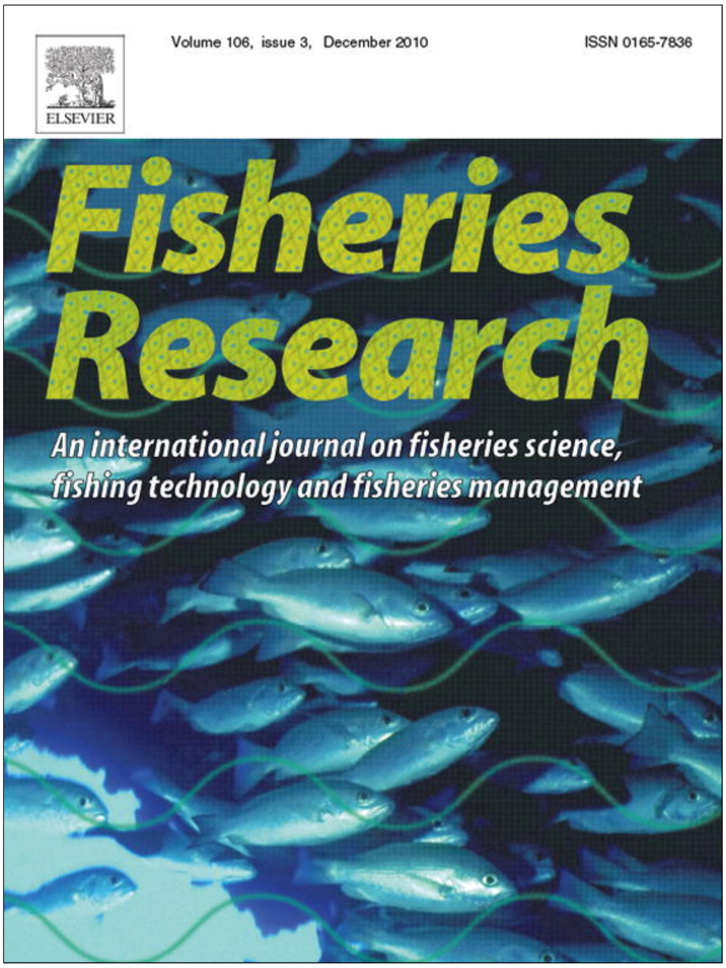
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Life cycle assessment of horse mackerel fisheries in Galicia (NW Spain): Comparative analysis of two major fishing methods

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ABSTRACT

Atlantic horse mackerel (*Trachurus trachurus*) is one of the main target pelagic species of the coastal purse seining and bottom trawling Galician fleets. The goal of this LCA study was to assess and compare the environmental impacts associated with the fishing operations related to Atlantic horse mackerel extraction in these two Galician coastal fisheries. This analysis included the operation of the vessels, together with major inputs related to the production of diesel, fishing nets or anti-fouling paints. Data regarding vessel operation was obtained from the questionnaires filled out by a total of 54 skippers. Results showed that environmental burdens regarding horse mackerel landing are associated mainly with activities related to diesel production, transport and consumption of the fishing vessels. Furthermore, cooling agent leakage from the cooling chambers was identified as a major impact regarding ozone layer depletion and global warming potentials. Horse mackerel captured by purse seiners presented reduced environmental burdens for all impact categories respect to horse mackerel landings by bottom trawlers. The environmental reduction ranged from 49 to 89%, depending on the impact category analyzed. Discard rates for coastal trawlers were also identified as a major environmental impact in this fishery. Revision of fishing quotas and fishing strategies for the horse mackerel fishery and reduction of energy consumption, through the introduction of new alternative fuels or technological actions, are necessary in order to reduce the environmental impacts of a highly fuel-dependent activity.

1. Introduction

1.1. The Galician continental shelf horse mackerel fishery

Atlantic horse mackerel *Trachurus trachurus* (Linnaeus, 1758) is a pelagic species of mackerel belonging to the Carangidae family. It is abundant in Northeastern Atlantic fisheries from Iceland to Senegal, including also the Mediterranean and Black Sea (Whitehead et al., 1986), congregating in large shoals in rocky coastal waters, feeding of smaller fish, crustaceans and squid. It is fished all year round, but the best quality individuals that are sold fresh and whole in markets are captured during the late spring and summer periods. Not surprisingly, two thirds of the horse mackerel landings in Galicia take place in that period, while lowest landings are identified during the winter months, when part of the landings are used for fishmeal production or for canning (Xunta de Galicia, 2010). The importance of this species at a national level is certified by a recent study carried out by the Spanish Ministry of Health, in which 42% of Spanish households declared buying horse mackerel on a regular basis (FROM, 2005).

The Galician stock for horse mackerel (ICES Divisions VIIIc and IXa) is characterized by a relative stability in catches and age composition throughout the year (Abaunza et al., 2003; Villamor et al., 1997), due mainly to the coincident location of the feeding and spawning grounds (Abaunza et al., 1995; HOMSIR, 2003). Identified patterns in this stock show that this area is not made up by a closed population, but receives an important input of fish from other areas (Murta et al., 2008), which may justify the good health of the Galician horse mackerel stock. The landings of this species in the year 2007 in Galician ports summed up to a total of 22,027 tons (Fig. 1), representing 49.9% of the total horse mackerel quota allowed for Spain in that year by the European Commission, 12.8% of the total landings in this region's ports and 10.8% of worldwide horse mackerel landings (FAO, 2008; Xunta de Galicia, 2010). The coastal purse seining and trawling fleets account for over 95% of the horse mackerel captures in Galicia.

1.2. The purse seining and trawling fleets in the Galician continental shelf

Coastal bottom trawlers in Galicia account for a total of 101 vessels distributed in 11 ports, with an average beam length of 28 m (Xunta de Galicia, 2010). They operate in areas close to the landing port, performing one or two landings per day. Most of the fleet is

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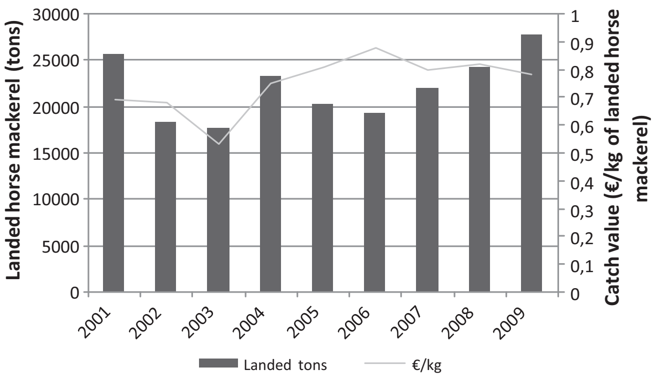

Fig. 1. History of annual Galician Atlantic horse mackerel, 2001–2009. Average yearly prize.
Source: Xunta de Galicia (2010).

constituted by pair trawlers that usually operate at ranges between 1.5 and 2.1 knots/h. On an average day they operate from 9 to 13 h, performing 1 or 2 throws. Single trawlers present slightly different operation patterns, trawling at a speed that ranges from 3.2 to 4.5 knots/h and performing 3 or 4 throws per day for around 12 h.

The main species captured by coastal bottom trawlers along the Galician continental shelf are European hake (*Merluccius merluccius*) and blue whiting (*Micromesistius potassou*), two demersal species, and Atlantic mackerel (*Scomber scombrus*) and Atlantic horse mackerel, both semi-pelagic. Other species that might be caught incidentally, but are also commercialised are megrim, black bellied angler, Norway lobster and pouting. Spanish marine laws, however, do not allow landings of sardine (*Sardina pilchardus*), tuna species (mainly *Thunnus alalunga*) or anchovy (*Engraulis encrasicholus*) by bottom trawlers. Furthermore, bottom trawling was limited to depths above 100 m in 1999. In this year, pelagic trawling in ICES Divisions VIIIc and IXa was also banned (MARM, 2010).

