. In fact, they used the Fisheries in Balance (FiB) method as an auxiliary tool to LCA, finding a strong correlation between years with low stock

abundance and higher environmental impacts. In this case study, the LCA+DEA method is applied to the Basque trawling fleet in ICES Division VIIIabd, with the aim of determining whether the abovementioned environmental profile variability of pelagic species can also be observed in demersal species (i.e., mainly European hake – *Merluccius merluccius* – in the present study), which tend to show lower natural fluctuations in stock abundance (ICES, 2013; see Figure 1). Furthermore, the complementary use of DEA aims to detect not only timeline variance, but also differences between fishing vessels, as well as estimating the environmental consequences of inefficiencies in vessel operations. Consequently, the main objective of the study is focused on assessing annual variability of the environmental impacts of fishing activity in the Basque bottom trawling fishery.

Methodological Framework

Definition of the Case Study

Characteristics of the Production System Analyzed

The offshore trawling fleet in the Basque Country had a total of 20 vessels in 2006, which target a set of high and medium economic value demersal fishing species in the Celtic Sea (Figure 2), sharing the fishery stocks with vessels from France, United Kingdom, Ireland, Denmark and other Spanish regions, mainly Galicia (Murillas *et al.*, 2008). European hake constitutes the main target species for the Basque trawling fleet, due to its culinary importance and its attractive sale price in Basque fish markets. Nevertheless, other species, such as blue whiting (*Micromestimius poutassou*), megrim
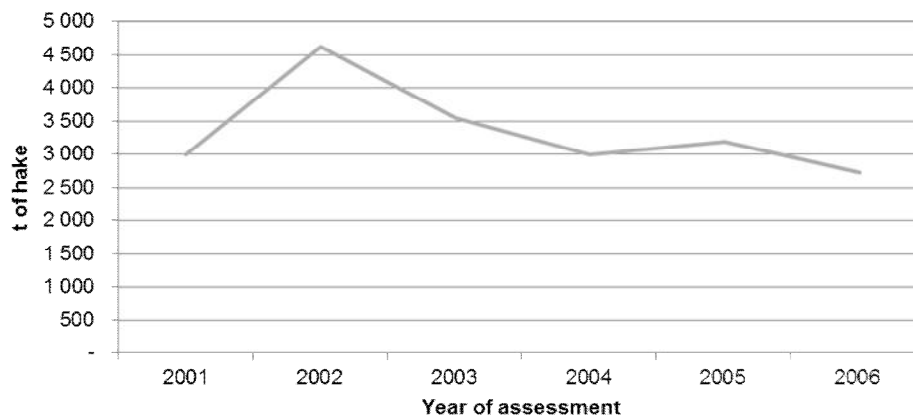
Figure 1. European hake landings in the Basque Country in the 2001-2006 period. Source: AZTI (2010).
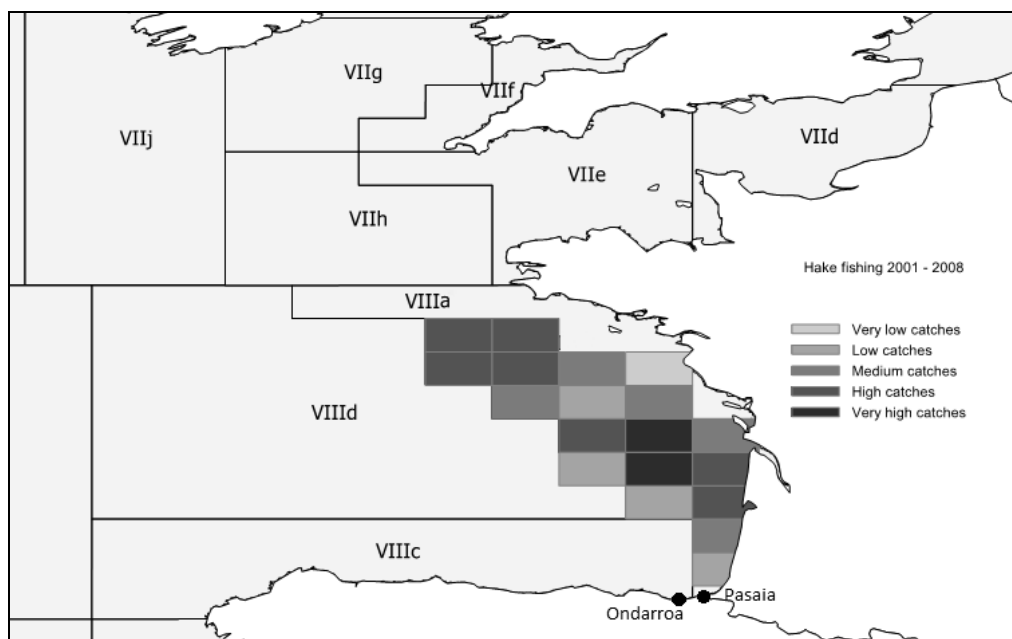
Figure 2. Map illustrating the main fishing areas of the Basque trawling fleet. Roman numbers on graph refer to the ICES areas. The variable tones of grey in zone VIII refer to the amount of hake caught by Basque vessels. Dark grey tones reflect increasing levels of catch.

