Computation of Operational and Environmental Benchmarks Within Selected Galician Fishing Fleets

Ian Vázquez-Rowe, Diego Iribarren, Almudena Hospido, Mª Teresa Moreira, and Gumersindo Feijoo

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Summary

Increasing the eco-efficiency of fishing fleets is currently a major target issue in the seafood sector. This objective has been influenced in recent years by soaring fuel prices, a fact particularly relevant to a sector whose vessels present high energy consumption rates. Efforts to minimize fuel consumption in fishing fleets result in economic benefits and also in important reductions regarding environmental impacts. In this article, we combine life cycle assessment (LCA) and data envelopment analysis (DEA) to jointly discuss the operational and environmental performances of a set of multiple, similar entities.

We applied the "five-step LCA + DEA method" to a wide range of vessels for selected Galician fisheries, including deep-sea, offshore, and coastal fleets. The environmental consequences of operational inefficiencies were quantified and target performance values benchmarked for inefficient vessels. We assessed the potential environmental performance of target vessels to verify eco-efficiency criteria (lower input consumption levels, lower environmental impacts).

Results revealed the strong dependence of environmental impacts on one major operational input: fuel consumption. The most intensive fuel-consuming fleets, such as deep sea trawling, were found to entail the diesel consumption levels nearest to the efficiency values. Despite the reduced environmental contributions linked to other operational inputs, such as hull material, antifouling paint, or nets, these may contribute to substantial economic savings when minimized. Finally, given that Galicia is a major fishing region, many of the conclusions and perspectives obtained in this study may be extrapolated to other fishing fleets at the international level.

Address correspondence to:
Ian Vázquez-Rowe
Department of Chemical Engineering, School of Engineering
University of Santiago de Compostela
Santiago de Compostela, Spain
ian.vazquez@rai.usc.es

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Introduction

The Galician Fishing Sector

Galicia (in northwest Spain) is the main fishing region in Spain, comprising 17.8% of fishing captures and 42.6% of fishing vessels (Xunta de Galicia 2009). Galician fishing activities constitute a key economic sector that provides 10% of the regional gross domestic product (GDP; Sainz et al. 2008). Two main activities can be distinguished in the Galician fishing sector: commercial fishing and fish farming (aquaculture). On the one hand, commercial fishing comprises the coastal, offshore, and deep-sea fishing of fish, bivalves, cephalopods, crustaceans, and other landings. On the other hand, aquaculture encompasses the three main aquaculture types: extensive aquaculture, marine-intensive aquaculture, and continental-intensive aquaculture.

Galician fishing fleets are not exempt from the threats that most fleets are facing in recent years concerning overexploitation and depletion of fishing grounds worldwide (SOFIA 2008). Thus, deep-sea and offshore fleets contribute to the increase in fishing stress in international fisheries, producing direct ecological impacts on targeted species (Pauly et al. 2002; Christensen et al. 2003; Myers and Worm 2003), generating excessive by-catch (Alverson et al. 1994; Glass 2000; Davies et al. 2009), disturbing and displacing benthic communities (Johnson 2002), and altering trophic dynamics (Jackson et al. 2001). Similarly, the Galician coastal fleets are also responsible for many of the impacts generated by offshore fleets; moreover, the special characteristics of the Galician *rias* (bays and inlets) make the ecosystem highly sensitive to marine toxicity or eutrophication (Rodríguez-Lado and Macías 2006).

Nevertheless, the impacts generated in fisheries are not limited to biological aspects of target stocks. Therefore, the environmental analysis of fisheries can also include the impacts related to vessel operations (Hospido and Tyedmers 2005). These operations involve the use of an energy carrier (diesel), antifouling and regular boat paint consumption, net usage and ghost fishing, as well as ice and other minor consumptions. In this respect, energy consumption by fishing vessels can be very intensive, becoming one of the major sources of environmental impact related to fish extraction (Ziegler et al. 2003; Thrane 2004; Hospido and Tyedmers 2005; Ziegler and Valentisson 2008; Schau et al. 2009; Vázquez-Rowe et al. 2010a). Furthermore, fuel consumption nowadays is the main economic cost in all major fisheries, representing as much as 45% of the total costs of an average Spanish fishing vessel (FEOPE 2009; MARM 2009). This situation is leading to financial difficulties in many fishing fleets, particularly those with energy-intensive gear types (Schau et al. 2009).

In this framework, eco-efficiency is an interesting concept for researchers to address when evaluating nonstandardized processes, such as fisheries, to follow resource use and environmental impact minimization principles. Traditionally, "eco-efficiency" refers to the delivery of competitively priced goods and services that satisfy human needs and bring quality of life while progressively reducing environmental impacts of goods and resource intensity throughout the entire life cycle to a level at least in line with the earth's estimated carrying capacity (Schmidheiny 1992). Main current indicators proposed to assess eco-efficiency are based on consumption rates of material and energy and rates of waste production and pollution dispersion.

The Galician fleet, in keeping with global trends and in an effort to remain competitive in the international market, must focus on reducing the environmental and economic costs of vessel operational activities. This policy is clearly in accordance with the traditional eco-efficiency concept. Under this perspective, the current article presents the use of a novel methodology to implement operational efficiency in the environmental assessment of fishing fleets so that eco-efficiency verification is achieved in quantitative terms. Hence, key operational items are to be benchmarked to support decision making by different stakeholders of fishery supply chains, such as skippers, managers, and policy makers, verifying quantitatively that optimized consumption levels lead to a better environmental performance. In this study, the eco-efficiency scope is therefore limited to its operational dimension and does not cover biological issues suggested in recent studies (Willison and Côtè 2009).

Life Cycle Assessment and Data Envelopment Analysis

Life cycle assessment (LCA) is an internationally standardized technique for assessing the environmental aspects and potential impacts associated with a product by compiling an inventory of relevant inputs and outputs of the product system, evaluating the potential environmental impacts associated with those inputs and outputs, and interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study (ISO 2006a, 2006b). It has proved to be a suitable environmental management tool when it comes to evaluating the environmental performance of fisheries (Ayer et al. 2007). Nevertheless, in the field of seafood, LCA should be understood as a complementary environmental assessment tool to studies on the biological effects of fishing. This is linked to the fact that fishery-specific impact categories are currently underrepresented in LCA studies (Pelletier et al. 2007).

Furthermore, fishery-related LCA shows a number of challenges regarding the lack of methodologies to assess the social and economic dimensions of product or service systems (Vázquez-Rowe et al. 2010b). Consequently, some methodology development efforts have been made in this area, including the integration of LCA with data envelopment analysis (DEA) in an attempt to link environmental and economic assessments of fisheries (Lozano et al. 2009, 2010; Vázquez-Rowe et al. 2010b).

DEA is a linear programming method to measure the efficiency of multiple similar entities (designated as decision-making units [DMUs]) when the production process involves multiple inputs and outputs (Cooper et al. 2007). A DMU is defined as the entity object of assessment that is responsible for the conversion of inputs into outputs. DEA nonparametrically estimates the relative efficiency of a number of DMUs. Therefore, DEA neither requires the user to set weights for each input and output nor demands the establishment of any functional form. Rather, DEA simply relies on the observed data for the inputs and outputs and on a minimum of basic assumptions to solve an optimization model formulated for every DMU. The result for each DMU is an efficiency score and, for those DMUs identified as inefficient, a target operating point (Lozano et al. 2009).