Purse seiners developed as artisan vessels in Galicia for centuries, mainly to catch sardines and other pelagic species, but thanks to technological improvements regarding shoal detection, these vessels have turned into an important fleet within Galician fishing activities. In 2008, Galicia had a fleet of 165 coastal purse seiners, distributed in 29 different harbors. The average beam of this fleet is 17 m, ranging from 7 to 27 m (Xunta de Galicia, 2010). Most purse seiners in Galicia set to sail before nightfall, since target pelagic species are easier to capture after sunset and at dawn. Captured fish are stored in wet-fresh conditions until they are landed for auction sale. Most vessels perform one or two landings per day, depending on fish availability and sale price among other factors.

The pelagic target species captured by the vessels are sardine, Atlantic mackerel, Atlantic horse mackerel and anchovy. However, anchovy landings have been banned by the European Commission in this area throughout most of the past decade, due to the increased overexploitation of the fishery. Other by-catch species include bogue, white sea bream and common sole.

1.3. The environmental impacts of fishing

Seafood is one of the major sources of proteins for the world's population. The fact that fishing is still the only food producing activity that relies mainly on the extraction of organisms from wild ecosystems (Christensen et al., 2003), creates numerous problems in these ecosystems, regarding the stability of the stocks of targeted species, the effect of discards on the marine environment or the damage of the seabed due to trawling (Hall-Spencer et al., 2002; Guyonnet et al., 2008). Linked to these problems, fishery data suggests a steady decrease in landings due mainly to the overexploitation of the world's major stocks (FAO, 2008). According to a recent report published by FAO, in 2007, 52% of world fisheries are fully exploited, whereas only 20% of them are under-exploited or moderately exploited. The remaining 28% represents overexploited (19%), depleted (8%) and recovering from depletion (1%) fisheries (SOFIA, 2008). Finally, the increasing consequences of climate change are also changing the physical properties of world oceans, leading to additional pressure on fish stocks (Badjeck et al., 2010). Therefore, the improvement of fishery management not only must be linked to efforts to reduce by-catch and discards, the disturbance created in benthic communities due to the use of trawlers and other types of gear, or the alteration of trophic dynamics (Fonseca et al., 2005), but also to analysing and mitigating the effects that global warming may produce over world fisheries.

However, environmental analysis of fisheries usually focuses on these biological concerns and underestimates other impacts caused by fishing activities. For instance, the energy and material use in fishing vessels can create important environmental impacts, related mainly to fuel consumption, gear usage and loss at sea, anti-fouling agents and paint or ice consumption (Hospido and Tyedmers, 2005).

In this context, life cycle assessment (LCA) has proved to be an important methodology when it comes to evaluating the environmental performance of seafood (Pelletier et al., 2007), as a result of increasing demand for environmental information regarding seafood products by different stakeholders of seafood supply chains, such as authorities, consumers, companies related to the fishing sector and skippers (Luten et al., 2006). Nevertheless, further efforts are required to improve seafood supply transparency and accountability (Iles, 2007; Ayer et al., 2009).

In this study, Atlantic horse mackerel captured by two different types of fishing vessels (bottom trawlers and purse seiners) was analyzed from an environmental perspective. The horse mackerel landed by purse seiners was compared to that landed by coastal bottom trawlers in order to describe major differences between the fleets and to identify the main hot spots.

2. Materials and methods

2.1. Goal and scope definition

The goal of this LCA study is to assess and compare the environmental burdens associated with the fishing operations related to Atlantic horse mackerel extraction in two Galician coastal fisheries: purse seining fleet and bottom trawling fleet.

The functional unit (FU) is a measure of the function of the studied system and it provides a reference to which the inputs and outputs can be related (ISO 14040, 2006). The FU considered in this study was 1 ton of landed round Atlantic horse mackerel in a Galician port in the year 2008. This FU is based on the assumption that the main objective of the study is to compare the environmental profile of one same product (horse mackerel) fished with two different techniques (trawling and purse seining).

The system under study comprised the different stages considered for fish extraction performed by the different vessels in the fishery (Fig. 3), including diesel consumption, anti-fouling, oil and trawl net use, ice consumption and cooling agent usage and leakage. The construction and maintenance of the vessels was also included. The product was followed starting from the production of supply materials, such as fuel, nets or ice, until landing for sale, constituting a "cradle to gate" analysis (Guinée et al., 2001). On land landing operations at port have been excluded from the system boundaries, as can be observed in Fig. 2, as well as a series of biological issues, such as seafloor use, given that their consideration involves impact categories that are not fully developed in current LCA methodology. Nevertheless, a brief discussion on the discard rates of the two

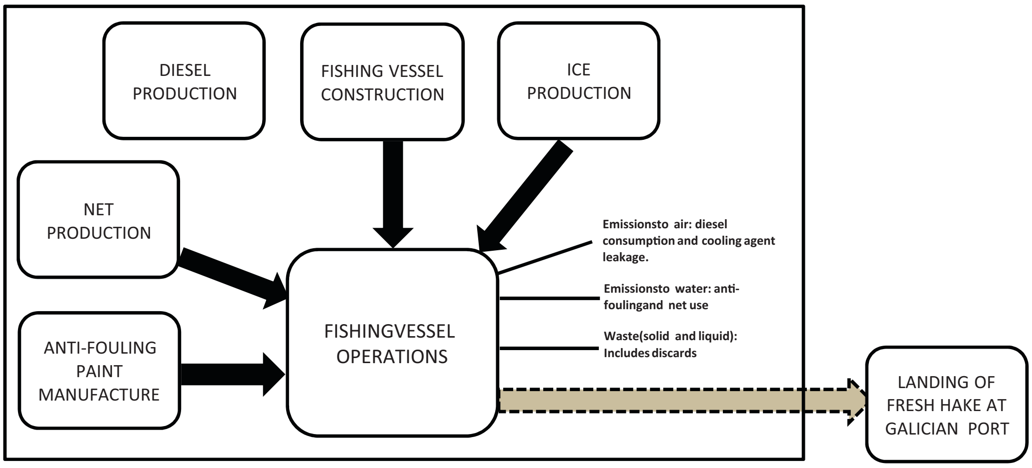

Fig. 2. Block diagram of the studied system. Dotted line represents system boundaries.

fleets is included in the study. Finally, emissions linked to cooling agent leakage were included in the system, since recent studies suggest that their associated environmental impact may be significant when assessing global warming and ozone layer depletion potentials in fishing fleets (Klingenberg, 2005; SenterNovem, 2002; Winther et al., 2009). Therefore, a brief discussion on cooling agent leakage in the horse mackerel fishery is also included in Section 4.3.

2.2. *Data acquisition*

2.2.1. *Primary activity data*

Previous LCA and other environmental performance system studies have shown a clear dominance of vessel operations when it comes to impact assessment, especially those linked to fuel consumption (Hospido and Tyedmers, 2005; Thrane, 2004; Ziegler et al., 2003; Ziegler and Valentisson, 2008). The sample used for this study is a group of 24 trawling vessels and 30 purse seining vessels belonging to the Galician fishing fleet. These vessels represent 24% and 18% of the Galician continental shelf trawling and purse seining fleet, respectively (Xunta de Galicia, 2010).

Primary data was obtained through a series of questionnaires filled out by skippers from three of the main coastal trawling ports in Galicia (Celeiro, Muros and Ribeira) and from seven of the most important purse seining ports (Sada, Camariñas, Portosín, Ribeira, Cambados, Portonovo and Vigo). Questionnaires comprised a wide range of operational aspects (annual consumption of diesel, discard rate, net consumption and dimensions, days at sea, crew size, etc.) as well as aspects related to capital goods (hull material, vessel dimensions, life span, etc.).

Anti-fouling and paint production were also taken into account in this study. Skippers reported sending their vessels to the docks for maintenance once a year, so these products were considered important inputs in the vessel operation activities of the Galician coastal fleets. Data regarding the composition of the main paints and anti-fouling agents, as well as the emissions related to their production were included in the inventory. This data was obtained from a leading world producer.