(*Lepidorhombus* spp.) and common sole (*Solea solea*), are also landed by these vessels.

This fleet is constituted by two different types of bottom trawlers, known as *baka* and bottom pair trawlers. *Baka* trawlers operate as single boat trawlers and are, therefore, using otter doors to spread the trawl. Their trips last on average 6 days, with haul durations that range from 4 to 5 h. Catch is generally landed in two specific Basque ports: Ondarroa and Pasaia. Bottom pair trawlers are composed of two vessels trawling a single net. The average trip for these vessels is usually 5 or 6 days, with longer hauls 7-8 h (Murillas *et al.*, 2008).

Unit of Assessment Determination and Data Acquisition

Decision making units (DMUs) are each of the independent entities that make up the multiple unit system (Cooper *et al.*, 2007). When assessing fishing systems with the LCA+DEA method, the chosen unit of assessment in previous studies has been the fishing vessel, since this approach guarantees a realistic perception of the vessels' performance (Vázquez-

Rowe *et al.*, 2010). Nevertheless, for this specific fleet it may be argued that pair trawlers do not represent two separate entities, since they operate under the same operational and environmental conditions. However, in this article all vessels were considered as independent DMUs for two main reasons: on the one hand, the fact that all pair trawlers also performed trips as single operating vessels at given times of the year; on the other, pair trawlers did not always operate with the same vessels, with several changes observed on an annual and interannual scale.

Figure 3 shows a schematic representation of the main material and energy flows that were considered in the production system. The system boundaries were limited to the fishing activities and their background processes, excluding the on-land phases of fish supply chains. This perspective was considered due to the fact that industrial processes of transformation and transport are not expected to vary much from one year to another in terms of environmental impact, at least when the existing processing industry is working close to its full capacity (Benedetto *et al.*, 2014). In fact, any variations in these stages would not be primarily affected by changing landing rates by the
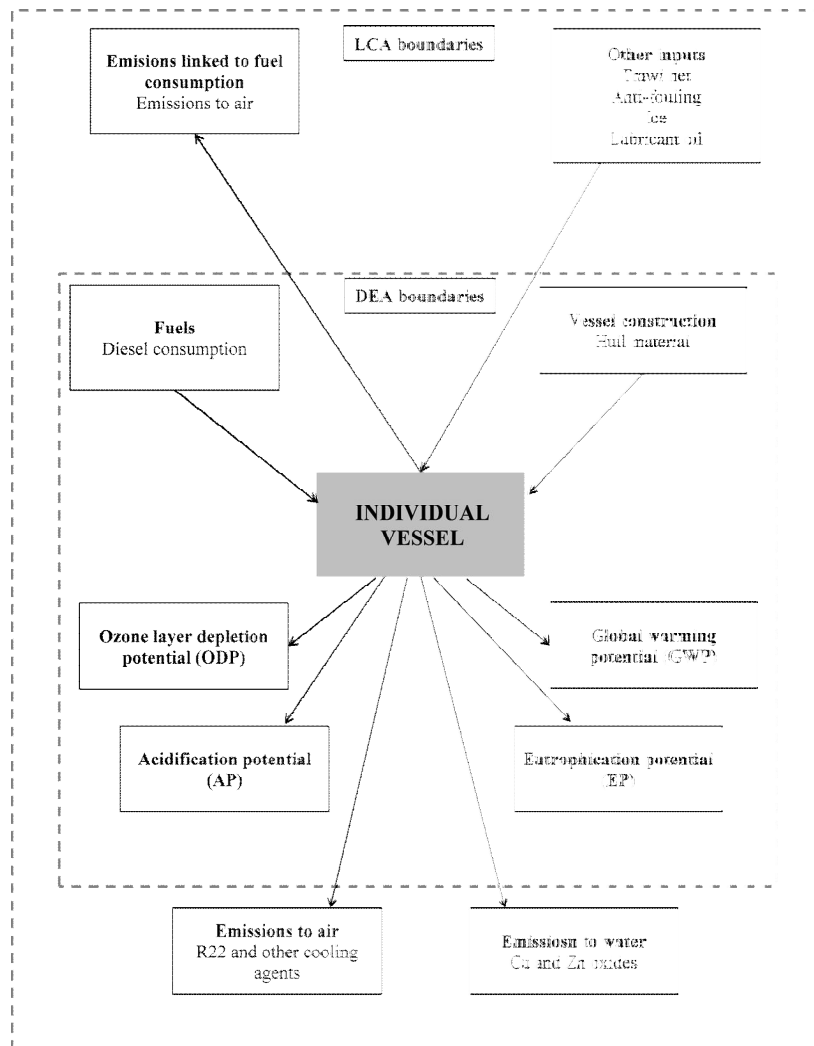
Figure 3. Inputs and outputs included in the production system for LCA+DEA implementation.

vessels. A final issue that was taken into account to limit the boundaries to the fishing stage was the complexity of the supply chain. Fish products, especially those consumed fresh, such as hake in Spain, are part of highly complex market flows in which the existence of clearly comparable units of assessment, as needed for DEA implementation, are very diffuse and not homogenized with the fishing stage (Kaplan, 2000; Ilbery and Maye, 2005; Martín-Cerdeño, 2010).