The use of LCA + DEA methodological approaches in fisheries entails appealing characteristics, among which the following are highlighted: (1) inclusion of an economic dimension to the assessment through the evaluation of the vessels' operational performance, which facilitates result interpretation for multiple LCAs; (2) avoidance of standard deviations when a high number of similar facilities are studied, on the basis of not average inventory data but individual data for each vessel; and (3) means for eco-efficiency verification, which quantifies the environmental consequences of operational inefficiencies (Vázquez-Rowe et al. 2010b).

Purpose of the Study

As a result of the growing demand by different social groups for environmental information regarding seafood products, environmental assessment studies are becoming increasingly important in this field (Luten et al. 2006). Although researchers usually tend to approach environmental and operational issues independently, we present an attempt to integrate both aspects here to obtain a more comprehensive view of some of the most important fishing fleets in Galicia.

To do so, we analyze, using LCA + DEA methodology, a broad number of vessels within selected Galician fishing fleets that use different types of fishing gear and work in several geographical areas. We use this approach to attain operational benchmarking and eco-efficiency verification while assessing the environmental performance of the different fishing vessels. Consumption levels of fuel as well as of other relevant operational inputs, such as hull material, nets, and antifouling paint, are benchmarked for each vessel, which links environmental improvements to optimized values.

Materials and Methods

Fishing Fleet Selection

The Galician fishing fleet as a whole is composed of more than 6,000 vessels, with a total

Table 1 Number of vessels in each Galician fishing fleet according to the fishing zone (2008)

Fishing zone	*Description*	*No. vessels*
Deep-sea fishing	Purse seiners	63
	Long liners	87
	Trawlers Mauritanian fishery	27
	Other deep-sea trawlers	46
Offshore fishing	NEAFC long liners	58
	NEAFC trawlers	66
	Other offshore trawlers	4
Coastal fishing	Trawlers	98
	Purse seiners	166
	Auxiliary vessels for aquaculture	1,181
	Other coastal fishing vessels	4,327
Total Galician fishing fleet		**6,123**

Note: NEAFC = North East Atlantic Fisheries Commission.

capture of 368,631 tons of landed fish (landing of cultured species included) in 2008. According to its current distribution (table 1), most of the fishing effort is concentrated along the Galician rias (i.e., coastal fishing), where 95% of the fleet works. This coastal fleet comprises mainly artisanal vessels and auxiliary boats for extensive aquaculture. The artisanal fishing vessels represent a traditional small-scale fishing production system, with a highly heterogeneous profile and increased gear variability (Garza-Gil and Amigo-Dobaño 2008), which makes this fleet difficult to analyze from an environmental point of view. Nevertheless, the Galician coastal fishery also has a series of commercial fleets, with a reduced number of vessels when compared to the artisanal fleet but with a much higher engine power and gross tonnage (GT). These fleets include purse seiners, which are the main source of pelagic fish landings, such as sardines and mackerels, and trawling vessels, which land mainly young hake and other demersal species (Xunta de Galicia 2009). The catch value of coastal fishing is very variable and depends on a great number of factors, which range from the time of year to the target species.

The remaining part of the fleet is composed of highly specialized commercial fishing vessels that perform their captures at offshore or deep-sea fisheries. They represent only 5% of the fishing vessels, but they account for more than 50% of the engine power and of the GT. Their target species are quite varied, depending on the gear type and the geographical zone where they fish, but always of high economic value. Most offshore fleets work in the Northern Stock fisheries (International Council for the Exploration of the Sea [ICES] Division VII), whereas deep-sea fleets mainly work in fisheries along the African coast and Newfoundland and Labrador.

In this study, we propose the application of an LCA + DEA approach for six Galician fleets that comprise the main fishing zones (coastal, offshore, and deep-sea) and gear types, to cover major fleets and fisheries of the Galician fishing sector. In particular, the assessed fleets include the following: auxiliary mussel raft vessels ($n = 12$ vessels), coastal purse seiners ($n = 15$), coastal trawlers ($n = 20$), offshore long liners ($n = 12$), deep-sea trawlers ($n = 8$), and deep-sea purse seiners ($n = 9$).

Goal and Scope

The main goal of this LCA + DEA study is to attain the operational benchmarking of individual fishing vessels within the selected fleets. Furthermore, the environmental gains linked to optimized consumption levels are quantified through the implementation of a five-step LCA + DEA methodological approach. In particular, the following objectives are pursued:

- Inclusion of an economic dimension to the environmental assessment of the Galician fishing fleets by evaluation and targeting of the operational performance of the vessels, through resource usage optimization.
- Benchmarking of the environmental and operational performance of the vessels to provide a basis for targeting effective means of reducing environmental impacts if the determined operational targets are achieved.
- Comparison of the operational and environmental performance among the selected

fleets, with the aim of finding trends in the environmental consequences of operational choices, such as fishing zone, energy intensity, and catch rates.

The functional unit (FU) considered for the LCA of all fishing fleets was 1 ton of landed fish. The reasoning behind the FU choice is linked mainly to the fact that the analysis of this study focuses on the operational and environmental performance of the different vessels, rather than a product perspective. Most of the fishing fleets in this study work in multispecies fisheries, so an FU that referred to only one specific product would prevent the assessment from obtaining a realistic perception of the vessels' performance.

All LCAs carried out in this study comprised the operational stages of fish extraction up to landing at port, which involved key operational aspects, such as the production and use of fuel, antifouling, nets, and lubricant oil. Vessel construction was also considered within the system boundaries. This approach from the fishery until landing for sale corresponds with a "cradle-to-gate" analysis (Guinée et al. 2001).

A series of processes and inputs were excluded from the system boundaries. In the first place, emissions that arose from cooling agent leakage were not included in the life cycle inventory (LCI) due to the lack of feasible data regarding Spanish fishing vessels. Nevertheless, further efforts to provide data in this field are encouraged, because recent studies suggest that their associated environmental impact may be significant in assessments of the global warming impact potential of offshore and deep-sea fishing fleets (Winther et al. 2009). Second, certain issues, mainly related to biological aspects, were left out of the system, given that they involve impact categories that are not fully developed in current LCA methodology (Pelletier et al. 2007).

Unlike LCA, DEA does not use all the items included in the life cycle of the fishing activity but considers a subset of the relevant inputs and outputs for each fleet. The inputs and outputs chosen for the DEA of each fishing fleet are detailed in table 2. A total of three inputs and one output were considered for the six fishing fleets, which are related to the vessels' main activities. Emissions to air due to diesel consumption and emissions to oceanic waters due to net loss or antifouling agents were not considered in the DEA matrix, given their direct proportion with respect to the amounts of diesel, nets, or antifouling consumed. Note that other aspects potentially related to inefficiencies, such as the age of the boat or the type of engine, are regarded indirectly in some of the considered inputs (e.g., diesel consumption). Finally, all the fishing fleets assessed met minimum sample size requirements (Boussofiane et al. 1991; Cooper et al. 2007).