Despite fishing gear provision being excluded from prior LCA analyses (Hospido and Tyedmers, 2005; Tyedmers, 2000; Ziegler et al., 2003), in this particular study net production, transport and consumption was included for two main reasons. In the first place, seine and trawl nets represent an important percentage in the total weight of the vessels for these particular fleets. Secondly, questionnaires were sent to the main net sowing associations in Galician harbors, providing us with data on material content and gear lifespan. They reported that in recent years the production of nylon nets has shifted from local enterprises to South-East Asia (Philippines, Thailand, etc.). Therefore, there has been an increase in transport related environmental impacts that will be assessed in this study. The average life span of trawl nets was 4 years. For seine nets, the average life span was slightly above 5 years, although the nets are usually renewed by at least 25% each year due to net losses at sea.

Despite the fact that vessel construction has been found to have a small contribution to the environmental impacts of different seafood products (Hayman et al., 2000; Hospido and Tyedmers, 2005), data availability lead to the inclusion of some construction inputs, such as steel and wood used for the hull and the steel used for the engines. A Galician shipyard, specialized in the construction of coastal seiners and trawlers was contacted (Abeijón Hermanos SL Shipyard, April 2009, pers. commun.) and data was also provided by two large engine manufacturers. In order to account for vessel repairs and maintenance, the amount of steel or wood required for building was increased by 25% (Tyedmers, 2000). The total amount of construction material was then divided by the lifespan of each vessel (the mean for inventoried vessels was 31, ranging from 30 to 40 years lifespan), in order to calculate annual consumption.

None of the 54 skippers interviewed reported having an ice-making machine on board. Instead, the analyzed fleets buy the ice off the port authority, like the great majority of the Galician coastal fleet. Ice production data was obtained from two different port ice-making factories (Sales Department in the ports of Sada and Malpica, May 2009, pers. commun.).

Finally, cooling agent data were obtained from two specialized Galician companies. The consulted technicians agreed that the great majority of fishing vessels based in Galician ports use R22, an HCFC with a high ozone depletion and global warming potential. Despite this situation, they also pointed out that the industry is slowly shifting to other types of refrigerants, such as R507, R404A and, in very specific cases, NH_3, due to new policy rules that promote the use of agents that are less harming to the ozone layer. Both companies reported an average annual leakage of 150 kg per vessel for R22 in coastal trawlers, while the leakage for purse seiners was approximately 10 kg per vessel (José Manuel Juncal, Frimarte; Kinarca, S.A., June 2010, pers. commun.).

2.2.2. *Secondary data*

Background data regarding the production of diesel fuel was obtained from the ecoinvent database. The process data for diesel production includes oil field exploration, crude oil production, long distance, transportation, oil refining, regional distribution, etc. (Frischknecht et al., 2007). Additional situations where no direct data were available are linked to the production of supply materi-

Table 1
Mass and economic allocation factors for horse mackerel fishing fleets.

Species	Landings (t)	Mass allocation	Value (€/kg)	Economic allocation
Purse seining coastal fleet				
Atlantic horse mackerel	101	23.9%	0.82	47.4%
Atlantic mackerel	116	27.7%	0.51	18.4%
Sardine	203	48.4%	0.65	34.2%
Bottom trawling coastal fleet				
Atlantic horse mackerel	119	17.7%	0.82	11.3%
Hake	118	17.7%	3.72	50.7%
Atlantic mackerel	142	21.2%	0.51	8.3%
Blue whiting	290	43.4%	0.89	29.7%

als, such as materials for vessel and gear, anti-fouling agents and electricity. Background data from the ecoinvent database (version 2.0) were also used for these cases, since the data are representative for European conditions.

2.2.3. Un-monitored emissions

The emissions resulting from fuel combustion were calculated on the base of the EMEP-Corinair Emission Inventory Handbook of 2006 (EMEP-Corinair, 2006). The loss of paint and anti-fouling to the marine environment was set as two thirds of the total employed (Hospido and Tyedmers, 2005). It is important to point out that in this study the LCA recommendation to set the toxicity characterization factors applied to essential metals, such as zinc and copper, in oceanic waters to be set as zero was not followed (Aboussouan et al., 2004). Instead, copper and zinc ions were included as inventory data. The rationale behind this decision is related to the fact that the studied vessels operate in highly fragile and in some cases polluted, coastal waters (the Galician *rias*) with high marine traffic (Alzieu, 1998; Hospido and Tyedmers, 2005; Matthiessen and Law, 2002).

Solid waste and wastewater related to daily life on board were not taken into account in this study, due to the insignificant importance shown in other studies (Hospido and Tyedmers, 2005) and to the fact that they are not directly connected to the production activity (Ziegler et al., 2003). Finally, bilge waters were also assessed and included in the inventory.

2.3. Co-product allocation strategies

In both fleets more than one species is captured simultaneously during fishing operations. Allocation in past studies has been important in most mixed fisheries (Ayer et al., 2009). For this particular study, mass allocation was considered the most appropriate approach. This selection was based, in the first place, on the fact that three or four species are obtained from the same process, so inputs and outputs from the inventory data affect all species in identical manner. Secondly, species targeted by purse seiners all have a similar economic value (Table 1). In the case of the bottom trawling fleet, one of the species (hake), reported approximately 50% of the economic turnover in 2008, but vessels are not allowed to land more than 20% of the total catch. The other three target species also had a similar economic value in that year. However, the increased volatility of fish prices (especially for hake and sardine in the past few years) makes economic allocation difficult to interpret. Nevertheless, economic allocation is also included and discussed in Section 4.2.

2.4. Life cycle inventory

Life cycle inventory (LCI) involves the collection and computation of data to quantify relevant inputs and outputs of a product system, including the use of resources and emissions to air, water and soil associated to the system (ISO 14040, 2006).

2.4.1. Coastal bottom trawlers

According to the questionnaires obtained for the trawling fleet, the 24 vessels landed a total of 16,056 tons of fresh fish. Blue whiting was the most captured species, followed by Atlantic mackerel and horse mackerel (Table 1). Hake, the species with highest economic value, only represented 17.7% of the landings.

The average allocated inventory data per FU can be seen in Table 2. As observed, vessel operations created an annual aver-

Table 2
Inventory for horse mackerel landed in Galician ports by coastal bottom trawlers (data per FU: 1 ton of landed round horse mackerel).

Inputs

From the technosphere				From the technosphere			
Materials and fuels	Units	Value	SD	Materials and fuels	Units	Value	SD
Diesel	kg	496	±97	Boat paint	g	223	±45
Steel	kg	5.1	±1.2	Marine lubricant oil	kg	2.2	±0.9
Seine net (nylon + lead + cork)	kg	2.4	±0.7	Ice	kg	323	±77
Anti-fouling	g	639	±86				

Outputs

To the technosphere			To the environment					
Products	Units	Value	Emissions to the ocean	Units	Value	Emissions to the atmosphere	Units	Value
Horse mackerel	t	1	1. Xylene	g	58.5	1. CO_2	kg	1571
			2. Dicopper oxides	g	133	2. SO_2	kg	5.0
			3. Zinc oxides	g	60.0	3. VOC	kg	1.2
			4. Nylon	kg	189	4. NO_x	kg	35.7
			5. Lead	g	100	5. CO	kg	3.7
						6. R22	g	223

SD: standard deviation.

Table 3
Inventory for horse mackerel landed in Galician ports by coastal purse seiners (data per FU: 1 ton of landed horse mackerel).

