Int J Life Cycle Assess (2014) 19:297–306
DOI 10.1007/s11367-013-0646-5

Environmental assessment of sardine (*Sardina pilchardus*) purse seine fishery in Portugal with LCA methodology including biological impact categories

Cheila Almeida · Sofia Vaz · Henrique Cabral · Friederike Ziegler

Received: 1 February 2013 / Accepted: 13 August 2013 / Published online: 10 September 2013

Abstract
Purpose The purse seine fishery for sardine is the most important fishery in Portugal. The aim of the present study is to assess the environmental impacts of sardine fished by the Portuguese fleet and to analyse a number of variables such as vessel size and time scale. An additional goal was to incorporate fishery-specific impact categories in the case study.
Methods Life Cycle Assessment methodology was applied, and data were collected from nine vessels, which represented around 10 % of the landings. Vessels were divided into two length categories, above and below 12 m, and data were obtained for the years 2005 to 2010. The study was limited to the fishing phase only. The standard impact categories included were energy use, global warming potential, eutrophication potential, acidification potential and ozone depletion potential. The fishery-specific impact categories were overfishing, overfishedness, lost potential yield, mean trophic level and the primary production required, and were quantified as much as possible.
Results and discussion The landings from the data set were constituted mainly by sardine (91 %), and the remainders were other small pelagic species (e.g. horse mackerel). The most important input was the fuel, and both vessel categories had the same fuel consumption per catch 0.11 l/kg. Average greenhouse gas emissions (carbon footprint) were 0.36 kg CO_2 eq. per kilo sardine landed. The fuel use varied between years, and variability between months can be even higher.

Fishing mortality has increased, and the spawning stock biomass has decreased resulting in consequential overfishing for 2010. A correlation between fuel use and stock biomass was not found, and the stock condition does not seem to directly influence the global warming potential in this fishery. Discards were primarily non-target small pelagic species, and there was also mortality of target species resulting from slipping. The seafloor impact was considered to be insignificant due to the fishing method.
Conclusions The assessment of the Portuguese purse seine fishery resulted in no difference regarding fuel use between large and small vessels, but differences were found between years. The stock has declined, and it has produced below maximum sustainable yield. By-catch and discard data were missing but may be substantial. Even being difficult to quantify, fishery impact categories complement the environmental results with biological information and precaution is need in relation to the stock management. The sardine carbon footprint from Portuguese purse seine was lower than that of other commercial species reported in.

Keywords Fisheries · Fuel · GHG · Life cycle assessment · Purse seining · Sardine · Seafood

Responsible editor: Mary Ann Curran

Electronic supplementary material The online version of this article (doi:10.1007/s11367-013-0646-5) contains supplementary material, which is available to authorized users.

C. Almeida · H. Cabral
Centro de Oceanografia, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal

C. Almeida · S. Vaz
Centre for Environmental and Sustainability Research, Faculdade de Ciências de Tecnologia, Universidade Nova de Lisboa, Lisbon, Portugal

C. Almeida (✉) · F. Ziegler
The Swedish Institute for Food and Biotechnology,
402 29 Gothenburg, Sweden
e-mail: cpa@sik.se

1 Introduction

Sardines are a small pelagic fish that due to their small size and schooling behaviour serves as prey for other animals (Tacon and Metian 2009). *Sardina pilchardus* is an abundant species along the continental shelf of Atlantic Iberian waters, divisions VIIIc and IXa (Carrera and Porteiro 2003; ICES 2012). The spawning is driven locally and can differ depending on the environment variables that may reduce egg and larval survival (Silva et al. 2009).

Portugal is the third largest fishing nation for this species after Morocco and Algeria (Tacon and Metian 2009). Since 1980, ICES has defined an Atlanto-Iberian stock jointly managed between Spain and Portugal and around 71 % is caught by Portugal (ICES 2012). Sardine is the most important species for the Portuguese fleet, around 35 % in terms of volume of total landings and 14 % in value (average price 0.7 EUR/kg) (INE 2011). Purse seine is one of the oldest fisheries and the most economically important fleet in Portugal (Anderson et al. 2012). Management measures for this fishery were implemented in 1998 and include an overall limitation in fishing days and annual catch limits set by the Portuguese authorities (Wise et al. 2005).

The fishery is under Marine Stewardship Council (MSC) certification since 2010, but it was suspended in 2012 due to low recruitment and high fishing mortality (ICES 2012). Management measures were implemented after an action plan decided between producers and the government with a catch limit and a fishing ban of 45 days (Fishery Management Group 2012).

The fishing fleet of Portuguese purse seiners consists of 200 vessels, but the bulk of sardine catches are taken by 75 vessels that correspond to larger purse seiners (18 to 40 m size; Stratoudakis and Marçalo 2002; Anderson et al. 2012). Almost half of the fleet (89 vessels) are below 12 m size and have low significance in terms of landing volume (roughly 9 % of total landings; Anderson et al. 2012). These smaller vessels, called *rapas* or *tucas*, are modified to capture also demersal species in relatively shallow water and can target species more valuable than sardine such as sea bream (Gonçalves et al. 2008).