Regarding the selection of inputs and outputs to be included in the system, there are certain discrepancies that can be identified between LCA and DEA. For the LCA methodology an integrated life cycle inventory, as defined by ISO 14044 (ISO, 2006b) was followed, considering all the sources of potential environmental impacts, as described in published LCA review and case studies of fishing fleets (Pelletier *et al.*, 2007; Parker, 2012; Vázquez-Rowe *et al.*, 2012a; Avadí and Fréon, 2013), especially those analyzing trawling fleets (Vázquez-Rowe *et al.*, 2011b; 2012b). However, it should be noted that the inclusion of certain inputs is only attributed to LCA due to the fact that DEA analysis only takes into account a selection of the most significant inputs and outputs (Vázquez-Rowe *et al.*, 2010).

The inputs that have been considered for LCA computation include a series of operational items in the vessels, such as diesel consumption, anti-fouling paints, ice consumption or vessel characteristics. Inputs such as vessel characteristics, fuel consumption or fish landings were obtained mainly from a specific register of fish at first sale available at AZTI-Tecnalia. Furthermore, a series of additional information, such as the number of nets used per vessel or the amount of refrigerant loss to the atmosphere, were retrieved through anonymous surveys carried out on Basque skippers. Background data associated with the production of fuel, nets or anti-fouling paints were taken from the ecoinvent® database (Frischknecht *et al.*, 2007). The LCA stage of the study also included the computation of the derived emissions from the different processes, such as diesel combustion or anti-fouling loss to sea (Hospido and Tyedmers, 2005). Finally, fishery-specific inventory items, such as the amount of area swept by trawlers or discards were not available for this dataset and were excluded from the assessment. Nevertheless, it is important to remark that these excluded items are currently not required items in standardized LCA impact categories (Pelletier *et al.*, 2007).

In contrast, the DEA matrix employed only included operational inputs that have proved to be either of key importance in previous environmental assessment studies or which imply an important economic expenditure. Consequently, based on a preliminary LCA assessment of the analyzed fishing fleet (Ramos *et al.*, 2011b) and other LCA trawling fleet studies, diesel production and consumption, and hull material (provision and use) were the two inputs selected while total landed catch was the output (Vázquez-Rowe *et al.*, 2010; 2011a; Ziegler *et al.*, 2011). Other operational activities, such as the use of trawl net or the emissions of refrigerants involved lower environmental burdens, except for specific impact categories (e.g. cooling agents in terms of ozone depletion). Therefore, following the three step LCA+DEA, which is explained in section 2.2, a set of commonly used impact categories in fisheries LCA were also integrated as inputs in the DEA matrix so as to account for an integrated environmental assessment of the fishing vessels.

LCA+DEA Framework

Two different methods have been developed within the LCA+DEA methodology. In the first place, the five-step method has been used mainly for eco-efficiency verification and to determine the consequences on environmental impacts of operational inefficiencies (Vázquez-Rowe *et al.*, 2010). Secondly, the three-step method seeks mainly the estimation of environmental impact efficiency, while performing a simultaneous benchmarking of a set of operational and environmental parameters (Iribarren *et al.*, 2011). To analyze the Basque trawling fleet over the selected years a modified three-step LCA+DEA methodology has been chosen (Lozano *et al.*, 2010), with the objective of estimating environmental impact efficiencies from a timeline approach (Figure 4):

LCI for each of the DMUs

The first step was to obtain a representative LCI of each selected DMU. Each DMU, as mentioned above, is a trawl vessel. For the inventory the most relevant aspects which influence the impact analysis have been taken into account, as discussed in section 2.1.

i. *Life Cycle Impact Assessment (LCIA) for each of the DMUs:* The second step consists of an environmental impact characterization based on the LCI developed in the first step. For this characterization the CML baseline 2000 method was selected as the computational framework for the LCA analysis (Guinée *et al.*, 2001).

ii. *DEA analysis from the characterization values obtained in the second step.* The final step of the three step approach consists of the DEA computation. Hence, the DEA matrix is generated by compiling a set of operational items and environmental impact categories as inputs, as well as the desired output. In this modified version of the method, and in order to capture the variations of efficiency over time, the technique called 'window analysis' was proposed (Charnes *et al.*, 1985). Window analysis assesses the performance of a particular DMU over time by

treating it as a different entity in each time period (Charnes *et al.*, 1985). Therefore, the performance of a DMU during a particular period is compared not only to the performance of other units, but also to its own performance in other periods.

When computing window analysis in DEA, it is important to note that a window length must be selected, which determines the extent of the relative comparability between DMUs (Charnes *et al.*, 1985). For instance, if a window length of 1 is assumed, this implies that the DMU efficiencies are calculated independently from a temporal perspective. In contrast, if the window length is expanded to 2 or more, efficiency calculation is based on the total entities in this period. If this second approach is extended to the complete panel dataset the reference set will refer to the entire matrix, but will not account for changes in technology, natural resources or other assumptions over time (Wu, 2005).