Diesel consumption and steel for hull construction as inputs for each vessel in all the assessed fleets are highlighted as the major common features identified. The third input included for the different fleets was variable (antifouling paint consumption or net usage), depending on the characteristics of the fleets or data availability. Catch value was the selected output for the entire study. The rationale behind this selection is linked, in the first place, to the attempt to

Table 2 Selection of input/output items for data envelopment analysis (DEA)

Fishing fleet	*Input 1 (l/year)*	*Input 2 (kg/year)*	*Input 3 (l/year or kg/year)*	*Output (€/year)*
Auxiliary mussel raft vessels	Diesel	Hull material	Antifouling	Catch value
Coastal purse seining	Diesel	Hull material	Net	Catch value
Coastal trawling	Diesel	Hull material	Net	Catch value
Offshore long lining	Diesel	Hull material	Antifouling	Catch value
Deep-sea trawling	Diesel	Hull material	Net	Catch value
Deep-sea purse seining	Diesel	Hull material	Antifouling	Catch value

Notes: l/year = liters per year; kg/year = kilograms per year; €/year = euros per year.

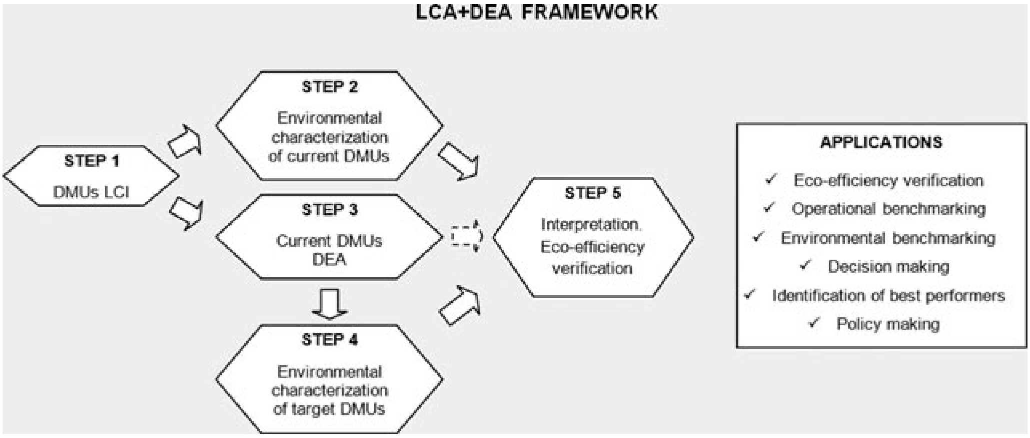

Figure 1 Schematic representation of the five-step life cycle assessment plus data envelopment analysis (LCA + DEA) method for fisheries. DMU = decision-making unit; LCI = life cycle inventory.

standardize captures due to the fact that species captured by different vessels are not uniform. Second, an inclusion of the catch rates for the different species would increase the number of outputs and, hence, the number of vessels needed for each fishing fleet, especially those with an increased number of species. Finally, the use of catch value as the output allows DEA to enhance the economic nature of this tool.

The Five-Step Life Cycle Assessment Plus Data Envelopment Analysis Method

Figure 1 presents a summary of the LCA + DEA methodology chosen for this study: the five-step LCA + DEA method (Lozano et al. 2009; Iribarren 2010; Vázquez-Rowe et al. 2010b). In brief, the five steps that one must take to follow this methodology are (1) LCI for each of the DMUs, (2) life cycle impact assessment (LCIA) for every DMU, (3) DEA with selected data from the LCIs of the first step, (4) environmental characterization of the target vessels by means of an LCIA with the new LCI data from the previous step, and (5) quantitative comparison of the potential environmental impacts for the virtual vessels versus those for the current vessels.

Step 3 computes the operational efficiency of each vessel and determines the target vessels. These targets represent virtual units that consume less input or produce more output. Hence, this stage entails the operational benchmarking of multiple vessels, whereas the fourth phase leads to the corresponding environmental benchmarking. Both benchmarking applications are highlighted as the driving force to undertake an LCA + DEA study. Nonetheless, additional applications of this methodology include, for instance, identification of best performers and environmental policy making (Iribarren et al. 2010a).

Application of the Five-Step Life Cycle Assessment Plus Data Envelopment Analysis Method

Summary of Step 1: Data Acquisition and Current Life Cycle Inventories

The six fishing fleets assessed are briefly described in table 3. Primary data were obtained through a series of questionnaires filled out by skippers from several Galician ports. Questionnaires comprised a wide range of operational aspects (annual consumption of diesel, oil and antifouling paint, days at sea, crew size, etc.) as well as aspects related to capital goods (hull material, vessel dimensions, etc.).

Target ports were selected according to the fleet census provided by the regional government

Table 3 Brief description of the samples for the selected Galician fishing fleets

	F1	F2	F3	F4	F5	F6
Sample size	12	15	20	12	8	9
Percentage over fleet	1.01	9.04	20.41	20.69	29.63	24.32
Year of inventory	2007	2008	2008	2008	2009	2000–2004
Total landings (tons)	3,703	7,500	12,093	3,416	5,000	72,000
Catch value (€/year)	22,442,732	4,912,747	17,309,604	10,534,064	13,053,600	371,320,440
Target species	Mussels	European pilchard Horse mackerel Atlantic mackerel	Blue whiting Horse mackerel Atlantic mackerel European hake	European hake Fork beard Common ling Atlantic pomfret	Varied cephalopods Varied flatfish Senegal hake	Yellowfin tuna Skipjack tuna

Note: F1 = auxiliary mussel raft vessels; F2 = coastal purse seining; F3 = coastal trawling; F4 = offshore long lining; F5 = deep-sea trawling; F6 = deep-sea purse seining; €/year = euros per year.

(Xunta de Galicia 2009). On the basis of this census, the data collection strategy focused on inventorying the highest possible number of vessels in key Galician ports, according to availability criteria. The assessed fish-farming vessels take charge of mussel rafts in the ria of Arousa, the main mussel culture zone in Galicia, with roughly 70% of the total rafts (ASESMAR 2010).

We considered background processes for LCA by using the ecoinvent database as the main source of secondary data (Frischknecht et al. 2007). When possible, we included more specific data on the Galician fishing context: (1) antifouling paint production (Hempel 2009), and (2) net production for a series of specific gear types, such as trawlers and coastal purse seiners (Costa 2009).

The emissions resulting from fuel combustion were calculated on the basis of the EMEP-Corinair emission inventory handbook of 2006 for all the selected fishing fleets (EMEP-Corinair 2006). The loss of antifouling to the marine environment was set as two-thirds of the total used (Hospido and Tyedmers 2005). For the LCIA stage, the toxicity characterization factors—related to the marine toxicity potential—applied to essential metals, such as zinc and copper, in oceanic waters was stated as zero, as suggested by Hospido and Tyedmers (2005). To maintain a uniform criterion, we followed this suggestion for all the fishing fleets, despite the fact that some of the vessels operate in highly vulnerable coastal waters: the Galician rias.

Table 4 supplies key information on data acquisition regarding each of the selected fleets. Specific data for each vessel within each fleet are shown later when we deal with DEA matrices.

Step 2: Environmental Characterization of Selected Galician Fishing Fleets

The LCIA phase was carried out according to the CML baseline 2000 method (Guinée et al. 2001). The impact categories considered were abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), and marine aquatic eco-toxicity potential (METP). Moreover, the cumulative energy demand (CED) indicator was also included, according to the method developed by VDI-Richtlinien (1997).