In Portugal, sardines are not used for feed and are mainly consumed fresh. Around 45 % of the landings supply the processing industry, most of it to produce canned products (Ernest and Young 2009). The domestic market is best during spring and summer, when sardine is traditionally eaten grilled, and in autumn and winter most of the landings go to processing (da Mata personal communication).

Food is becoming increasingly important to be produced in an environmentally sustainable and transparent way (Nijdam et al. 2012). Life Cycle Assessment (LCA) method offers a convenient means of quantifying the impacts associated with the energetic and material inputs and outputs of food products (Pelletier et al. 2007). The number of LCA studies about seafood products originating in fisheries has increased rapidly in the last years (see Parker and Tyedmers 2012; Vázquez-Rowe et al. 2012a). Previous LCA studies have shown that conventional impact categories are heavily associated with the fuel use in the fishery (e.g. Ramos et al. 2011). Three previous LCA studies of purse seine fisheries in the North Atlantic have been published (Vázquez-Rowe et al. 2010; Ramos et al. 2011; Ziegler et al. 2013) but none about the Portuguese fleet. Furthermore, most seafood LCA studies analyse data from one single year, but Ramos et al. (2011) demonstrate the need to expand fishery LCAs in time. While there are many opinions on the sustainability of larger versus smaller fishing vessels, to our knowledge, no LCA studies have investigated resource efficiency in relation to vessel length.

This study is a first attempt to quantify the environmental impacts of the Portuguese purse seine fishery for sardine. We will do this by applying LCA methodology. Our goal is to quantify the overall environment impact of the fishery and to assess whether vessel length is an important factor for the fishery efficiency. Furthermore, we examine the variability of impacts over time.

2 Methods

2.1 Goal and scope definition

The main goal of this study is to assess the environmental impacts related to the Portuguese purse seine fishery targeting sardine. Additional goals are to analyse the fishery performance on a temporal basis (years; trimesters) and to compare different vessel size categories in terms of resource efficiency. The data analysed are from between 2005 to 2011. The functional unit (FU) is defined as 1 kg. of whole sardine, landed in a Portuguese port, reflecting the function of delivering raw material for further processing to canned or frozen sardines or directly for consumption as fresh sardines. In accordance with the goals of the study, the system was limited to the fishing phase, and the system studied hence comprised only production of supply materials until landing operations so this assessment constituted a so called cradle-to-gate study.

Capital goods such as vessel and gear were not included since previous findings showed that they have minor contribution to the overall environmental impacts of fisheries and seafood products (Nijdam et al. 2012; Ziegler et al. 2013). Their long life span in combination with large volumes of landings (especially in pelagic fisheries) is responsible for low influence in other studies (e.g. Svanes et al. 2011; Parker and Tyedmers 2012). The greenhouse gas (GHG) emissions linked to capital goods represented less than 1 % of the carbon footprint for species from commercial fishing (Iribarren et al. 2010). Also, burdens related to gears do not presented relevant contributions, and most cases were below 5 % (Vázquez-Rowe et al. 2012a). Anti-fouling paint is mainly linked to toxicity impact categories, which were not analysed in this study (e.g. Vázquez-Rowe et al. 2012b).

For co-product allocation, we decided to use mass allocation to avoid the volatility in the market prices connected with economic allocation. Also because it can give misleading results such as that lower value species are more sustainable if caught together with high-value species than if caught separately (Vázquez-Rowe et al. 2012a). Sardine is the target species, and it represents the bulk of the fishery, with almost 80 % of the landings (Stratoudakis and Marçalo 2002). For more detail on LCA methodology, see Baumann and Tillman (2004), Pelletier et al. (2007), and Vázquez-Rowe et al. (2012a).

2.2 Data acquisition

The samples used for this study correspond to a set of vessels belonging to different organizations based in the north of Portugal (Matosinhos, Póvoa de Varzim, Aveiro). The organizations altogether represent approximately 38 % of the Portuguese sardine landings. The data obtained were from nine vessels, in average they represent 10 % of the landings for the years assessed. The vessels were divided into two size categories: larger vessels (L), above 12 m length, and smaller (S), under 12 m. This division was in accordance with the fleet segment published by the earliest Joint Research Council (JRC) report, where we can find three main segments: 0–12, 12–24, and 24–40 m (Anderson and Guillen 2010).

The primary data for fishing vessel operations were obtained personally from questionnaires made to skippers and officers of the producer organizations (PO). Fuel use data were obtained from skippers' accountability and catches, from the PO officers' reports. In order to achieve a representative picture of the environmental performance of the analysed system and to understand how the resource efficiency varies over time, we aimed at collecting data for several years. Vessel specific data requested included the overall length, gross tonnage, propulsive engine power and an annual base of operations between 2005 and 2010. For each vessel, operational data requested included the type and amount of fuel used, coolants, ice, and lubricant oils. Annual data from landings for each vessel were obtained from the producer organization officers. For one vessel, it was possible to have a monthly data series of operations and fuel per landings during the year of 2011. Differences in averages between size categories and years were tested by means of a t test for unequal variances. Landings data for the overall Portuguese purse seine fishery were provided by the Portuguese Institute of Statistics (INE 2011). Sardine economic values in month variability were obtained for the overall fleet from 2011 (INE 2012).