**Application of the Proposed Method and Results**

Step 1: Inventory Data

Inventory data for Basque trawlers were obtained for a total of 7 vessels, belonging to the ports of Pasaia (43°19′N, 1°55′ O) and Ondarroa (43°19′ N, 2°25′O). Despite the fact that data of up to 27 vessels were available in some of the specific years, only the included vessels reported data for the entire period of study. The selected period included annual data for a total of 6 years (2001-2006). The most important target species of this fleet is European hake, as can be seen in Table 1. Nevertheless, given the vessel perspective used in this study, inventory data, which are shown in Table 2, were assigned to the total catch, rather than allocating the inputs and outputs to hake. Therefore, the functional unit (FU) was set as one tonne of gutted fresh landed fish caught by bottom trawlers from 2001 to 2006 in ICES division VIIIabd.

Direct air emissions from fuel combustion were calculated based on the EMEP-Corinair Emission Inventory Handbook of 2006 (EMEP-Corinair, 2006). Cooling agent emissions were included in the inventory based on the data provided by a specialized retailer (José Manuel Juncal, Kinarca S.A., June 2010, personal communication).

Step 2: Environmental Characterization of Current DMUs

Impact category selection in the assessment was based on commonly used categories in fishery systems (Pelletier *et al.*, 2007; Vázquez-Rowe *et al.*, 2012a), from the CML Baseline 2000 method (Guinée *et al.*, 2001): Acidification Potential (AP), Eutrophication Potential (EP), Global Warming Potential (GWP) and Ozone Layer Depletion Potential (ODP). Moreover, these impact categories have been identified as having a high level of convergence with ILCD recommendations in order to compute the LCIA (ILCD, 2011). The software used
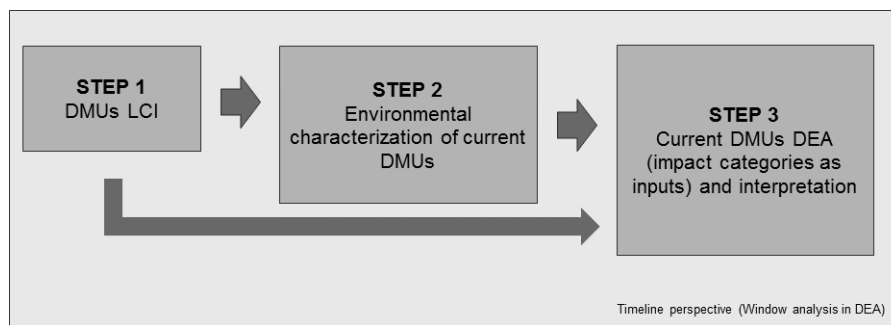
Figure 4. Three-step LCA+DEA method adapted to window analysis. NOTE: DMU= decision making unit; LCI= life cycle inventory; DEA= data envelopment analysis.

Table 1. Annual relative amount of landed individual marine species in the assessed sample (Values in % over total catch) and brief description of the assessed fleet

Fishery data						
Species	2001	2002	2003	2004	2005	2006
European hake	54.33	83.29	88.03	84.16	85.91	83.29
Other species	45.67	16.71	11.97	15.84	14.09	16.71
Total	100.00	100.00	100.00	100.00	100.00	100.00
Northern Stock trawling fleet data						
Number of vessels	52	50	47	45	40	34
Inventoried sample	7	7	7	7	7	7
% over total	13.5	14	14.9	15.6	17.5	20.6
Total gross tonnage (GT)	15,396	14,984	14,195	14,229	13,058	11,287
Average beam (m)	30.8	30.8	30.6	30.6	30.3	29.6

for the impact assessment was Simapro 7.3 (Goedkoop *et al.*, 2010). Figure 5 presents the characterization results for each of the assessed vessels on an annual basis referred to the FU for the different impact categories. The results show that in all categories there is a considerable variability in

Table 2. Brief average life cycle inventory of the selected sample (data per tonne of landed catch)