Inputs

From the technosphere				From the technosphere			
Materials and fuels	Units	Value	SD	Materials and fuels	Units	Value	SD
Diesel	kg	176	±69	Boat paint	g	113	±31
Steel	kg	2.7	±0.6	Marine lubricant oil	g	447	±147
Wood	g	2.3	±0.4	Ice	kg	321	±117
Anti-fouling	g	365	±61	Seine net (nylon + lead + cork)	kg	10.2	±4.2

Outputs

To the technosphere			To the environment					
Products	Units	Value	Emissions to the ocean	Units	Value	Emissions to the atmosphere	Units	Value
Horse mackerel	t	1	1. Xylene	g	33.1		t	2.0
			2. Dicopper oxides	g	75.7	1. CO_2	kg	558
			3. Zinc oxides	g	34.3	2. SO_2	kg	1.8
			4. Nylon	kg	1.03	3. VOC	g	422
			5. Lead	g	229	4. NO_x	kg	13
						5. CO	kg	1.3
						6. R22	g	23.3

SD: standard deviation.

age fuel consumption of 496 kg per ton of landed round horse mackerel. Ice consumption translated in an average of 323 kg per ton, whereas specialized companies reported an average annual leakage of 0.23 kg per ton for R22 in cooling chambers of coastal bottom trawlers. Another important operation, trawl net consumption involved that each vessel consumed 2.4 kg per ton of horse mackerel.

Discard data from the trawlers were provided by the skippers of each vessel. The discards comprised a wide range of undersized and non-marketable species. The main undersized species reported by the skippers were hake juveniles (*carioca*). Individual vessels' discard data can be observed in Table A.1 in Appendix A.

2.4.2. Coastal purse seiners

Inventory data for Atlantic horse mackerel landed by coastal trawlers was obtained from the average data provided by the 30 purse seiners. The mean inventory data allocated per FU has been included in Table 3. According to these questionnaires, the 30 purse seiners landed a total of 12,597 tons of fresh fish in the year 2008. Sardine was the most captured species (48.4%), followed by Atlantic mackerel and horse mackerel (Table 1).

The purse seiner's vessel operations created an annual average fuel consumption of 176 kg per ton of landed round horse mackerel and 320.6 kg per ton of ice consumption, being the two main inputs used in the fishery. Seine net consumption involved that each vessel consumed 10.1 kg per ton of horse mackerel.

Discard data for purse seiners was reported as being close to zero by the interviewed skippers. This situation is confirmed by Kelleher (2008), stating that discard rates in pelagic purse seining fisheries are very low. Therefore, the discards generated by this fleet were disregarded.

A final observation of the inventory data in Tables 2 and 3, is that the standard deviation for the purse seining vessels is slightly higher than the deviation within the trawling fleet. This circumstance is related to two main factors: (i) the semi-artisanal characteristics of the purse seining fleet, and (ii) the low non-intensive fuel characteristics of this fleet. More analysis on this specific issue can be found in Vázquez-Rowe et al. (submitted for publication).

2.5. Selection of impact categories

The life cycle impact assessment phase was carried out using the CML baseline 2000 method (Guinée et al., 2001). Impact categories considered in the study were: abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone layer depletion potential (ODP), human toxicity potential (HTP), freshwater aquatic eco-toxicity potential (FETP), marine aquatic eco-toxicity potential (METP), terrestrial eco-toxicity potential (TETP) and photochemical oxidant formation potential (POFP). SimaPro 7 was the software used to lead the computational implementation of the inventories (Goedkoop et al., 2008).

3. Results

3.1. Environmental performance of Atlantic horse mackerel landed by bottom trawlers

According to the results shown in Fig. 3, there are two main activities that produce most of the environmental impact. In the first place, vessel operations accounted for most of the impact in all categories, except ADP and ODP. Therefore, vessel operations dominated the contribution to ODP (97%), EP (93%), AP and GWP (87%) and PO (64%). Nevertheless, vessel operations include a wide variety of activities, so they will be analyzed in depth later on. Secondly, diesel production is also an important contributor to ADP (97%) and POFP (33%). Its contribution to the other categories is in all cases below 15%.

The other subsystems included in the analysis had reduced environmental impact on the different categories. Net production and transport contributes to 1% in ADP and GWP, whereas ice production contributed by 2% to ADP and GWP. The manufacture of paint and anti-fouling products, as well as the vessel construction parameters barely had any effect in the different impact categories.

The environmental impact associated to human toxicity and eco-toxicity impact categories for coastal trawlers can also be observed in Fig. 3. Vessel operations account for 99% of the environmental impact for HTP, 87% for FETP and 52% for TETP. The contribution to METP is only 59%. Diesel production contributes to METP in 38%, 33% to TETP and 9% to FETP. Other activities have very low contributions to all the impact categories, always below 2%. Absolute values for the different activities can be consulted in Table A.2 of Appendix A for all the assessed impact categories.

Vessel operational activities, as seen above, are the main contributors to most impact categories. However, most of the impacts generated (Fig. 4) are due mainly to fuel consumption for all impact

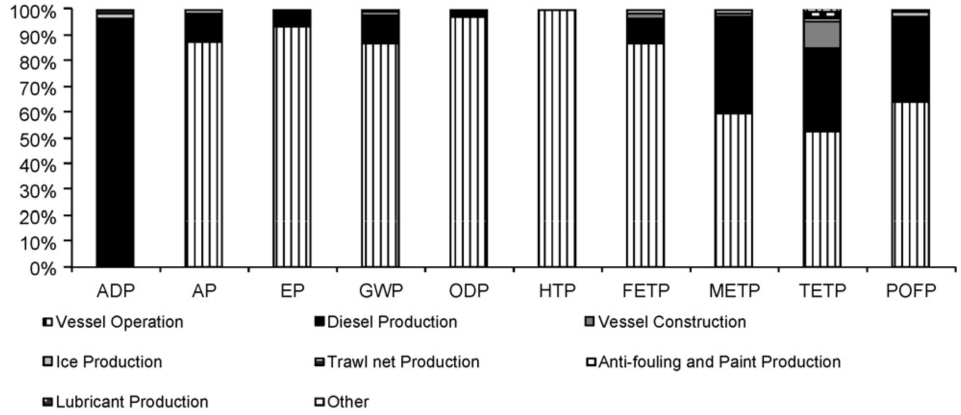

Fig. 3. Relative contribution to environmental impacts associated with the Galician bottom trawling horse mackerel fishery. Impact category acronyms: ADP = abiotic depletion potential; AP = acidification potential; EP = eutrofication potential; GWP = global warming potential; ODP = ozone layer depletion potential; HTP = human toxicity potential; FETP = freshwater aquatic eco-toxicity potential; METP = marine aquatic eco-toxicity potential; TETP = terrestrial eco-toxicity potential; POFP = photochemical oxidant formation potential.

categories, except for METP (3%) and ODP (no contribution). For the rest of impact categories its contribution is over 99%, except for GWP, where it represents 81% of the environmental burdens. Cooling agents also have a relevant contribution for GWP (19%) and especially for ODP (100%). In METP, anti-fouling and paint consumption represent the most important impact in the operational inputs subsystem (96%). Net usage and bilge waters have minimal impacts overall (<1%).

The annual average amount of discarded fish was 487.2 tons per vessel. This means that for every ton of Atlantic horse mackerel landed, 727 kg of discard were returned to the ocean.

3.2. Environmental performance of Atlantic horse mackerel landed by purse seiners

Fig. 5 shows the relative contributions that the different fishing-related subsystems produce in each impact category. The highest contributions are linked to vessel operations in all impact categories except for ADP. Their influence is of 90% in EP and ODP, 83% in AP and 76% in GWP. The percentage is lower for POFP (58%).

Diesel production is the second activity in importance in terms of environmental impact. In fact, diesel production has important contributions to ADP (84%). Its importance decreases in other impact categories, with contributions ranging from 29% (POFP) to 6% (EP).

Net and ice production are the only other subsystems with relevant contributions to certain impact categories. On the one hand, net production and transportation presents contributions of 11% for ADP or 9% for GWP. On the other hand, ice production contributes in 5% for POFP and 4% for ADP.

The environmental impact associated to human toxicity and eco-toxicity impact categories, as seen in Fig. 5, shows that vessel operation and diesel production are the main contributors in all the impact categories. Vessel operation accounts for 99.9% of the environmental impact for HTP, 83% for FETP and 47% for TETP. The contribution to METP is 68%. Diesel production contributes to METP in 27%, 29% to TETP and 9% to FETP. Other relevant contributions are linked to vessel construction and ice production for TETP (13% and 4%, respectively). Absolute values for the different activities can be seen in Table A.3 of Appendix A.