Neither discard amounts nor fishery data from a discard monitoring programme were available for this fleet. Nevertheless, a discussion based on literature data for this fishery was included since in lack of more specific data, the use of average previous estimations from published literature is recommended (Vázquez-Rowe et al. 2012a). Ice production information was obtained through personal communication with the ice production plant.

Background data (e.g. production of fuel) were compiled from the LCA database Ecoinvent 2.0 (Frischknecht et al. 2007). Emissions from fuel combustion on fishing vessels for marine diesel (e.g. CO_2, SO_x) and related to the engine (e.g. NO_x) were calculated based on Ziegler and Hansson (2003).

2.3 Impact assessment

The LCA was modelled in SimaPro Software version 7.1.6 (SimaPro7 software 2007) using impact assessment method CML baseline 2 2002 (Guinée et al. 2001). The standard impact categories included were energy use (E), global warming potential (GWP), eutrophication potential (EP), acidification potential (AP), and ozone depletion potential (ODP). The choice of these categories is consistent with the impact category choices typical for other seafood LCA research (Pelletier et al. 2007; Vázquez-Rowe et al. 2012a).

In addition, a series of fishery-specific biological impact categories were evaluated and, as far as possible, quantified. These are three LCA impact categories proposed by Emanuelsson et al. (in review): overfishing through fishing mortality (OF), overfishedness of biomass (OB), and lost potential yield (LPY). The OF category is based on the ratio between current fishing mortality (F) and fishing mortality at maximum sustainable yield (MSY; F_{MSY}). It is expressed for LCA purposes as $F/F_{MSY}-1$ to adjust the scale so that zero corresponds to the point of "no impact" in accordance with other impact categories. OB is quantified in terms of the ratio between B_{MSY} (spawning stock biomass at MSY) and B (current spawning stock biomass)−1, and it is also set to increase with increasing environmental harm, starting at zero ($B_{MSY}/B-1$). Lost potential yield is a projection of the current exploitation scenario with regard to F and B sustained for T years forward. It represents the difference between current exploitation and more optimal exploitation with B at B_{MSY} and F at F_{MSY}. We chose 20 years as the default time perspective. For formulas and more details, see Emanuelsson et al. (in review).

Two trophic indicators evaluated by Hornborg et al. (2013) were included: the mean trophic level (MTL) and the primary production required (PPR). The MTL represents the mean trophic level in the landings of a fishery based on each species trophic level and their proportion in the total catch (Pauly et al. 1998). The trophic levels were obtained from Froese and Pauly (2012). PPR is an estimate of the magnitude of primary production needed to produce 1 kg of a species at a certain trophic level (Hornborg et al. 2013). It was calculated on landings and estimated by species groups based on 10 % mean transfer efficiency between trophic levels (Pauly and Christensen 1995). We also evaluated by-catch, discards, and seafloor impact potential proposed by Nilsson and Ziegler (2007). Due to lack of specific data for these impact categories, only qualitative data were used, based on previous studies, reports or published papers: Stratoudakis and Marçalo

(2002); Wise et al. (2005); Kelleher (2008); Gonçalves et al. (2008); Gutiérrez et al. (2012); Vázquez-Rowe et al. (2012b).

2.4 Sensitivity analyses

Ramos et al. (2011) highlighted the fact that, in fisheries with low fuel use intensity (FUI), gear use may be an important source of GHG emissions. We do not account for this potential source of uncertainties since we do not include capital goods. Also the only information we gathered is based on a personal communication, and it can be very different depending on the vessel or the fishery or even the years as we can see in Ramos et al. (2011) inventory data. To analyse the impact assessment for the gear, we made a sensitivity analysis using an average data of 0.003 kg/kg fish landed from Ramos et al. (2011).

3 Results

3.1 Inventory results

The fishing operation starts once schools of pelagic fish have been detected. On the largest purse seiners, large nets (up to 800 m long and 400 m deep) are set rapidly with the help of an auxiliary vessel (6 m long), and hauled in a largely manual operation involving all members of the crew (Stratoudakis and Marçalo 2002). Vessels operate from the ports, on daily trips (around 8 h), and the net is set once or twice per fishing day (Wise et al. 2005). The fishery is open all year round, except during unfavorable weather conditions or during restricted periods set by producers' organization.

Main operational inputs were use of fuel, marine lubricant oil, and ice (Fig. 1). There is no use of coolants, and the vessels have isothermal containers with ice and water, so-called *dornas* (Wise et al. 2005). The ice is produced on land, and it is sourced before each journey from ice plants based in ports. At landing, the fish is moved from the vessel into small boxes used for the auction. Lubricant oils are used for vessel engine and hydraulic machinery that helps with net operations.