Inventory items	2001	2002	2003	2004	2005	2006
INPUTS						
			From the technosphere			
Fuel (kg)	2776	1896	1793	2625	2008	2034
Steel (kg)	45.7	16.7	12.0	15.8	14.1	16.7
Trawl net (kg)	6.6	4.4	5.1	6.0	5.2	4.6
Anti-fouling (kg)	152.1	152.1	150.0	149.2	151.0	148.3
OUTPUTS						
			To the technosphere			
Landed fish (t)	1.0	1.0	1.0	1.0	1.0	1.0
Emissions to air						
CO_2 (kg)	8801	6010	5683	8322	6365	6447
CO (kg)	20.5	14.0	13.3	19.4	14.9	15.1
NO_x (kg)	199.9	136.5	129.1	189.0	144.6	146.4
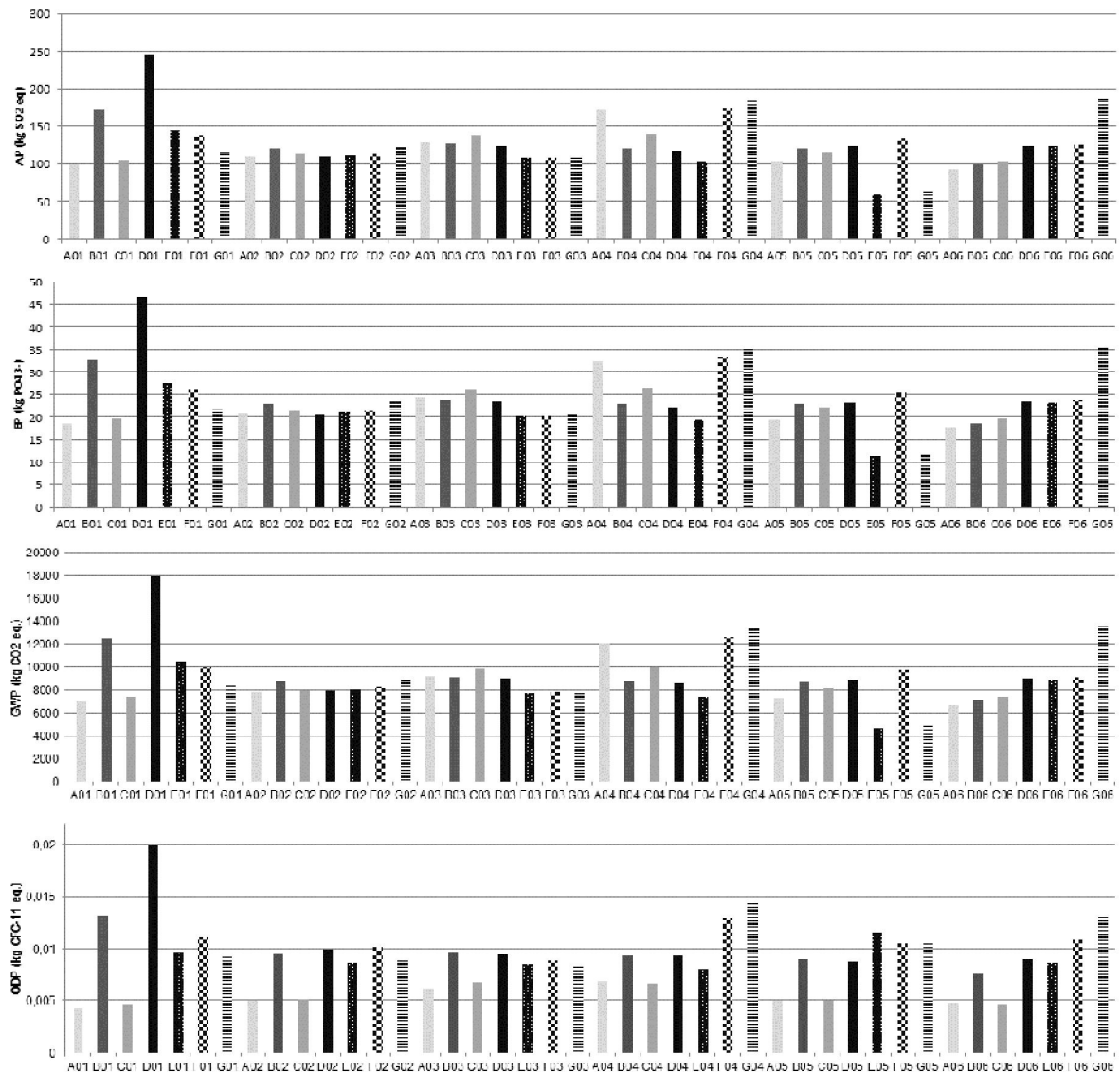
Figure 5. Current environmental characterization values per FU for individual DMUs (letters A-F represent the different vessels; the two final digits represent the year of assessment: 01= 2001; 02= 2002, etc.).

environmental impacts between the assessed vessels. For instance, in the GWP category the average impact for the entire period per FU was 9,300 kg CO_2, although the annual averages ranged from 7,150 kg CO_2 to 10,900 kg CO_2. In addition, variability between vessels within one year of operation ranged from a standard deviation of 3,700 kg CO_2 in 2001 to 640 kg CO_2 in 2002. Finally, it should be noted that the remaining impact categories showed similar trends.

Step 3: Current DMUs DEA and Result Interpretation

Once step 2 was accomplished, a DEA matrix was established based on the LCI data gathered in step 1. As mentioned above, the DEA matrix in the 3-step method jointly computes inventory inputs and outputs together with environmental input results. Consequently, the four impact categories assessed in step 2 were included as inputs in the matrix, together with the two operational inputs (diesel and hull material) and the output (landed catch), as can be seen in Figure 3. Table 3 presents the matrix referring to the first year of assessment (2001). The DEA matrices for the other years evaluated are available in Online Resource 1.