Table 4 Brief summary of the average inventory data for the selected fishing fleets (data per functional unit)

Inputs	*Units*	*F1*	*F2*	*F3*	*F4*	*F5*	*F6*
From the technosphere							
Materials and fuels							
Diesel	kg	28.29	158.94	524.33	1,305.48	1,725.65	419.38
Steel	kg	–	3.64	5.46	14.07	11.04	5.35
Wood	m^3	$3.37 \cdot 10^{-3}$	–	–	–	–	–
Nylon	kg	–	7.42	1.99	–	3.11	–
Lead	kg	–	1.64	0.44	–	0.69	–
Cork	g	–	0.07	0.02	–	0.03	–
Antifouling	g	336.41	371.71	639.45	1,878.36	–	190.85
Outputs							
To the technosphere							
Products							
Catch rate	t	1.00	1.00	1.00	1.00	1.00	1.00
To the environment							
Emissions to the atmosphere							
CO_2	kg	89.68	503.84	1,662.12	4,138.38	5,470.32	1,329.45
SO_2	kg	0.283	1.59	5.24	13.05	17.26	4.19
VOC	g	67.90	381.45	1,258.39	3,133.16	4,141.57	1,006.52
NO_x	kg	2.04	11.44	37.75	93.99	124.28	30.20
CO	kg	0.21	1.18	3.88	9.66	12.77	3.10
Emissions to the ocean							
Xylene	g	28.03	30.62	60.44	171.15	–	15.90
Copper oxides	g	69.72	76.15	132.53	425.66	–	39.55
Zinc oxides	g	31.53	–	–	192.50	–	17.89
Nylon	kg	–	0.91	0.25	–	0.38	–
Lead	g	–	205.43	55.13	–	86.18	–

Note: F1 = auxiliary mussel raft vessels; F2 = coastal purse seining; F3 = coastal trawling; F4 = offshore long lining; F5 = deep-sea trawling; F6 = deep-sea purse seining; kg = kilograms; m^3 = cubic meters; g = grams; t = metric tons; CO_2 = carbon dioxide; SO_2 = sulfur dioxide; VOC = volatile organic compounds; NOx = nitrogen oxides; CO = carbon monoxide.

SimaPro 7 was the software used to lead the computational implementation of the different inventories (Goedkoop et al. 2008). The results of this step are discussed in the interpretation phase (Step 5) when compared to the target environmental characterization results determined in Step 4.

Step 3: Efficiency Scores and Target Values for the Current Selected Fishing Vessels

The first task in DEA is the production of a well-defined DEA matrix from the data included in the LCI of each vessel in each fleet. The DEA matrix for each fleet is presented in table 5.

The solution of a DEA optimization model leads to an efficiency score and to the definition of operational targets for the selected inputs and output. For the DMUs, these results were calculated with the DEA-Solver Professional Release 6.0 software (Saitech 2009). A wide range of models to perform DEA are available. In this case study, an input-oriented slacks-based measure of efficiency (SBM-I) model was chosen. Further details on the formulation of this model are included in the appendix available as supporting information on the Web.

Target vessels were defined within each fleet. Target units mean vessels whose input consumption levels have been minimized (while output production is maintained) so that current vessels become efficient. Note that efficiency is reached on the basis of feasible operating points from observed data for a sample set whose individual components are assumed to be comparable.

Table 5 Input/output data envelopment analysis (DEA) matrices for the selected Galician fishing fleets

DMU	*Input 1*	*Input 2*	*Input 3*	*Output*
F1-1	3,600	816	50	2,175,221
F1-2	5,500	816	25	2,272,500
F1-3	7,000	612	50	5,090,400
F1-4	5,000	904	25	2,060,400
F1-5	10,000	1,233	100	2,424,000
F1-6	7,000	707	80	1,636,200
F1-7	3,000	816	20	969,600
F1-8	1,400	816	60	1,087,611
F1-9	5,225	816	100	1,212,000
F1-10	5,000	612	25	1,515,000
F1-11	40,000	592	70	1,454,400
F1-12	25,000	493	30	545,400
F2-1	110,000	2,467	5,000	274,505
F2-2	110,000	1,592	4,100	214,399
F2-3	120,000	2,587	5,130	368,961
F2-4	120,000	2,587	5,198	350,205
F2-5	103,700	2,477	10,838	439,576
F2-6	64,500	1,129	4,667	372,569
F2-7	120,000	2,258	3,422	380,904
F2-8	96,750	1,458	5,690	360,694
F2-9	90,000	2,516	5,058	282,878
F2-10	90,500	2,516	5,058	289,285
F2-11	32,250	649	1,580	261,438
F2-12	33,000	621	1,580	259,051
F2-13	60,000	1,871	4,214	294,364
F2-14	107,500	1,355	3,718	291,064
F2-15	86,000	1,321	3,522	472,854
F3-1	404,000	3,933	2,059	443,996
F3-2	404,000	3,074	1,416	718,655
F3-3	404,000	2,416	1,416	718,655
F3-4	440,000	4,333	1,294	917,952
F3-5	480,000	4,333	1,294	917,952
F3-6	404,000	4,840	1,416	796,224
F3-7	350,000	4,707	1,392	1,214,898
F3-8	347,000	3,330	1,392	1,214,898
F3-9	404,000	3,032	1,392	521,226
F3-10	404,000	3,712	1,392	521,226
F3-11	330,000	2,781	1,051	1,005,718
F3-12	355,000	2,390	1,051	1,005,718
F3-13	292,900	3,257	1,051	1,326,989
F3-14	305,000	1,827	1,051	1,326,989
F3-15	383,800	2,222	2,796	1,353,235
F3-16	242,400	3,234	2,024	575,377
F3-17	250,400	3,773	2,024	575,377
F3-18	303,000	3,029	1,416	660,298
F3-19	378,750	2,809	1,173	928,290
F3-20	242,400	3,029	1,568	565,931
F4-1	680,000	3,138	298	1,633,578
F4-2	654,000	3,450	290	1,583,310
F4-3	952,000	6,320	340	945,792
F4-4	349,550	4,067	250	472,936
F4-5	315,000	3,983	274	726,600
F4-6	300,000	4,240	274	691,900
F4-7	340,000	4,182	290	690,700
F4-8	325,000	2,829	221	792,410
F4-9	320,000	2,954	233	643,910
F4-10	258,400	5,000	320	771,328
F4-11	163,200	2,819	156	732,448
F4-12	353,600	5,067	325	849,152
F5-1	1,080,000	3,533	1,792	2,016,000
F5-2	920,000	5,667	2,242	1,702,400
F5-3	900,000	5,933	2,242	1,685,600
F5-4	1,155,000	7,000	2,615	1,492,400
F5-5	1,140,000	7,000	2,242	1,408,400
F5-6	930,000	5,667	2,242	1,534,400
F5-7	870,000	7,000	2,242	1,596,000
F5-8	1,050,000	9,667	2,242	1,618,400
F6-1	3,311,656	32,135	750	46,274,160
F6-2	3,387,186	25,417	750	39,535,400
F6-3	3,432,000	32,135	600	38,547,660
F6-4	3,421,379	26,616	750	56,218,620
F6-5	4,360,683	32,979	750	58,848,660
F6-6	3,164,000	32,479	960	52,625,040
F6-7	4,360,452	42,683	750	46,377,180
F6-8	3,988,933	35,550	750	32,893,680
F6-9	4,712,000	49,792	984	67,708,380

Note: F1 = auxiliary mussel raft vessels; F2 = coastal purse seining; F3 = coastal trawling; F4 = offshore long lining; F5 = deep-sea trawling; F6 = deep-sea purse seining. The number following the dash in the DMU column represents the specific vessel within the fleet. For example, F2-4 represents the fourth vessel in the coastal purse seining fleet.