Landings from overall data collected for the study were constituted mainly of sardine (90 %). The remainders were other small pelagic species such as Atlantic chub mackerel (*Scomber colias*) and horse mackerel (*Trachurus trachurus*). These two species represent almost 9 % of the total landings. Other species caught during purse seine fishing for sardine were documented, but their catch proportion is very small and they were aggregated as other species in the data set. Discard data for purse seiners were reported as being close to zero by the interviewed skippers. They were not quantifying slipping, the discard fish directly from the net during purse seine activities mainly for quality reasons. An inventory summary regarding the main inputs and outputs of the studied is shown in Table 1. Data are aggregated for all years and per vessel length category. More detailed data for all the years assessed can be consulted in the Electronic supplementary material (ESM).

The two vessel categories demonstrated highly different catch profiles, and the average landing composition was different. Smaller boats catch less quantity and more species. The average proportion of sardine landed by the smaller vessels is only 77 % compared with 91 % for the larger vessels. The landings varied between years, and the largest catches for the biggest vessels were obtained in 2008, and in 2006 for the smaller vessels.

The FUI per sardine landed was neither statistically different between years nor between vessel size categories (*t* test, $p=0.35$). Average values for the different years assessed varied between 0.9 (SD=0.02) and 0.14 (SD=0.03)l/kg and the fuel consumption use was highest in 2008, coinciding with the year for the largest landings of large purse seiners (Fig. 2). Both vessel categories had almost the same consumption per catch, and the overall average was 0.11 (SD=0.03)l/kg.

The use of ice and lubricant was significantly different between vessel size categories (ice, *t* test, $p=0.001$, lubricants, *t* test, $p=0.01$). Larger vessels use more ice in their operations, and smaller vessels have a higher lubricant oil use when we compare the inputs to produce 1 kg of sardine (Table 1).

3.2 Impact assessment

The fuel was the process with the highest contribution in all the impact categories selected for the impact assessment (Fig. 3). For the energy use, it was responsible almost 100 % and more than 80 % of the others. The relative contribution of ice production was highest for ozone depletion with 6 % of contribution in that category. Lubricant combustion had almost the same contribution in all the impact categories, around 4 %, apart from energy. Due to the dominance of fuel and the correlation between all LCA impact categories, we chose to focus on analysing the GWP results more in detail and in relation to the biological impact categories.

The average global warming potential (GWP) for the overall fleet was 0.36 kg CO_2 eq. The GWP for the two size vessel categories were almost equal: 0.35 for larger and 0.36 kg.CO_2 eq for smaller boats. The same trend happens with the other impact categories due to the dominance of fuel combustion and production. For the categories EP, AP, and ODP the results for the overall fleet were 0.0024 kg SO_2 eq; 0.0005 kg PO_4 eq; and 0.48 kg CFC-11 eq, respectively.

The GWP varied between years from 0.29 to 0.47 kg CO_2 eq, and the highest value was found for 2008 (Fig. 4). The annual variability of the remaining impact categories can be consulted in the ESM. The GWP variation between months was even higher (Fig. 5). In 2011, it varied between 0.23 in the first quarter; and 0.67 kg CO_2 eq in the third quarter of the year. The months with the highest GWP were the months when

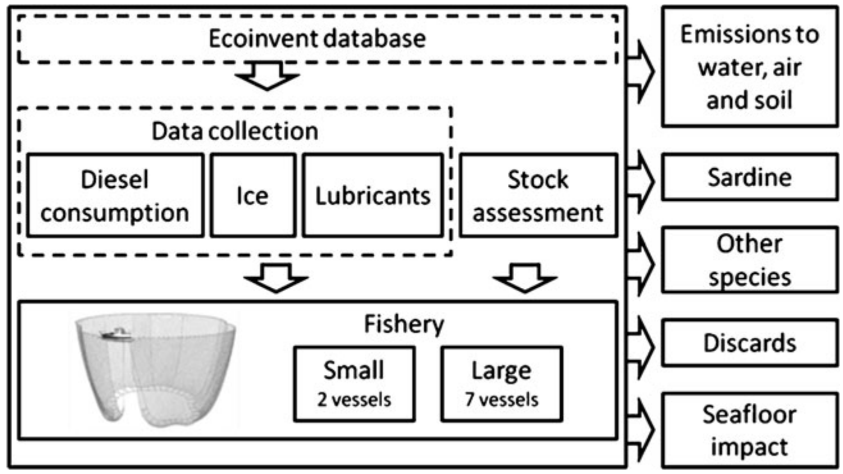


Fig. 1 System under study for sardine (purse seine figure adapted from www.seafoodscotland.org). The sample data for diesel, ice, lubricants, and stock assessment were assessed for different years, from 2005 until 2011

sardine had the lowest economic value per weight. When we analyse the economic value of sardine during 2011, the third quarter of the year had almost half of the value comparing to the first months, 1.9 and 1.0 EUR/kg, respectively.

The sensitivity analyses demonstrate low contribution of gear data for the overall assessment. The highest contribution in percentage was for the EP, representing 4.5 % of the impact category (Fig. 6).