Window analysis in the slacks-based measure (SBM) framework was selected as the model to compute the matrix. More specifically, an input oriented model was selected for two main reasons. On the one hand, European hake and the other landed species constitute a limited natural resource (Vázquez-Rowe and Tyedmers, 2013). On the other hand, the existence of a rigid quota system in this fishing area for the different national fleets (Council Regulation, 2009) also involves an important constraint that makes it more feasible to target a minimization of inputs while maintaining outputs. A constant return to scale (CRS) approach was assumed for the model given the fact that the fleet operates in a competitive market (Cooper *et al.*, 2007; Lozano *et al.*, 2009). Model formulation can be consulted in Appendix A.

DEA-solver Pro was the specific software used to compute the DEA matrix (Saitech, 2012). The matrix was then assessed using two different lengths of window: 1 and 6. This choice was based on two factors. On the one hand, the vessels in the sample operate in a given area every year under a series of specific quota limitations and biological moratoria. Therefore, year after year, these vessels compete for the same natural resource, but under different environmental, social and political conditions, due to changes in fisheries management, stock abundance, etc. Consequently, a length of window of 1 in the DEA results is justified as a way of comparing the annual efficiency between vessels and their individual interannual fluctuations. This perspective is commonly referred to as a *contemporaneous* approach (Tulkens and Vanden Eeckaut, 1995). On the other hand, a window length of 6 makes it possible to compare the entire six year period under the same reference set, permitting a broader comparison throughout the entire window. This perspective was chosen to provide efficiency trends in the fishing fleet over time in order to evaluate if any underlying factor may influence the overall annual results. This approach is named *intertemporal* since it provides an assessment based on the observation of the entire study period. However, it should be noted that in the selected case study the selected period only illustrates the timeline for which data were available, while the entire lifespan of the vessels or the existence of the fishery is not accounted for; therefore, in literature it is named *local intertemporality* (Cullimane and Wang, 2006).

Average efficiency scores, based on the first approach of window analysis (length of window = 1), are shown in Table 4. As can be observed, 57.1% of DMUs were efficient ($\Phi = 1$). In fact, vessels 1 and 3 presented an efficiency of 100% for the entire period. Additionally, only 21.4% of the DMUs showed average efficiency scores below 95%. Consequently, the average efficiency scores for each individual vessel for the entire period were all above 90%, with vessel 7 showing the lowest value ($\Phi = 0.93$). Finally, on an annual basis, average efficiencies in the 2001-

Table 3. DEA matrix with individual vessel inputs and outputs for the selected trawling fleet sample for one selected year (2001)

DMU	O Catch (kg/year)	I-1 Diesel (l/year)	I-2 Hull material (kg/year)	I-3 AP (kg SO_2 eq./year)	I-4 EP (kg PO_4^{3-} eq./year)	I-5 GWP (t CO_2 eq./year)	I-6 ODP (g CFC-11 eq./year)
1	438,567	801,223	3754	43,415	8321	3426	8973
2	251,376	798,997	6810	27,659	5244	2155	5164
3	400,480	769,605	37,455	41,771	7948	3285	8211
4	159,668	724,860	6671	39,290	7454	2869	3463
5	327,119	881,456	5406	47,762	9057	3615	6800
6	284,848	724,860	6671	39,290	7454	2991	5911
7	327,119	707,861	6052	38,369	7279	2970	6742

DMU= decision making unit; O= output; I-1= input 1; I-2= input 2; I-3= input 3; I-4= input 4; I-5= input 5; I-6= input 6; AP= acidification potential; EP= eutrophication potential; GWP= global warming potential; ODP= ozone layer depletion potential.

2003 period were higher ($\Phi > 0.98$) than in the second period of assessment (<95%), in which standard deviations ranged from ±8.0 (2006) to ±11.1 (2005). Figure 6 presents a comparison between the average original DMU and the average virtual target DMU in terms of the environmental impact category values (per FU) that were included in the DEA matrix.

The alternative approach that was followed for window analysis took into account the entire panel (length of window = 6). In this case, the best performing DMUs were limited to 14.3% of the assessed sample (Table 5). In fact, only 3 vessels attained full efficiency at least in one year of assessment. Average fleet efficiencies ranged from 91.8% in 2005 to 71.6% in 2001. Concerning individual vessels, their average efficiency scores throughout the window ranged between 91.2% (vessel 1) and 70.9% (vessel 7). All vessels presented high

Table 4. Average efficiency scores (Φ_0) in percentage (%) per fishing vessel for the assessed period (length of window = 1)

Year	Vessel 1	Vessel 2	Vessel 3	Vessel 4	Vessel 5	Vessel 6	Vessel 7	Average	SD
2001	100	97.0	100	94.3	98.4	98.6	99.3	98.2	±2.0
2002	100	99.2	100	100	100	99.8	99.0	99.7	±0.4
2003	100	99.1	100	100	100	100	100	99.9	±0.3
2004	100	94.8	100	100	100	82.8	80.7	94.0	±8.6
2005	100	75.0	100	79.1	100	100	98.4	93.2	±11.1
2006	100	100	100	89.6	100	84.3	82.9	93.8	±8.0
Average	100	94.2	100	93.8	99.7	94.3	93.4		
SD	±0.0	±9.6	±0.0	±8.4	±0.6	±8.3	±9.0		