Vessel operations, as seen in Fig. 6, include a series of independent activities in the daily activity of the vessels'. These activities are the main contributors to most impact categories. However, most of the impact generated is due mainly fuel consumption (over 90%) for all impact categories, except for METP and ODP. For ODP, cooling agent leakage represents 100% of the environmental impact. This same activity generates 7% of the contributions to GWP. In METP, paint and anti-fouling consumption are the main impact in the operational inputs subsystem (96%), while fuel and net consumption account for 2% each.

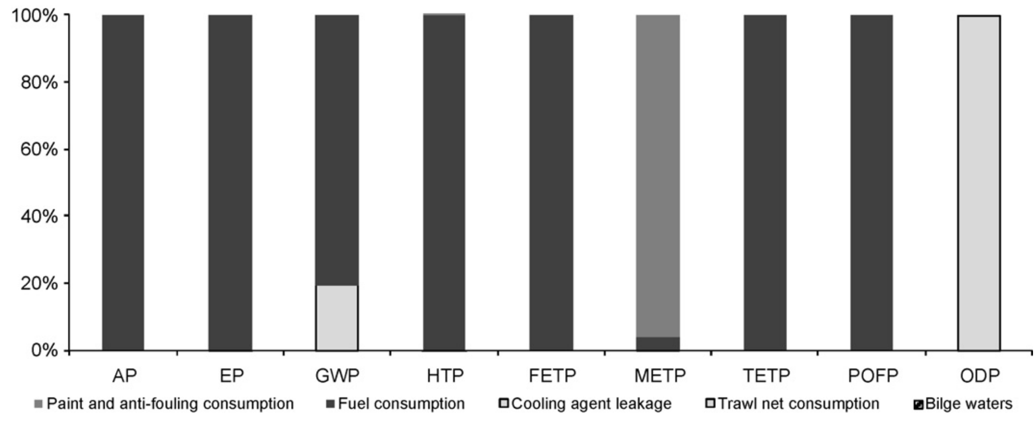

Fig. 4. Relative contribution to selected impact categories for the activities considered in the vessel operation subsystem. Bottom trawling fleet. Impact category acronyms: AP = acidification potential; EP = eutrofication potential; GWP = global warming potential; ODP = ozone layer depletion potential; HTP = human toxicity potential; FETP = freshwater aquatic eco-toxicity potential; METP = marine aquatic eco-toxicity potential; TETP = terrestrial eco-toxicity potential; POFP = photochemical oxidant formation potential.

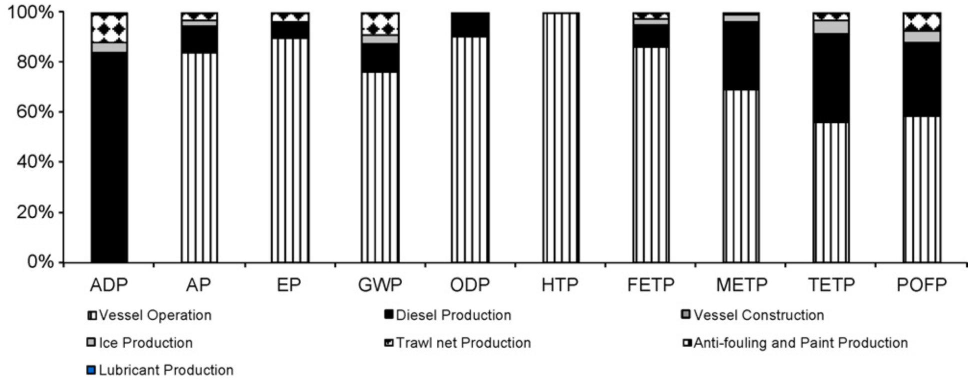

Fig. 5. Relative contribution to environmental impacts associated with the Galician purse seining horse mackerel fishery. Impact category acronyms: ADP = abiotic depletion potential; AP = acidification potential; EP = eutrofication potential; GWP = global warming potential; ODP = ozone layer depletion potential; HTP = human toxicity potential; FETP = freshwater aquatic eco-toxicity potential; METP = marine aquatic eco-toxicity potential; TETP = terrestrial eco-toxicity potential; POFP = photochemical oxidant formation potential.

4. Discussion and conclusions

4.1. Identification of hot spots

The environmental characterization for the horse mackerel fishery off the coast of Galicia led to the conclusion that the most important environmental impacts assessed in this study are related to the production, transportation and consumption of fuel, regardless of the fleet that is performing the landing. This finding is not new in fisheries LCA or in other fishery impact assessment studies, and echoes results previously presented in other works (Edwardson, 1976; Hospido and Tyedmers, 2005; Schau et al., 2009; Thrane, 2004; Tyedmers et al., 2005; Watanabe and Okubo, 1989; Ziegler et al., 2003). Nonetheless, it is interesting to point out that purse seiners present a considerably lower fuel consumption pattern than bottom trawling vessels.

The obtained results show that the environmental impact for bottom trawling vessels is mainly due to operational issues, linked to the intensive use of fuel and to cooling agent leakage in these vessels. Purse seiners, however, even though the main hot spot is still the operation of the fishing vessels also have important environmental impacts related to ice production and emissions of anti-fouling and boat paint compounds to the sea. Despite the fact that anti-fouling and boat paint manufacture showed reduced burdens for the different impact categories in both fleets (always below 1%) their contribution to marine toxicity is highly relevant due to ocean emissions of copper and zinc oxides. Ice production is also important in many impact categories due to the fact that it is produced directly in ports from the Spanish electricity mix, which is still nowadays highly dependent on fossil fuels.

Finally, seine net production and transport, vessel construction and bilge waters do not present relevant contributions. This fact leads to the conclusion that they are not key subsystems within the calculation of the environmental impacts linked to horse mackerel extraction.

4.2. Comparison between bottom trawlers and purse seiners for horse mackerel fisheries

Purse seiners and bottom trawlers constitute the main competitors for horse mackerel landings in Galician ports. When the two fleets are compared, as seen in Table 5, horse mackerel captured by purse seiners presents reduced environmental impacts in all the assessed categories. The main reason for this reduced impact is linked to lower fuel consumptions by purse seiners. Trawlers consume an average of 496 kg fuel per ton of horse mackerel, while purse seiners consume an average of 176 kg fuel/ton horse mackerel, 64.5% less. These results are in accordance with other reports that conclude that trawling in general is a highly energy-intensive fishing technique (Schau et al., 2009). Furthermore, fuel-intensive fishing operations not only present increased contributions to the assessed impact categories in this article, but usually represent the

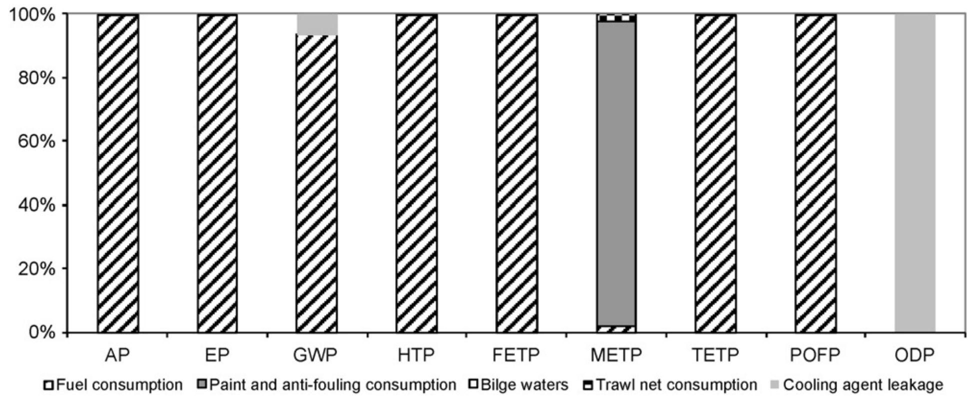

Fig. 6. Relative contribution to selected impact categories for the activities considered in the vessel operation subsystem. Purse seining fleet. Impact category acronyms: AP = acidification potential; EP = eutrofication potential; GWP = global warming potential; ODP = ozone layer depletion potential; HTP = human toxicity potential; FETP = freshwater aquatic eco-toxicity potential; METP = marine aquatic eco-toxicity potential; TETP = terrestrial eco-toxicity potential; POFP = photochemical oxidant formation potential.