Table 6 shows the percentage reductions in input consumption levels that would enable current vessels to perform their activity efficiently, as well as the efficiency score (Φ) calculated for each individual vessel. As observed, relevant improvements are possible for all the inputs included in the study, with significant differences between fleets and also between vessels belonging to the same fleet.

These results constitute the operational benchmarking of each individual vessel. Fisheries

Table 6 Input reduction (%) for the definition of the target vessels for each fleet and efficiency (Φ) of the individual vessels

DMU	*Input 1* (%)	*Input 2* (%)	*Input 3* (%)	*Efficiency* (Φ)
F1-1	16.91	67.95	57.27	52.62
F1-2	43.18	66.52	10.71	59.86
F1-3	0.00	0.00	0.00	100.00
F1-4	43.33	72.59	19.05	55.01
F1-5	66.67	76.35	76.19	26.93
F1-6	67.86	72.16	79.91	26.69
F1-7	55.56	85.71	52.38	35.45
F1-8	0.00	0.00	0.00	100.00
F1-9	68.10	82.14	88.10	20.55
F1-10	58.33	70.24	40.48	43.65
F1-11	95.00	70.44	79.59	18.32
F1-12	97.00	86.70	82.14	11.39
F2-1	69.22	72.37	66.82	30.53
F2-2	75.17	67.72	68.11	29.67
F2-3	62.07	64.58	56.53	38.94
F2-4	64.00	66.38	59.28	36.78
F2-5	47.71	55.94	75.49	40.29
F2-6	26.42	20.90	51.31	67.12
F2-7	60.84	58.11	32.73	49.44
F2-8	52.51	40.70	61.34	48.48
F2-9	61.23	72.08	66.20	33.50
F2-10	60.57	71.45	65.44	34.18
F2-11	0.00	0.00	0.00	100.00
F2-12	0.00	0.00	0.00	100.00
F2-13	39.48	60.93	57.79	47.27
F2-14	65.51	48.50	52.25	44.58
F2-15	29.96	14.19	18.12	79.24
F3-1	74.74	84.46	82.92	19.29
F3-2	59.11	67.82	59.80	37.76
F3-3	59.11	59.05	59.80	40.68
F3-4	52.05	70.84	43.82	44.43
F3-5	56.04	70.84	43.82	43.10
F3-6	54.70	77.35	55.46	37.50
F3-7	20.22	64.47	30.86	61.48
F3-8	19.53	49.78	30.86	66.61
F3-9	70.35	76.34	76.34	27.66
F3-10	70.35	80.67	70.34	26.21
F3-11	29.95	50.22	24.21	65.20
F3-12	34.89	42.07	24.21	66.28
F3-13	0.00	0.00	0.00	100.00
F3-14	0.00	0.00	0.00	100.00
F3-15	18.96	16.16	61.66	67.74
F3-16	45.44	75.51	77.48	33.86
F3-17	47.19	79.01	77.48	32.11
F3-18	49.91	69.99	63.06	39.01
F3-19	43.67	54.51	37.30	54.84
F3-20	46.34	74.28	71.41	35,99
F4-1	0.00	0.00	0.00	100.00
F4-2	0.00	10.38	0.12	96.50
F4-3	58.65	71.25	49.26	40.28
F4-4	43.68	77.66	65.49	37.72
F4-5	48.60	29.79	43.29	59.44
F4-6	48.61	37.19	46.00	56.06
F4-7	54.74	36.43	49.14	53.23
F4-8	0.00	44.48	34.18	73.78
F4-9	16.24	58.13	49.59	58.68
F4-10	33.49	40.63	48.53	59.12
F4-11	0.00	0.00	0.00	100.00
F4-12	46.49	35.50	35.50	57.93
F5-1	0.00	0.00	0.00	100.00
F5-2	0.87	47.35	32.49	73.09
F5-3	0.00	0.00	0.00	100.00
F5-4	30.78	62.64	49.27	52.44
F5-5	33.82	64.74	44.15	52.43
F5-6	11.61	52.55	39.15	65.56
F5-7	1.72	60.04	36.71	67.17
F5-8	17.43	70.66	35.82	58.70
F6-1	14.96	31.82	17.69	78.51
F6-2	28.97	26.36	29.68	71.67
F6-3	31.64	43.21	14.29	70.29
F6-4	0.00	0.00	0.00	100.00
F6-5	0.00	0.00	0.00	100.00
F6-6	0.00	0.00	0.00	100.00
F6-7	35.27	48.56	17.51	66.22
F6-8	49.81	56.19	41.49	50.83
F6-9	12.55	35.62	8.20	81.21

Continued.

Table 6 Continued

Note: F1 = auxiliary mussel raft vessels; F2 = coastal purse seining; F3 = coastal trawling; F4 = offshore long lining; F5 = deep-sea trawling; F6 = deep-sea purse seining. The number following the dash in the DMU column represents the specific vessel within the fleet. For example, F2-4 represents the fourth vessel in the coastal purse seining fleet.

managers are highly encouraged to take this information into account as a relevant support for decision making. Table 6 proves that relevant amounts of operational inputs are wastefully consumed, gathering reduction percentages as high as 97%. Individual skippers could use the computed operational benchmarks to plan corrective actions.

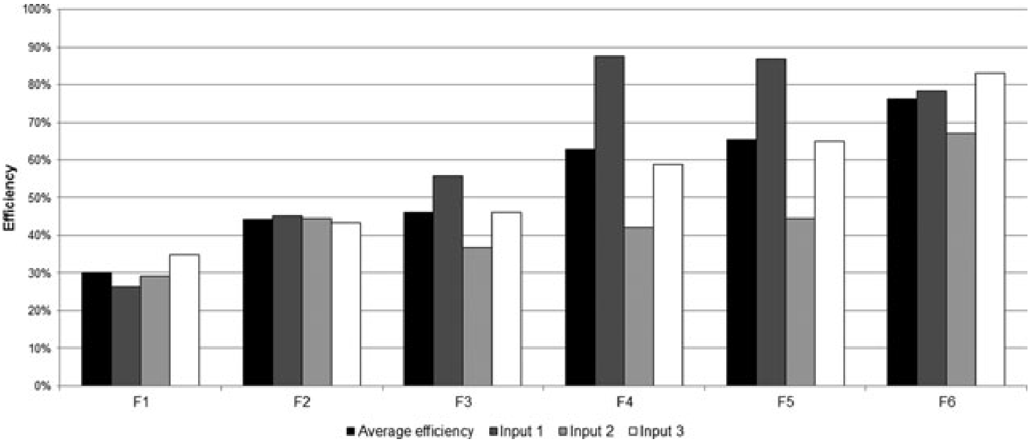

Figure 2 Efficiency score of the average vessel as compared to the individual input efficiencies of the average vessel in the selected fleets. F1 = auxiliary mussel raft vessels; F2 = coastal purse seining; F3 = coastal trawling; F4 = offshore long lining; F5 = deep-sea trawling; F6 = deep-sea purse seining.