SD= standard deviation, length of window= indicates the number of temporal units that are assessed together for DEA computation.
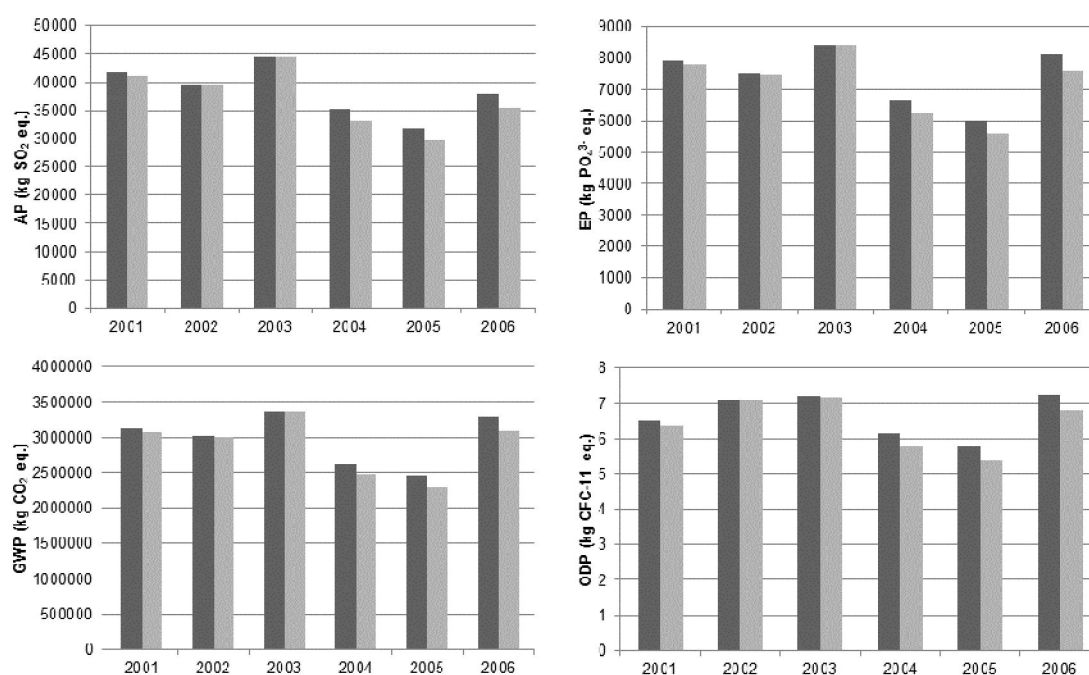
Figure 6. Environmental impact potentials for the current average vessel (dark bar) and the target average vessel (light bar).

Table 5. Average efficiency scores (Φ_0) in percentage (%) per fishing vessel for the assessed period (length of window = 6)

Year	Vessel 1	Vessel 2	Vessel 3	Vessel 4	Vessel 5	Vessel 6	Vessel 7	Average	SD
2001	100	53.5	100	40.8	67.8	63.8	75.3	71.6	±22.3
2002	91.7	72.4	93.5	75.6	82.3	73.0	73.3	80.1	±8.9
2003	77.8	70.6	73.3	75.8	78.5	86.7	80.5	77.6	±5.2
2004	84.3	73.1	73.7	100	81.7	53.1	50.3	73.7	±17.5
2005	98.2	74.0	100	77.7	97.7	100	95.0	91.8	±11.1
2006	96.4	87.1	100	77.1	80.0	64.3	51.2	79.4	±17.3
Average	91.2	71.8	90.1	74.5	81.3	73.5	70.9		
SD	±8.7	±10.7	±13.1	±19.0	±9.6	±17.2	±17.4		

SD= standard deviation, length of window= indicates the number of temporal units that are assessed together for DEA computation.

standard deviations from year to year while higher variability in standard deviation was observed on an annual basis.

Discussion

Environmental and Operational Performance of the Basque Trawling Fleet

The *contemporaneous* approach results obtained for this fleet shows low relative inefficiency levels between vessels within each time period (Table 4), suggesting similar operational patterns in all the vessels assessed. In fact, in Figure 5 it can be seen that despite substantial changes in environmental impacts between the assessed years, the potential for obtaining environmental benefits if vessels were to perform in an efficient manner is limited. For instance, the vessels assessed would have saved approximately 595 tonnes of GHG emissions in the period under analysis if they had performed in an efficient way. Nevertheless, results for years 2001-2003 showed an insignificant potential for reducing environmental impacts, while the following three years showed a higher potential for reduction.

Consequently, the results suggest that, taking into account the political and stock abundance constraints that exist in the fishery, the vessels assessed are operating at a high capacity level. Nevertheless, this conclusion should be taken with caution due to the fact that DEA only measures relative efficiencies (Charnes *et al.*, 1994). Hence, another alternative may be that vessels simply showed similar levels of inefficiency, and that due to the absence of a best performing vessel throughout the period evaluated, these inefficiencies are not visible (Vázquez-Rowe and Tyedmers, 2013).