3.3 Fishery-specific environmental impacts

Landings from sardine Atlanto-Iberian stock are considered by ICES, but no specific management objectives are given and there is no total allowable catch set for this stock. So ICES gives advice and regarding that, fishing mortality has increased between 2006 and 2011. The spawning stock biomass of sardine, based on the biomass of age 1 and older, decreased over the same period (Fig. 7).

The results of the three impact categories included concerning overfishing of the target species (LPY, OF, and OB). The LPY obtained was highest for 2010 (LPY=0.12 kg/kg; OF=0.78; OB=0.62). Gutiérrez et al. (2012) also concluded that the stock was in a poor condition, below the limit of reference point for 2010, and recruitment to the population could be impaired. Biomass was low and the exploitation rate was high (B/B_{MSY}=0.32 and F/F_{MSY}=1.37). The GHG emissions were highest for 2008, and no correlation between GWP and stock data was found for this stock (Fig. 8).

Table 1 Inventory for fish landed in Portugal by purse seiners

Inputs	Unit	Overall	Large	Small
Diesel	l	0.11 (0.03)	0.11 (0.03)	0.10 (0.03)
Ice	kg	0.12 (0.05)	0.13 (0.03)	0.07 (0.06)
Marine lubricant oil	l	0.005 (0.01)	0.001 (0.001)	0.019 (0.016)
Outputs				
Sardine	kg	0.90 (0.89)	0.91 (0.85)	0.77 (0.68)
Other species	kg	0.10 (0.11)	0.09 (0.15)	0.23 (0.32)
CO_2	kg	0.364	0.352	0.365
SO_2	g	0.526	0.513	0.512
NO_x	kg	0.003	0.003	0.003

Values per FU= 1 kg of sardines (standard deviation) of fish landed for the overall fleet and for different vessel size categories

Purse seine fisheries can be considered to have zero discard rate because they have not been reported (Vázquez-Rowe et al. 2010). Kelleher (2008) reports an average discard rate for purse seine of 1.6 % (almost negligible comparing with other fisheries), while Vázquez-Rowe et al. (2012b) reported a discard rate of 3.2 %. However, discard rates can be much higher if slipping is considered as discard. There is also fish mortality resulting from slipping, but it is based on estimates since it relies on visual evaluation (Stratoudakis and Marçalo 2002; Vázquez-Rowe et al. 2012b). Borges et al. (2001) reported a mean discard rate for purse seiners in the south coast of Portugal from 20 to 30 % of the total catch. Stratoudakis and Marçalo (2002) included the slipping and estimated an even higher discard rate in sardine fishery—that some two thirds of the total catch was slipped, leading to unaccounted mortality. Based on these literature data, we assumed that per each 1 kg of sardine landed; 0.2 to 0.7 kg

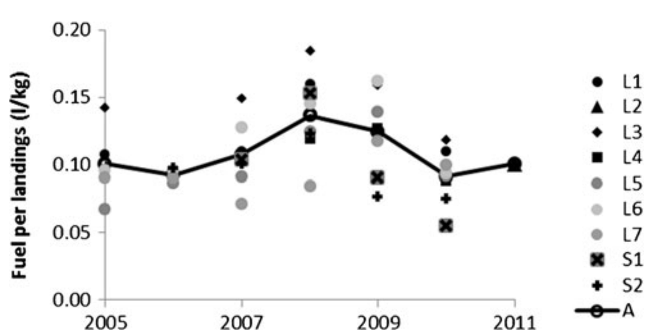


Fig. 2 Fuel per landings of each vessel in the different years assessed (*L* large, *S* small, and *A* overall average)

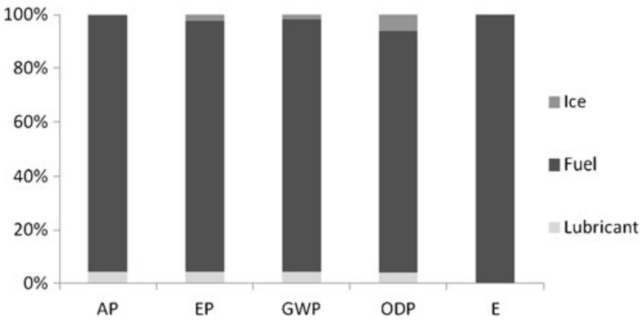


Fig. 3 Relative results of impact assessment of the process contribution (fuel, lubricant, and ice) for each impact category for the overall purse seine fishery: acidification potential (*AP*), eutrophication potential (*EP*), global warming potential (*GWP*), ozone depletion potential (*ODP*), and energy use (*E*)

of fish is discarded. The discards primarily consist in non-target small pelagics with chub mackerel being the species most often slipped and discarded (Wise et al. 2005; Kelleher 2008). Catches of pelagic crab (*Polybius henslowi*) are also discarded, but their survival rate is probably high (ICES 2012). Portuguese purse-seining appears not to be a threat to marine mammals; however, there was reported an annual by catch for this fishery of about 528 dolphins with 157 mortalities (Wise et al. 2007; Hough et al. 2010).