Furthermore, we calculated the efficiency score for the average vessel of each fleet by including the average vessel for each fleet as an additional DMU over the total number of vessels considered. The rationale behind this approach is to optimize and calculate the efficiency of the average vessel, rather than to just calculate the average efficiency of the fleet. Consequently, as can be observed in figure 2, the two deep-sea fleets, purse seiners and trawlers, were highlighted as those with the most efficient average vessel, presenting an efficiency score of 76.17% and 65.45%, respectively. Offshore long liners had an average vessel efficiency of 62.79%, whereas the two coastal fleets analyzed (trawlers and purse seiners) achieved average vessel efficiencies of 46.04% and 44.26%, respectively. Finally, auxiliary vessels for mussel cultivation rafts had the lowest average vessel efficiency score (30.05%).

Taking into account that these values are the result of averaging out the individual input efficiencies for the average vessel, figure 2 depicts the differences in efficiency for the individual inputs. The diesel input efficiency of the average vessel was found to be higher than the total efficiency of the average vessel for each fleet, except for the auxiliary vessels' fleet, whose diesel efficiency was only 26.22%. The highest diesel input efficiency values corresponded to the average vessels of the offshore long lining and the deep-sea trawling fleets; these reached a diesel efficiency of 87.51% and 86.92%, respectively, which represents a 20% to 25% increase with respect to the total efficiency score of the average vessel. The coastal fleets (trawling and purse seining) presented diesel efficiency values close to the total scores obtained for the average vessels.

The efficiency of the vessel construction input of the average unit generally showed lower values when compared to the total efficiency of the average vessel, except for the coastal purse seining fleet. In this particular case, the average coastal purse seiner presented an individual input efficiency value close to the total score. The lowest vessel construction input efficiency was related to the auxiliary vessels fleet (29.23%), whereas the highest corresponded to the deep-sea purse seining fleet (67.10%). Overall, hull material was the input that presented lowest efficiency values. Finally, the individual input efficiency computed for the third input (antifouling paint or nets) generally showed values close to the total efficiency of the average vessel for each fleet.

Step 4: Environmental Characterization of Target Values

Once the target values were obtained with the DEA model for the inefficient vessels, the target vessels underwent a new LCIA. This new

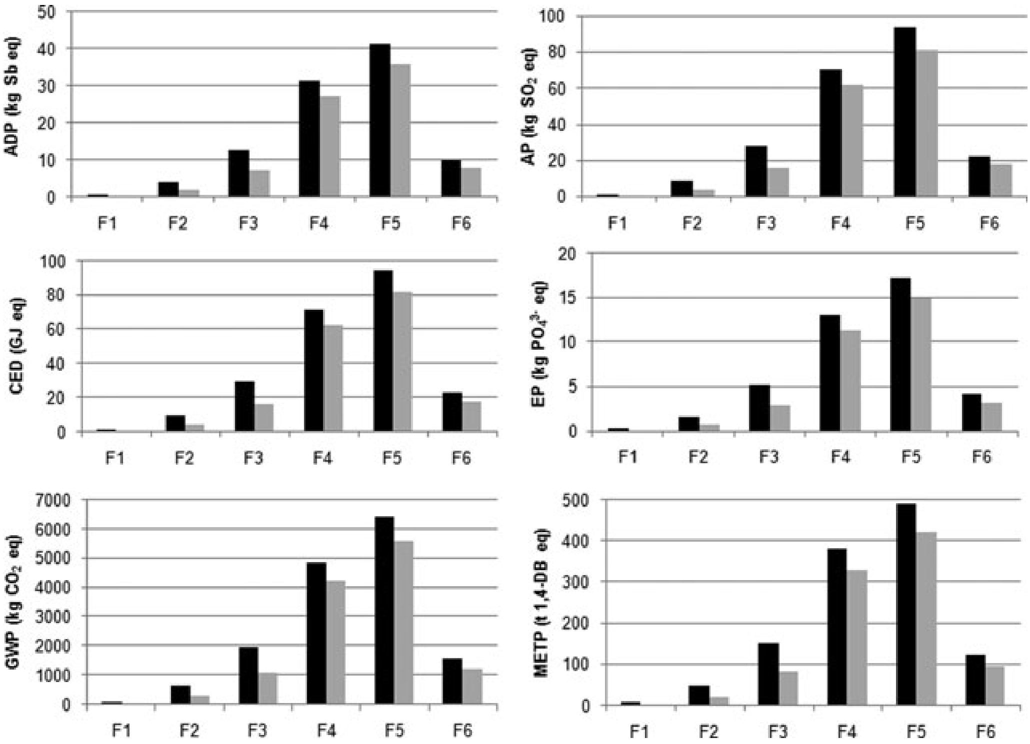

Figure 3 Average environmental impact potentials of the original vessels (black bars) and the virtual targets (gray bars) per functional unit. F1 = auxiliary mussel raft vessels; F2 = coastal purse seining; F3 = coastal trawling; F4 = offshore long lining; F5 = deep-sea trawling; F6 = deep-sea purse seining; ADP = abiotic depletion potential; AP = acidification potential; EP = eutrophication potential; GWP = global warming potential; METP = marine eco-toxicity potential; CED = cumulative energy demand; kg CO_2 eq = kilograms of carbon dioxide equivalents; GJ eq = gigajoule equivalents; kg Sb eq = kilograms of antimony equivalents; t 1,4 DB eq = metric tons of 1,4-dichlorobenzene equivalents; kg PO_4^{3-} eq = kilograms of phosphate equivalents; kg SO_2 eq = kilograms of sulfur dioxide equivalents.

assessment was made with the objective of calculating the potential environmental impacts of these vessels if they are operated in an efficient way. This procedure entails the environmental benchmarking of the sample.

Figure 3 presents the average potential environmental impacts per ton of output (i.e., per FU) of the current vessels versus those of the associated target vessels for each fleet. The average environmental impacts for the virtual DMUs were lower than the ones of the original DMUs, due to the optimization of resources, except for those vessels that were found to be efficient, for which the target vessels were the same as the current ones.

Step 5: Interpretation and Eco-efficiency Verification

The five-step LCA + DEA method allows the comparison between the potential environmental impacts of the current DMUs and those of the associated targets. Therefore, the environmental consequences of operational inefficiencies are revealed, and eco-efficiency criteria (less input, less environmental impact) can be verified.