Table 4
Characterization values associated with the Galician horse mackerel fishery in terms of 1 ton of round horse mackerel in Galician ports.

Impact category	Horse mackerel captured by purse seiners		Horse mackerel captured by bottom trawlers		%Difference seining/trawling landings (mass allocation)
	Mass allocation	Economic allocation	Mass allocation	Economic allocation	
ADP (kg Sb eq)	4.99	7.12	12.27	7.82	59.3
AP (kg SO_2)	10.1	14.48	27.22	17.35	62.9
EP (kg PO_4^{3-})	1.84	2.62	4.97	3.17	63.0
GWP (kg CO_2)	796	1136	2278	1454	65.1
ODP (kg CFC 11)	8.7E−4	1.2E−3	7.9E−3	5E−3	89.0
HTP (kg 1,4DCB)	2.0E5	2.9E5	5.7E5	3.62E5	64.9
FETP (kg 1,4DCB)	73.3	104.6	196	125	62.6
METP (kg 1,4DCB)	1.78E5	2.54E5	3.5E5	2.26E5	49.1
TETP (kg 1,4DCB)	1.34	1.91	3.38	2.15	60.4
POFP (kg C_2H_4)	0.21	0.30	0.53	0.34	60.4

ADP = abiotic depletion potential; AP = acidification potential; EP = eutrofication potential; GWP = global warming potential; ODP = ozone layer depletion potential; HTP = human toxicity potential; FETP = freshwater aquatic eco-toxicity potential; METP = marine aquatic eco-toxicity potential; TETP = terrestrial eco-toxicity potential; POFP = photochemical oxidant formation potential.

most damaging alternative concerning the damage that may be caused to seabed habitats (Thrane, 2006).

When results are compared with those obtained in other studies, it is important to highlight the risks of doing so, due to the different characteristics the fisheries and the fleets may have. The Norwegian coastal purse seining fleet was the fleet with closest characteristics to the seining fleet assessed in this study, mainly thanks to the similarity in landing breakdown. However, only 90 kg of fuel were consumed on average per ton of landed mackerel (in this case, *Scomber scombrus*) by the Norwegian fleet (Schau et al., 2009), representing only 51.1% of the fuel intensity of horse mackerel landing by Galician seiners. Other consulted studies, such as the offshore tuna fisheries assessed by Hospido and Tyedmers (2005), show an increased fuel effort (420 kg of fuel per landed ton of tuna) respect to that of Galician purse seiners. To our knowledge, there are no references in literature of bottom trawling vessels being used for horse mackerel extraction as a target species in other fisheries. Nevertheless, the use of bottom trawlers rather than pelagic trawlers when catching horse mackerel due to the ban of this gear in Spanish oceanic waters is obviously a major factor contributing to a high energy use in this fishery.

Results show that horse mackerel landed by coastal bottom trawlers has higher impact respect to purse seining captures, especially for ODP and GWP impact categories (89.0 and 65.1%, respectively), whereas ADP and METP present the lowest differences between the two fishing techniques (59.3% and 49.1%). When an economic allocation was performed (data available in Table 4), horse mackerel landed by purse seiners showed an increase of roughly 30% for each environmental impact, linked mainly to the fact that this species was the one with the highest economic value in 2008 and that anchovy landings (traditionally being of high economic value) were banned at the time. For the bottom trawlers, environmental impacts derived from an economic allocation perspective were about 36% lower on average than those obtained through mass allocation. This notable difference is due mainly to the fact that hake landings represented on average over 50% of a trawlers' economic turnover, due to the increased value of the species (3.72€/kg) respect to the other three species.

Regarding the discard rate of the two fishing fleets, it is important to point out the increased rate for bottom trawling vessels (42.1% of the total catch), while purse seiners reported very low discard rates, always below 5.0%. Both average results are very close to those reported by Kelleher (2008). In this recent FAO report, a discard rate of 38% was attributed to the Spanish coastal trawling fleet, while the discard rate for purse seiners was 1.6%. Nevertheless, the high standard deviation obtained for the reported trawling discards in the current study (±16.1%) is considerably high, showing not only a lack of transparency when the sector reports these data, but also the need to increase on board inspection of discards. Finally, taking into account that horse mackerel usually congregates in large shoals, it is probable that it generates less discards than other target species of this fleet, so the allocated 727 kg of discard per ton of landed horse mackerel may be slightly overestimated.

4.2.1. Effects of shifting to low ozone layer depletion cooling agents

The data provided in this article concerning cooling agent leakage, as mentioned previously, was based on personal communications obtained from technicians in different specialized companies in Galicia. However, it is important to stress that no reliable data was available at a Spanish level from institutions or research centers. Therefore, the quality of data linked to these emissions still has room for improvement.

Table 5 shows how this estimated leakage can translate into ODP and GWP contributions of 97 and 17%, respectively for the bottom trawling fleet and 90 and 5% for purse seiners (Scenario 1). If R22 is substituted by R404A (Scenario 2), maintaining the leakage values, ODP contributions due to refrigerant leaks are close to zero, while this refrigerant would represent 11 and 33% of the total GWP characterization values for purse seiners and bottom trawlers, respectively, due mainly to the high global warming potential of some of the main compounds in R404A. Hence, the prohibition to add newly produced R22 in cooling chambers starting in early 2010 will definitely help to reduce considerably the potential depletion of the ozone layer by fishing vessels. In contrast, the use of other compounds, such as R404A, does not seem to guarantee a reduction of burdens related to GWP.

4.3. Improvement opportunities

Taking into account the different hot spots identified in horse mackerel fishing through trawling or purse seining activities, some improvement actions can be proposed, together with the associated environmental reduction and the feasibility of the improvement.

The reduction of fuel intensity should be a major goal for both fleets when analyzing vessel operations. Nevertheless, there is a highly relevant difference in fuel consumption when purse seiners and bottom trawlers are compared, with consumption levels 65% lower for purse seiners. Therefore, considering that bottom trawlers have much more varied target species, targeting a variety of demersal and semi-pelagic species, a change in the fishing strategy for horse mackerel could be proposed. In this context, the current, horse mackerel quota for bottom trawlers is 4500 kg

Table 5
Effect of cooling agents on characterization values for selected impact categories (data per FU).

Impact category	Horse mackerel captured by purse seiners (mass allocation)		Horse mackerel captured by bottom trawlers (mass allocation)	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
GWP (kg CO_2)	796	855	2278	2852
ODP (kg CFC 11)	8.7E−4	8.4E−4	7.9E−3	2.3E−4

Scenario 1 = estimated global environmental burdens considering reported R22 leakage; Scenario 2 = total environmental impact considering the same leakage if R404A substitutes R22; GWP = global warming potential; ODP = ozone layer depletion potential.

per day, while the quota for seiners is 6000 kg per day (Xunta de Galicia, 2008). A quota increase for purse seiners and a steady reduction of quotas for bottom trawlers would reduce considerably the environmental impacts associated to horse mackerel landings, including a considerable reduction of the associated discards. This reduction could be complemented with an increased quota for other targeted species, in order to maintain the economic viability of the bottom trawlers.

Another alternative for fuel intensity reduction would be to propose the reintroduction of pelagic trawls in this fishery. Pelagic trawls, according to previous studies have a reduced fuel effort when compared to bottom trawls (Schau et al., 2009; Thrane, 2004). A recent study by Driscoll and Tyedmers (2010) proved the convenience of introducing management decisions in order to influence energy demands in fisheries. In their study, Atlantic herring from the New England fishery was found to have reduced the related fuel intensity substantially through the seasonal banning of midwater trawlers in favor of purse seining and fixed gears. Nevertheless, the introduction of pelagic trawls in this particular study would only be viable provided that an integral stock assessment study in the area recommended such an initiative.