Furthermore, the similar operational and environmental results for the different vessels suggest that the effects of the "skipper-effect", which is defined as the potential that the skill of fishermen has on the correct operation of fishing vessels, is minimal in this particular fleet. This observation is in line with previous studies that defend that the "skipper-effect" is more visible in fleets, such as purse seining, where individual strategies by skippers may have a higher influence on creating a higher yield, and therefore, minimizing environmental impacts (Gaertner *et al.*, 1999; Ruttan and Tyedmers, 2007; Vázquez-Rowe and Tyedmers, 2013). Moreover, it should be noted that the variations in efficiency between the vessels assessed may also be attributable to other factors, such as technical efficiency or data misreporting (Tingley *et al.*, 2005; Parker and Tyedmers, 2011).

From an LCA perspective, it is important to note that the environmental impact results obtained per FU for the different vessels throughout the period assessed are in accordance with impacts reported by other Spanish fishing fleets in the Northern Stock (Vázquez-Rowe *et al.*, 2011b). This finding does not

only suggest similar operational patterns for the two fleets, but also advocates an extended validity of the environmental impact trends for other similar fleets operating in the same area.

Time-dependent variations in environmental impacts identified in pelagic fisheries could also be occurring in other types of fisheries (Ramos *et al.*, 2011a). Results for the demersal trawling fishery assessed, despite showing changes on an annual basis, do not show substantial variations. Hence, provided that there are no significant changes in the way the fishery is being run, and biomass levels maintain their recovery (ICES, 2011), it is feasible to presume that environmental impacts in the fishery should not suffer abrupt changes in future years, unless specific technological, climatic or fishery management (including policy) changes occur.

Finally, an interesting future assessment would be to analyze the differences in operational efficiency at an inter-assessment level (Iribarren *et al.*, 2011), comparing the evaluated fleet with other national fishing fleets targeting demersal species in the area. This issue is of great importance since the European Union considers different quota limitations depending on the vessel flag. It would also have a relevant role when linking inter-fleet CU with the environmental profile of the vessels (Vázquez-Rowe and Tyedmers, 2013). Moreover, recent studies highlight that fisheries management can have a determining effect on changes in environmental impacts (Misund *et al.*, 2002; Driscoll and Tyedmers, 2010).

The Importance of Timeline Analysis in Environmental Impact Determination and Operational Inefficiency Mitigation

When the results obtained with a window length of the entire period –intertemporal approach– (length of window = 6) are analyzed, the average efficiencies for the average vessel varies considerably between years, suggesting that vessels have difficulties in maintaining their operational patterns, as well as the catch rates (Table 5). This inability, which can also be seen through the differing environmental impacts from year to year (Figure 5), can be due to a varied combination of factors, including stock abundance and distribution, changes in total allowable catches (TACs), meteorological conditions or even the price market (Asche and Guillen, 2012). However, it was not possible to establish any type of consistent pattern when crossing operational efficiency with a series of potential influencing factors (i.e., total biomass in the stock, total landings and TAC limitations) or environmental consequences evaluated in this research (ICES 2011). Nevertheless, expected technological improvements in this fleet, in accordance with average trends in European fleets that estimate a ~5% increase per year (Gelchu and Pauly, 2007; Villasante and Sumaila, 2010), would suggest an increase in efficiency through the 6 year

panel using the *intertemporal* approach. However, this was not the case for the analyzed sample, indicating that despite an expected technological improvement of the vessels, management and fishery-linked factors are the main underlying issues behind variability between years.

Consequently, the results illustrate the difficulty in setting a particular best-performing target for this type of production system, as developed in previous LCA+DEA analysis in other primary sector activities, such as farming (Vázquez-Rowe *et al.*, 2012b), given the high variance in input/output distribution in a timeline perspective detected in the system.

Conclusions and Perspectives

The combined LCA+DEA approach has been applied in this study in order to assess the variation of potential environmental impacts over time. As suggested in previous studies, environmental impacts in many primary sector activities, including fishing, are strongly influenced by temporal fluctuations in natural resources. In this context, this study was carried out focusing on the timeline variations in environmental impacts linked to the fishing of a demersal species, European Hake, and hence, detecting efficiency differences on vessels over the selected period.

While results certified the variable environmental impacts on an interannual basis, these fluctuations were substantially lower than those obtained for the Basque small pelagic fish fleet (Ramos *et al.*, 2011a). Additionally, the use of DEA highlighted the reduced space for input minimization under current operational patterns, given the similar performance of vessels within each year. Nevertheless, the high variability in efficiency levels when the entire period is examined underlines the existence of external factors that influence vessel performance. However, no correlations were found with any specific underlying factor that would explain this variation.

In any case, this study stresses the appropriateness of implementing a timeline perspective in the environmental assessment of fishing systems, as well as proving that LCA+DEA is an adequate method for identifying operational inefficiencies under these terms. Therefore, future development in this field may explore the specific sources that lead to operational inefficiency in fishing fleets, in order to provide specific strategies to implement the reduction of environmental impacts on a stakeholder or political level.

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