The fleet that would benefit the most from operational optimization was the auxiliary mussel raft vessels fleet: All the impact categories assessed achieved consequential improvements around 74%. Coastal purse seiners achieved improvements of around 55% for all impact

Table 7 Total annual input reduction for the average vessel of the selected fleets and associated economic savings estimation

Input		*F1*	*F2*	*F3*	*F4*	*F5*	*F6*
I-1	Reduction (l/year)	7,239	49,212	157,307	52,150	131,500	824,408
	Savings (€/year)	3,258	22,145	70,788	23,467	59,175	370,983
I-2	Reduction (kg/year)	545	1,014	2,112	2,318	3,574	339,765
	Savings (€/year)	52	730	1,521	1,669	2,573	244,631
I-3	Reduction (l/year or kg/year)	35	2,606	798	112	782	132
	Savings (€/year)	1,555	2,085	638	5,058	626	5,935
I-1,2,3	Total savings (€/year)	4,865	24,960	72,947	30,194	62,374	621,549

Note: F1 = auxiliary mussel raft vessels; F2 = coastal purse seining; F3 = coastal trawling; F4 = offshore long lining; F5 = deep-sea trawling; F6 = deep-sea purse seining; I-1 = input 1; I-2 = input 2; I-3 = input 3; l/year = liters per year; kg/year = kilograms per year; €/year = euros per year.

categories, and for coastal trawlers the benefit was slightly above 44%. The only offshore fleet assessed was the long-lining Galician fleet in the Northern Stock fisheries (ICES Division VII). This fleet achieved environmental gains ranging from 12.5% for AP to 14.1% for METP. Finally, deep-sea fleets reached advances of around 22% and 10.5% for all impact categories for purse seiners and trawlers, respectively.

Further Outcomes and Discussion

The operational and environmental benchmarking of the assessed vessels is the main outcome from the application of the five-step LCA + DEA method. Nevertheless, further results can be derived from this analysis, such as a profitability study on the basis of the reductions computed for input consumption levels. Moreover, a discussion of the LCA + DEA results is presented in this section.

Prioritization of Operational Inputs and Profitability Study

The dominance of energy use in the potential life cycle environmental impact is clearly visible in all the assessed fleets. This statement, which is in agreement with previous LCA studies on fisheries (Edwardson 1976; Watanabe and Okubo 1989; Ziegler et al. 2003; Thrane 2004; Tyedmers 2004; Hospido and Tyedmers 2005; Schau et al. 2009; Vázquez-Rowe et al. 2010a), is stressed with operational benchmarking. Thus, the total reduction of environmental impact for the global warming impact category and the total input reduction for diesel entailed very similar results, which demonstrates the importance of fuel use in fisheries. We found similar results when we compared the input reduction for diesel with the other impact categories used in this study. Hence, activities related to fuel production, distribution, and combustion were the main sources of environmental burdens for all the assessed fleets; all the other activities analyzed had a secondary role with respect to environmental impact minimization.

From an economic perspective, however, and when we take into consideration operational benchmarking, other inputs, such as hull material (strongly related to the vessel size), antifouling, and nets, had a significant influence in terms of reducing economic costs. According to conventional prices in the Spanish market for the selected inputs (Hempel 2009; Provimar 2009; FEARMAGA 2010; MITYC 2010) and the target values benchmarked for the average vessels, table 7 gathers the corresponding economic savings. As observed, nonfuel-related inputs can be an important feature for those fleets that present lower energy intensity, such as auxiliary vessels for mussel culture and deep-sea purse seiners. In this respect, around 32% of the estimated economic savings for mussel raft auxiliary vessels would be attributable to minimization of antifouling paint use, whereas approximately 40% of the savings for deep-sea purse seiners would be related to reductions in hull material consumption.

Determining Fleet Performance Through Operational Efficiency

When the fleets are analyzed separately, there is a considerable difference in the operational efficiency of the average vessel. The results obtained in this study show a regular trend that deep-sea and offshore vessels, which are more specialized than coastal vessels, have a significantly higher operational efficiency than coastal vessels.

Deep-sea fleets—which had highest global fuel consumption and therefore spent more financial resources on fuel-related operations—not only had the highest operational efficiencies for the average vessel (76% for deep-sea purse seining and 65% for deep-sea trawling) but also had the highest percentages of vessels operating in an efficient manner. This issue is strongly related to the increase in fuel prices in the past decade, which has led these fleets to develop efficiency strategies. Some fuel reduction methods are related to a series of operational activities linked mainly to onboard decisions, such as speed, engine maintenance, or route selection (Le Floc'h et al. 2007; Parente et al. 2008). Other factors, however, relate to hull design (e.g., diminishing vessel resistance or improving the propelling system), engine improvement (FAO 1980, 1986; Valls-Vilaespasa et al. 2010), and gear design (e.g., introducing innovative trawl designs; Sterling and Eayrs 2008; Priour 2009). Additionally, the trawling fleet that extracts mainly cephalopods and hake in Mauritanian waters has developed further actions to optimize energy use by implementing a remote sensing and geographic information system (GIS) in cooperation with several Galician organizations (Torres-Palenzuela et al. 2010). It is not surprising that the specific diesel input efficiency for this fleet (F5) reached 87% (figure 2). In the same direction, the only offshore fleet analyzed (Northern Stock long liners) presented similar results to deep-sea fleets, with an operational efficiency of 63% for the average vessel (88% efficiency for diesel), which also shows the efforts in input reduction already taken by the vessels.

By contrast, the vessels belonging to fleets with a lower rate of energy consumption, mainly coastal fleets, such as auxiliary mussel raft vessels and coastal purse seiners, had very low operational efficiencies: 30% and 44%, respectively. Data from auxiliary vessels must be taken with caution due to the different characteristics of this fleet. Auxiliary vessels for mussel rafts do not compete with each other for a limited resource (wild fish), like every other fleet included in this study. Instead, these vessels transport variable amounts of farmed mussels between two fixed positions: the mussel raft served, and the port where the mussels are landed. Therefore, the efficiency of this fleet is strongly dependent on three key factors: (1) the distance covered by the vessels, (2) the number of mussel rafts assigned to each vessel, and (3) the mussel production of each raft. Thus, auxiliary vessels that cover increased distances should try to assist a higher number of rafts.

Another important issue is the lack of consistency in divisions regarding the fishing gear used in the different fleets. Coastal and deep-sea purse seiners showed lower consumption of fuel per FU than coastal and deep-sea trawlers, respectively. The efficiency score of the average coastal trawler is higher than that of coastal purse seiners, however, whereas in the deep-sea fleets assessed, the highest efficiency score was identified for the purse seining fleet with respect to the trawling fleet working in Mauritanian waters. The highest recorded average vessel efficiency for all fleets corresponded to the deep-sea purse seining fleet. This outstanding finding could be linked to the fact that deep-sea vessels are integrated into highly commercialized, competitive, and specialized fleets, whereas coastal vessels, mainly purse seiners, show intermediate operational and target market characteristics between commercial and artisanal vessels.

Fleet Trends in Input Efficiency

The individual input efficiencies computed for the average vessels showed different trends depending on the specific fishing fleet. We had previously computed diesel input efficiency values for the average vessel of each fleet, therefore including average fuel consumption rates as additional observed data. These average rates are in the range of those reported for comparable fleets worldwide (Schau et al. 2009; Ramos et al. 2010). The diesel input efficiency of the average vessel for the offshore and deep-sea fleets was significantly higher than the operational efficiency score, especially for the most fuel-intensive fleet, deep-sea trawling. In addition, the coastal trawling fleet presented higher diesel efficiency (56%) compared to the efficiency score of the average vessel (46%). It is interesting to note that this fleet had a higher energy consumption rate than deep-sea purse seining vessels, but its efficiency was considerably lower than the efficiency of the latter. This low efficiency figure for coastal trawlers is probably linked to the heterogeneous nature of this fleet, as many of the vessels were originally designed for fish extraction in the Northern Stock or other offshore fisheries; due to the heavy restructuring of these fleets in recent years (EEA 2010), they had to redeploy their target stocks.