Technological improvements actions can also be included in the assessed fishing fleets. The introduction of new vessels into the fisheries with changes in hull shapes, in order to provide energy efficiency improvements of up to 20% (Schau et al., 2009) or changes in the energy carrier of the vessels could become long term solutions.

Other operational activities that could undergo potential improvements are anti-fouling loss to sea and net loss. Anti-fouling paints were identified as a main hot spot relating to marine toxicity potential in this study. However, it must be pointed out that anti-fouling paints with a high concentration of copper are already substituting TBT anti-fouling agents, which were banned by the International Maritime Organization in the year 1999 (IMO, 2008). Even so, the use of copper oxides in anti-fouling products was still identified as the main responsible for this impact. Net loss at sea was also found to entail a considerable impact in the marine toxicity category. However, most environmental burdens could be avoided with an increased prevention policy when it comes to loosing nets at sea. The effect of ghost nets on different ecosystems was not assessed in this study.

Ice production is relatively significant in certain impact categories, especially in the purse seining fleet. This is due mainly to the Spanish "electricity mix", which is still based mainly on fossil fuel energy. On the one hand, the impact linked to ice production may be reduced through the inclusion of fresh water generators on board, taking advantage of the heat loss of the motor. On the other hand, another option is to install a renewable energy production system in the port.

Finally, at this point it is obvious that cooling agent leakage has an increased potential impact on GWP and ODP. Nevertheless, this situation is currently shifting steadily, thanks to an international phasing out scheme on the use of R22 starting in the year 2010 (European Commission, 2000). Therefore, short term challenges will be to monitor the environmental impact shifts that may occur due to the use of substitutive products and to increase safety measures for leakage prevention.

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Appendix A.

Table A.1 gathers individual information relating to the discard figures for the 24 bottom trawling vessels assessed in this study.

Tables A.2 and A.3 present the characterization values – absolute figures – for the different subsystems for the trawling and purse seining horse mackerel fisheries, respectively.

Table A.1
Overall individual discards and discard rate for the bottom trawling fleet.

Trawling vessel	Discards (kg/year)	Discard rate (% over total capture)	Trawling vessel	Discards (kg/year)	Discard rate (% over total capture)
1	868,800	66.7	13	472,208	26.2
2	849,915	60.0	14	395,074	29.6
3	849,915	60.0	15	747,434	63.1
4	1,167,508	60.0	16	215,173	33.0
5	444,766	36.4	17	199,770	25.8
6	981,888	60.0	18	431,775	42.9
7	605,025	40.0	19	781,943	36.4
8	605,025	40.0	20	272,575	45.4
9	326,203	40.0	21	272,575	45.4
10	326,203	40.0	22	315,060	42.7
11	244,273	22.6	23	37,870	5.2
12	206,353	19.0	24	75,098	17.7

Table A.2
Individual subsystems characterization values for the horse mackerel trawling fishery.

Impact category	Vessel operation	Diesel production	Vessel construction	Ice production	Trawl net production	Anti-fouling and paint manufacture	Marine lubricant oil production	Refrigerants
ADP (kg Sb eq)	0	11.8	1.81E−2	0.21	0.13	1.31E−2	5.55E−2	0
AP (kg SO_2)	23.8	3.03	1.02E−2	0.27	7.67E−2	2.79E−2	1.16E−2	0
EP (kg PO_4^{3-})	4.64	0.30	1.5E−3	1.39E−2	1.57E−2	1.16E−3	9.50E−4	0
GWP (kg CO_2)	1.59E3	252	2.19	28.7	16.8	1.11	1.96	1.11E3
ODP (kg CFC 11)	0	2.29E−4	1.76E−7	1.57E−6	1.66E−7	1.23E−7	1.38E−7	7.76E−3
HTP (kg 1,4DCB)	5.67E5	174	3.50	5.27	1.47	16.5	0.86	0
FETP (kg 1,4DCB)	171	18.2	4.64	1.80	0.39	0.49	0.14	0
METP (kg 1,4DCB)	2.11E5	1.33E5	4371	4.81E3	424	886	307	0
TETP (kg 1,4DCB)	1.77	1.11	0.33	5.88E−2	9.04E−3	6.93E−2	1.25E−2	0
POFP (kg C_2H_4)	0.34	0.17	7.81E−4	1.00E−2	3.58E−3	1.25E−3	4.56E−4	0

Table A.3
Individual subsystems characterization values for the horse mackerel purse seining fishery.

Impact category	Vessel operation	Diesel production	Vessel construction	Ice production	Trawl net production	Anti-fouling and paint manufacture	Marine lubricant oil production	Refrigerants
ADP (kg Sb eq)	0	4.20	9.86E−3	0.21	0.54	7.27E−3	1.15E−2	0
AP (kg SO_2)	8.45	1.07	5.60E−3	0.27	0.33	1.59E−2	2.40E−3	0
EP (kg PO_4^{3-})	1.65	0.11	8.63E−4	1.38E−2	6.67E−2	6.60E−4	1.96E−4	0
GWP (kg CO_2)	564	89.3	1.19	28.5	71.5	0.63	0.40	39.7
ODP (kg CFC 11)	0	8.13E−5	9.70E−8	1.55E−6	7.04E−7	6.70E−8	2.86E−8	7.86E−4
HTP (kg 1,4DCB)	2.01E5	61.7	1.89	5.23	6.24	9.44	0.18	0
FETP (kg 1,4DCB)	60.6	6.45	2.47	1.79	1.67	0.28	2.82E−2	0
METP (kg 1,4DCB)	1.21E5	4.74E4	2.33E3	4.77E3	1.80E3	504	63.4	0
TETP (kg 1,4DCB)	0.63	0.39	0.18	5.84E−2	3.84E−2	3.96E−2	2.58E−3	0
POFP (kg C_2H_4)	0.12	6.10E−2	4.29E−4	9.94E−3	1.52E−2	7.10E−4	9.44E−5	0

References

Abaunza, P., Villamor, B., Pérez, J.R., 1995. Infestation by larvae of Anisakis simplex in horse mackerel, *Trachurus trachurus*, and Atlantic mackerel, Scomber scobrus, in ICES Divisions VIIIb, VIIIc and IXa (N-NW of Spain). Sci. Mar. 59, 223–233.

Abaunza, P., Gordo, L., Karlou-Riga, C., Murta, A., Eltink, A.T.G.W., Santamaria, M.T.G., Zimmermann, C., Hammer, C., Lucio, P., Iversen, S.A., Molloy, J., Gallo, E., 2003. Growth and reproduction of horse mackerel, *Trachurus trachurus* (Carangidae). Rev. Fish Biol. Fish. 13 (1), 27–61.

Aboussouan, L., van de Meent, D., Schönnenbeck, M., Hauschild, M., Delbeke, K., Strujis, J., Russell, A., Udo de Haes, H., Atherton, J., van Tilborg, W., Karman, C., Korenromp, R., Sap, G., Baukloh, A., Dubreuil, A., Adams, W., Heijungs, R., Jolliet, O., de Koning, A., Chapman, P., Ligthart, T., Verdonck, F., van der Loos, R., Eikelboom, R., Kuyper, J., 2004. Declaration of Apeldoorn of LCIA of Non-Ferrous Metals, Available at http://www.uneptie.org/pc/sustain/reports/lcini/DeclarationofApeldoorn_final.pdf.

Alzieu, C., 1998. Tributylin: case study of a chronic contaminant in the coastal environment. Ocean Coast. Manage. 40 (1), 23–36.

Ayer, N., Côté, R.P., Tyedmers, P.H., Willison, J.H.M., 2009. Sustainability of seafood production and consumption: an introduction to the special issue. J. Cleaner Prod. 17, 321–324.