The seafloor impact was considered to be negligible. Purse seines are not in contact with the seafloor under normal operation and therefore do not cause any damage (Ramos et al. 2011). However, the smaller vessels have modified gears for the capture of demersal species usually with higher commercial value, such as sea breams (e.g. *Diplodus* spp.) and European sea bass (*Dicentrarchus labrax*) (Gonçalves et al. 2008). These fleets can have seafloor contact and thereby some damage, but it is not related to the sardine fishery, and it was not considered as an end result.

Regarding the others fishery categories assessed, the primary production required (PPR) per landings was highest in 2005. It was due to the high proportion of horse mackerel landed in that year, which has a higher trophic level than sardine. In the three following years, the PPR was lowest and ranged between 14 and 16 kg C/kg fish landed. The

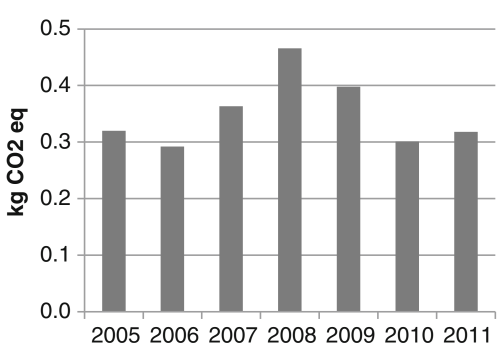


Fig. 4 Global warming potential (GWP) average to land 1 kg of sardine for 2005 until 2011

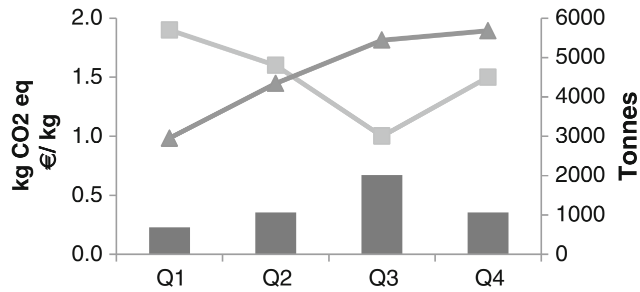


Fig. 5 Global warming potential (GWP) average to land 1 kg of sardine for a quarter over 1 year on a large purse seiner (*columns*), average landing value (*grey line*), and total landings for the overall fleet (*dark grey line*) during the same period (INE 2012)

MTL of the landings is 3.1, and it does not vary for the years assessed (Fig. 9).

4 Discussion

4.1 Environmental impact and variables

Fuel was the input with the largest contribution to the environmental impact of sardine fishing. We did not find differences regarding fuel use between different size categories. The different vessel sizes were roughly equally using as an average of fuel 0.11 l/kg of sardine landed and had about the same level of environmental impacts regarding the impact categories analysed. Smaller vessels were not more efficient in what relates to fuel consumption, even though they have a small scale production, and had somewhat higher discards and by-catch rates due to their more diverse targeting pattern.

To some extent, it is possible to compare the fishery performance based on liters of fuel consumed per landings. We may conclude that the sardine Portuguese purse seine fishery has a low fuel use as Ramos et al. (2011) has shown for purse seine fishery in Basque Country (average value of 0.03 l/kg).

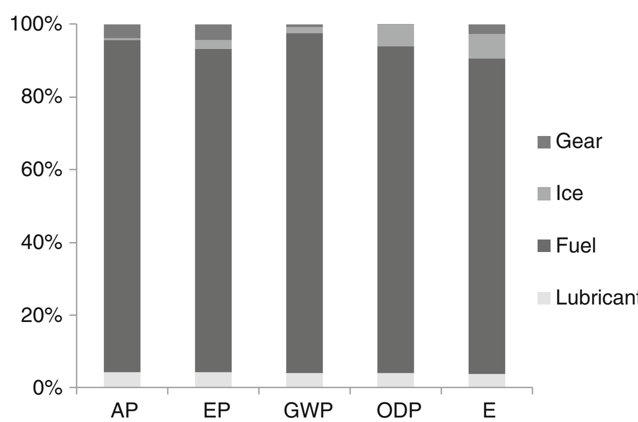


Fig. 6 Sensitivity analyses for gear data of relative results of impact assessment for each impact category for the overall purse seine fishery: acidification potential (*AP*), eutrophication potential (*EP*), global warming potential (*GWP*), ozone depletion potential (*ODP*), and energy use (*E*)