The diesel input efficiency of the average vessel for the coastal purse seining fleet was not significantly different from the operational efficiency score of the average vessel. This low difference may be due to the nonintensive fuel consumption and semi-artisanal characteristics of the vessels. The only fleet that presented a lower diesel input efficiency when compared to the average vessel efficiency score was the auxiliary mussel raft vessels fleet, linked to the lower importance of the operation of the boat in the overall mussel culture (Iribarren et al. 2010b, 2011).

In addition, the hull material input efficiency of the average vessel was significantly lower than the operational efficiency in all the selected fishing fleets, apart from the coastal purse seining fleet. These reduced efficiency levels may be related to the increasing overcapacity of European fishing fleets in the case of commercial fishing fleets (Martínez-López et al. 2010; Villasante 2010). In fact, recent studies suggest that the harvest capacity of European fishing fleets is much too high for it to be in balance with available stocks (Villasante and Sumaila 2010). Coastal fleets showed a higher degree of inefficiency for this particular input (e.g., 37% for coastal trawlers), whereas the fishing fleet with the highest hull construction input efficiency was the deep-sea purse seining fleet (67%).

Finally, antifouling and net input efficiencies presented efficiency scores similar to that of the operational efficiency of the average vessel, regardless of the fishing fleet. The fact that two different inputs were used depending on the selected fleet hinders the comparative analysis of the individual efficiency of the third operational input among fleets.

Environmental Gains Through Operational Benchmarking

With respect to the environmental improvement linked to operational benchmarking, clear tendencies were identified in the six independent fleets assessed. Results proved, as in previous studies (Lozano et al. 2009; Vázquez-Rowe et al. 2010b), that the link between operational efficiency and environmental impacts is achieved through the optimization of resource usage, which creates a reduction in the potential environmental impacts.

Compared to other assessment alternatives, the key strength of LCA + DEA methodology lies in its quantitative nature (Iribarren 2010). The applied method not only provides a qualitative proof of the environmental benefits linked to efficient operational practices but also quantifies these environmental gains. Moreover, unlike LCA sensitivity analyses, the five-step LCA + DEA method itself provides the benchmarking of the operational and environmental targets. In other words, this method quantitatively establishes the environmental consequences of operational inefficiencies, relying not on the mere assumption of hypothetical reductions in selected parameters but on the target operational values defined from observed data through DEA.

Coastal fisheries showed a higher relative potential reduction of their environmental burdens, due to the increased inefficiency of their vessels. Nonetheless, the environmental burdens of coastal fleets, mainly when they were not fuel intensive, were extremely low compared to those of more fuel-intensive fleets, such as trawlers and offshore and deep-sea fleets in general. Another important characteristic of fleets with nonintensive fuel-consuming vessels is that the minimization of other inputs besides fuel consumption, such as antifouling or net consumption, not only had an important influence on economic costs but also showed more significant environmental impact reductions.

Environmental target values obtained after operational benchmarking can provide a reference for policy making in the fishing sector (Iribarren et al. 2010a). In this way, LCA + DEA methodology can guide correcting measures on the basis of environmental impact efficiency and economic sustainability in fisheries.

Finally, in addition to interfleet observations, the usefulness of the LCA + DEA outcomes highly relies on the results obtained for the individual vessels regarding operational benchmarking and environmental assessment. In this respect, LCA + DEA methodology leads not only to an interfleet analysis but also to intrafleet assessments. In fact, this methodology usually focuses on the evaluation of a single set of DMUs (in this case, a single fishing fleet), which permits a thorough, individualized assessment of each vessel. This way, skippers have a valuable supporting tool for decision making that can help identify the main environmental burdens related to their vessels while assessing their operational performance for the purpose of optimization. Thus, LCA + DEA approaches guide skippers and fisheries managers toward environmental and economic gains that arise from the minimization of operational consumption levels to an extent deemed currently feasible. This integration of operational, economic, and environmental concepts in quantitative terms into only one methodology makes LCA + DEA a promising novel management tool for fisheries, among other potential application fields (Iribarren et al. 2010a).

Conclusions and Perspectives

The appropriateness of the use of LCA + DEA methodology for studies on the operational and environmental performance of fisheries is shown by the robustness of the obtained results. In fact, LCA + DEA methodology is of use for any case study in which multiple input and output data are available for multiple similar units of assessment (i.e., multiple DMUs).

Operational and environmental benchmarks regarding key consumption inputs and impact categories were computed by means of the five-step LCA + DEA method for a broad number of vessels belonging to six different Galician fishing fleets. We expect skippers, fisheries managers, and policy makers to use this set of results as a valuable support for decision making.

Results demonstrate the strong dependence of environmental impacts on one major operational input: fuel consumption. The potential for minimization of energy resources was greater for the less intensive fuel-consuming fleets, such as coastal purse seining and auxiliary mussel rafts vessels. Vessels belonging to fuel-intensive fleets generally showed an increased efficiency of the fuel-related inputs with respect to other operational inputs.

The operational efficiency of the average vessel for the deep-sea and offshore fleets analyzed was significantly higher than that for the coastal fleets. The percentage of vessels that were deemed efficient was also reduced for coastal fleets. Future research dealing with the joint assessment of fleets could focus on determining relations between the degree of exploitation of the different fisheries and the efficiency shown by the fleets working in them, to assess whether low efficiencies can also be linked to overexploitation. Additionally, it is important to highlight that current eco-efficiency indicators disregard relevant biodiversity parameters, so future efforts are needed to include biological aspects in fishery related eco-efficiency studies.

Other secondary issues besides fuel activities, such as vessel construction or net consumption, have slight impacts on the total environmental burdens of the vessels of the different fleets. The reduction of these inputs through operational benchmarking may offer the skippers substantial decrease in operational costs, however.

The five-step LCA + DEA method proved to be a suitable tool to quantify operational and environmental targets. The use of this method is recommended to enrich the results provided by the mere use of LCA or DEA as single tools in assessment of multiple similar entities. Finally, given that Galicia is one of the major fishing regions in the European Union, many of the conclusions and perspectives obtained in this study may be extrapolated to other fishing fleets at a European or international level.

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About the Authors

Ian Vázquez-Rowe is a researcher in the Department of Chemical Engineering at the

University of Santiago de Compostela, in Santiago de Compostela, Galicia, Spain. **Diego Iribarren** is a postdoctoral researcher at the Madrid Institute for Advanced Studies in Energy (Instituto IMDEA Energia) in Móstoles, Spain. **Almudena Hospido** is a postdoctoral researcher and **María Teresa Moreira** and **Gumersindo Feijoo** are professors in the Department of Chemical Engineering, also at the University of Santiago de Compostela.

Supporting Information

Additional supporting information may be found in the online version of this article:

Supporting Information S1: This supporting information contains details on the formulation of the input-oriented slacks-based measure of efficiency (SBM-I) model that was used for this case study.