Badjeck, M.C., Allison, E.H., Halls, A.S., Dulvy, N.K., 2010. Impacts of climate variability and change on fish-based livelihoods. Mar. Pol. 34, 375–383.

Christensen, V., Guenette, S., Heymans, J.J., Walters, C.J., Watson, R., Zeller, D., Pauly, D., 2003. Hundred-year decline of North Atlantic predatory fishes. Fish Fish. 4 (1), 1–24.

Driscoll, J., Tyedmers, P., 2010. Fuel use and greenhouse gas emission implications of fisheries management: the case of the new England Atlantic herring fishery. Mar. Pol. 34, 353–359.

Edwardson, W., 1976. The energy cost of fishing. Fishing News Int. 15 (2), 36–39.

EMEP-Corinair, 2006. Emissions Inventory Guidebook, Available at http://www.eea.europa.eu/publications/EMEPCORINAIR4.

European Commission, 2000. Regulation 2037/2000, Available at http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2000:244:0001:0024:EN:PDF (accessed June 2010).

FAO, 2008. World Review of Fisheries and Aquaculture. FAO, Rome.

Fonseca, P., Campos, A., Mendes, B., Larsen, R.B., 2005. Potential use of a Nordmore grid for by-catch reduction in a Portuguese bottom-trawl multispecies fishery. Fish. Res. 73, 49–66.

Frischknecht, R., Jungbluth, N., Althaus, H.J., Doka, G., Heck, T., Hellweg, S., Hischier, R., Nemecek, T., Rebitzer, G., Spielmann, M., Wernet, G., 2007. Overview and Methodology. Ecoinvent Report No. 1, Swiss Centre for Life Cycle Inventories, Dübendorf.

FROM, 2005. Consumo de pescado en hogares españoles (in Spanish). Available at http://www.mercadosmunicipales.es/uploads/pescados/Jurel_o_chicharro.pdf (accessed June 2010).

Goedkoop, M., de Schryver, A., Oele, M., 2008. Introduction to LCA with SimaPro 7. PRé Consultants, The Netherlands.

Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Wegener, A., Suh, S., Udo de Haes, H.A., 2001. Life Cycle Assessment. An Operational Guide to the ISO Standards. Centre of Environmental Science, Leiden, The Netherlands.

Guyonnet, B., Grall, J., Vincent, B., 2008. Modified otter trawl legs to reduce damage and mortality of benthic organisms in North East Atlantic fisheries (Bay of Biscay). J. Mar. Syst. 72, 2–16.

Hall-Spencer, J., Allain, V., Fossa, J.H., 2002. Trawling damage to Northeast Atlantic ancient coral reefs. R. Soc. Lond. 269, 507–511.

Hayman, B., Dogliani, M., Kvale, I., Fet, A.M., 2000. Technologies for Reduced Environmental Impact from Ships-Ship Building, Maintenance and Dismantling Aspects. ENSUS-2000, Newcastle upon Tyne, UK.

Horse Mackerel Stock Identification Research (HOMSIR), 2003. http://www.homsir.com (accessed June 2010).

Hospido, A., Tyedmers, P., 2005. Life cycle environmental impacts of Spanish tuna fisheries. Fish. Res. 76, 174–186.

Iles, A., 2007. Making the seafood industry more sustainable: creating production chain transparency and accountability. J. Cleaner Prod. 17, 321–324.

International Maritime Organization (IMO), 2008. http://www.imo.org.

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

Kelleher, K., 2008. Discards in the World's Marine Fisheries. An Update. FAO Fisheries Technical Paper 470. FAO, Rome.

Klingenberg, A., 2005. Enforcement of chlorofluorocarbons regulations on maritime vessels. In: Paper Prepared for the 7th International Conference on Environmental Compliance and Enforcement, 245–247 April 2005, Marrakesh, Morocco, Available from http://www.inece.org/conference/7/vol1/index.html (accessed May 2010).

Luten, J., Jacobsen, C., Bekaert, K., Saebø, A., Oehlenschläger, J., 2006. Seafood Research from Fish to Dish—Quality, Safety and Processing of Wild and Farmed Seafood. Wageningen Academic Publishers, Wageningen, the Netherlands.

Matthiessen, P., Law, R.J., 2002. Contaminants and their effects on estuarine and coastal organism in the UK in the late twentieth century. Environ. Pollut. 120 (3), 739–757.

Ministerio de Medio Ambiente, Rural y Marino (MARM), 2010. www.marm.es (accessed June 2010).

Murta, A., Abaunza, P., Cardador, F., Sánchez, F., 2008. Ontogenic migrations of horse mackerel along the Iberian coast. Fish. Res. 89, 186–195.

Pelletier, N.L., Ayer, N.W., Tyedmers, P.H., Kruse, S.A., Flysjo, A., Robillard, G., Ziegler, F., Scolz, A.J., Sonesson, U., 2007. Impact categories for life cycle assessment research of seafood production systems: reviews and prospectus. Int. J. Life Cycle Assess. 12 (6), 414–421.

Schau, E.M., Ellingsen, H., Endal, A., Aanondsen, S.A., 2009. Energy consumption in the Norwegian fisheries. J. Cleaner Prod. 17, 325–334.

SenterNovem, 2002. Fishery with Environmentally-Friendly Cooling Systems, Available from: http://www.senternovem.nl/mmfiles/Fishery%20with%20environmentally-friendly%20cooling%20systems_tcm24-196361.pdf (accessed May 2010).
SOFIA, 2008. The State of the World Fisheries and Aquaculture. FAO, Rome.
Thrane, M., 2004. Energy consumption in the Danish fishery. J. Ind. Ecol. 8, 223–239.
Thrane, M., 2006. LCA of Danish fish products. Int. J. Life Cycle Assess. 11 (1), 66–74.
Tyedmers, P., 2000. Salmon and sustainability: the biophysical cost of producing salmon though the commercial salmon fishery and the intensive salmon culture industry. PhD Thesis. University of British Columbia. Vancouver, BC, Canada.
Tyedmers, P., Watson, R., Pauly, D., 2005. Fuelling global fishing fleets. AMBIO 34 (8), 619–622.
Vázquez-Rowe, I., Iribarren, D., Hospido, A., Moreira, M.T., Feijoo, G., submitted for publication. The link between fuel consumption and eco-efficiency in fishing vessels. A case study on selected Galician fleets. J. Ind. Ecol.
Villamor, B., Abaunza, P., Lucio, P., Porteiro, C., 1997. 1989–1994. Distribution and age structure of mackerel (*Scomber scombrus* L.) and horse mackerel (*Trachurus trachurus* L.) in the northern coast of Spain. Sci. Mar. 61, 345–366.
Watanabe, H., Okubo, M., 1989. Energy input in marine fisheries in Japan. Jpn. Soc. Sci. Fish. B 53, 1525–1531.
Winther, U., Ziegler, F., Skontorp-Hognes, E., Emanuelsson, A., Sund, V., Ellingsen, H., 2009. Carbon footprint and energy use of Norwegian seafood products. SINTEF Fisheries and Aquaculture Report SFH80 A096068, Trondheim, Norway.
Whitehead, P.J.P., Bauchot, M.-L., Nielsen, J.-C., Tortonese, E., 1986. Fishes of the North-eastern Atlantic and the Mediterranean. Unesco, Paris.
Xunta de Galicia, 2008. Orden de 5 de junio de 2008 por la que se regula la captura y el desembarco de determinadas especies pelágicas (DOG de 19 de junio de 2008).
Xunta de Galicia, 2010. Fishing Technologic Platform (in Galician). www.pescadegalicia.com.
Ziegler, F., Nilsson, P., Mattsson, B., Walther, Y., 2003. Life Cycle Assessment of frozen fillets including fishery-specific environmental impacts. Int. J. Life Cycle Assess. 8 (1), 39–47.
Ziegler, F., Valentinsson, D., 2008. Environmental life cycle assessment of Norway lobster (*Nephrops norvegicus*) caught along the Swedish west coast by creels and conventional trawls-LCA methodology with case study. Int. J. Life Cycle Assess. 13, 487–497.