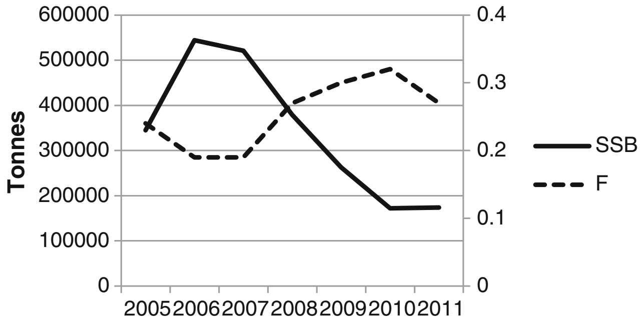


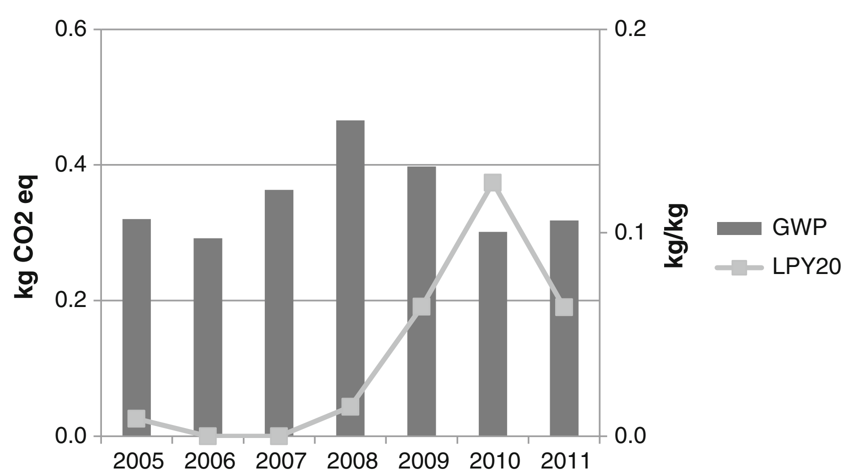
Fig. 7 Spawning stock biomass (SSB) (age 1 and older) (*left axis*) and recruitment (F) (*right axis*) for the assessed fishing years for the Atlantic Iberian sardine stock (from ICES 2012)

It is especially low when compared with other high-value commercial fisheries. Those are usually of larger and higher trophic level species, as for example cod, which can have a fuel use between 0.29 (Svanes et al. 2011) and 1.0 l/kg (Ziegler and Hansson 2003). The result obtained here is in the same range as other purse seine fisheries of small pelagic stocks. For example, the South American pilchard has a fuel use of 0.11 l/kg (Parker and Tyedmers 2012) and the Atlantic herring of 0.14 l/kg (Ziegler and Hansson 2003).

When the results are compared with JRC data for the Portuguese purse seine fishing fleet, the overall fuel use was around the same. In this study, we obtained for the overall fleet, in 2008, 2009, and 2010, a fuel use of 0.14; 0.12; and 0.09 l/kg, and in JRC data of 0.11; 0.12; and 0.13 l/kg for the same years assessed (Anderson and Guillen 2010, Anderson et al. 2011, 2012). Although there are differences in the fishery between ports and Portuguese regions (Stratoudakis and Marçalo 2002), we may conclude that the data collected seem to be representative of the Portuguese purse seine fleet. Our result that the fuel use does not vary with vessel size categories is also consistent with JRC data: smaller vessels are not more (and not less) energy efficient than larger ones. While we use the JRC data on energy use to verify our own results, one could also see this study as verification of the JRC data collection and up scaling methodology from a sample of vessels to cover a whole fleet. It also demonstrates that JRC data could be useful to use in analyses of this and similar fisheries, when there is not sufficient time to collect specific data. When we analyse other types of information, as employment or economic yield in the JRC data set, there are differences between small and large vessels: large vessels employed fewer fishermen and have lower revenue per landings (see Table 2). In contrast to other findings (e.g. Jacquet and Pauly 2008), in this fleet small scale does not seem to be more sustainable from the environmental point of view than large scale. Passive fishing methods (gillnet, lining and creel) have been shown to be more resource-efficient than active fishing methods like trawling (e.g. Ziegler and Hansson 2003; Iribarren et al. 2010). Boats fishing with passive gears are often smaller than those fishing with active gears and the widespread view that small-scale fisheries are more sustainable probably stems from this fact. Purse seines are considered as semi-active gear type and are difficult to fit in on this scale.

The fuel use varies between years, and the highest value was found for 2008. In the same year, landings were also highest, and the result might be related with the fact that in order to catch more fish (due to market demand) vessels were less efficient in their operations. Despite not being significant because we only had data for one vessel from 1 year, the variation within a year was larger than between years. The months with the highest fuel use were the months with lowest sardine market value and the highest landings. In these spring and summer months, it is a cultural habit to eat grilled sardines in Portugal, being the traditional dish in festivities. The rise on the demand decreases the value per weight as a consequence of the increased production and effort, resulting in a less efficient fishery. Even though these results should be interpreted with caution, they reinforce the need for a timeline analysis in different stocks and the timeframe expansion, perhaps even on a finer scale than years (Vázquez-Rowe et al. 2012a). Fisheries with different characteristics may vary

Fig. 8 Relative results of emissions of global warming potential (GWP) and lost potential yield (LPY) calculated for 20 years time perspective



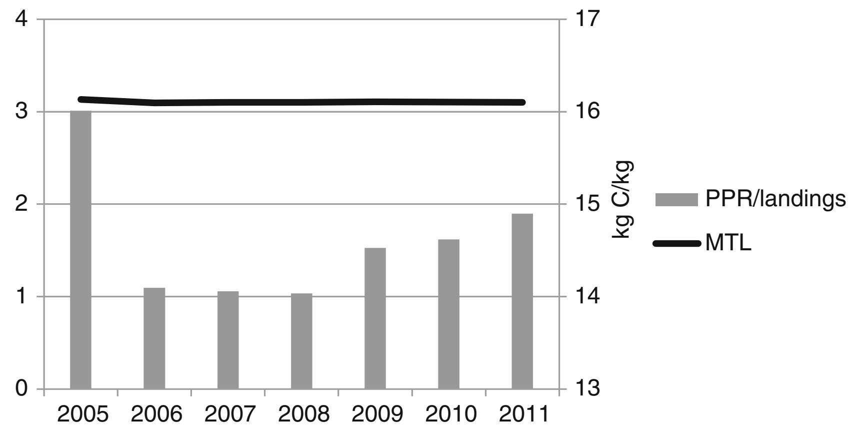


Fig. 9 Mean trophic level (*MTL*; *left axis*) and primary production required (*PPR*; *right axis*) per landings for the assessed years

on other time scales (e.g. Ramos et al. 2011), even between months and seasons, as we have seen in this study.

4.2 Fishery-specific impact categories for sardine

In recent years, the stock has decreased as a result of increased fishing mortality and low recruitment. Ecosystem-driven reasons, and some uncertainty regarding to the extent of sardine movement and surveys for the stock management, can justify the condition (ICES 2012). The biomass and exploitation rate relative to MSY reference points were higher than targeted values (Gutiérrez et al. 2012). The LPY, that reflects the difference between the long-term yield at current stock status and at more optimal levels, was highest for 2010. For each kilo of sardine landed in 2010, 0.12 kg of potential yield was lost due to over-exploitation. Nevertheless, it is a low LPY and when ranked with other stocks assessed by ICES, the sardine stock ranks as a median value compared with other species, as for example cod (Emanuelsson et al., in review). Values for 2011 demonstrate a slight recovery of the stock. More recently, the suspension of the MSC certification in 2012, and the consequent management program during that year, seemed to allow the stock recovery. Values of OF for 2012 were inferior to OF in 2010 (0.61 and 0.78, respectively), and in 2013, the certification was lifted (MSC 2013). It seems that a management plan can protect the stock in periods of poor recruitment, allowing a sustainable yield and also to avoid unnecessary fluctuation in the catches (ICES 2012).

The stock assessment data showed a poor relationship with GWP. We have not found evidence that the environmental performance of this pelagic species fishery is influenced by the availability of fish in a given time of period as did Ramos et al. (2011). Also, Emanuelsson et al. (in review) demonstrated for other pelagic species, that the stock–fuel relationship, that has been suggested especially for demersal species (e.g. Thrane 2006; Ziegler and Hansson 2003), is not a reliable two-way mechanism. Improved status will lead to a better environmental performance but better environmental performance does not necessarily indicate a better stock status. Due to the schooling nature of pelagic species, the "stock effect" is expected to be less pronounced as more time can be spent searching for the fish or in other words fishing effort-fuel use and catches are less closely correlated in pelagic fisheries. Many other factors in addition to fish abundance contribute to the environmental performance of the fishery, perhaps most importantly by fisheries management, through quota setting and distribution, but also the economic value of the fish. With a lower value, it can be worth staying out a little longer or go out more often, as was indicated by the monthly data in this study.

The Portuguese purse seine fishery had a low MTL of 3.1, and it does not vary through time as in Basque purse seine with a MTL range between 3.0 and 3.6 (Ramos et al. 2011). It only reflects the fleets perform, but it means less marine food web depletion and lower impact of the fishery on the ecosystem (Pauly et al. 1998). However, findings had alerted that fisheries are also depleting species from low trophic levels (Pinsky et al. 2011). A temporary collapse of the sardine stock could have impacts by reducing food supply for other marine animals and exert bottom-up control for predators or top-down control on prey species (ICES 2012). Even though

Table 2 Data from JRC for purse seine fishery in Portugal

Size	2008	2009	2010
Fuel per landings (l/kg)			
Small	0.09	0.13	0.15
Large	0.11	0.12	0.13
Overall	0.11	0.12	0.13
Labour per landings (crew/tonnes)			
Small	9	9	11
Large	53	41	42
Overall	39	23	28
Value per landings (m EUR/tonnes)			
Small	940	934	1,084
Large	1,591	1,421	6,928
Overall	1,517	1,019	1,373

Data for different years aggregated by size: small (0–12 m), large (12–40 m), and overall (0–40 m) (Anderson and Guillen 2010; Anderson et al. 2011, 2012) sardine is more sustainable when compared with other species from the marine food web, care should be taken in case of very high exploitation yields.

Other fishery impact categories such as by-catch and discards were described and had a high rate, especially when compared to other pelagic fisheries. Highly variable and sporadic discarding behaviours exist if slipping is considered as a discard practise (Wise et al. 2005). Based on published data, we assumed that per kilo of sardine landed, 0.2 to 0.7 kg of fish were discarded. Since these data are sparse and very variable, a monitoring program for discards in this fishery would be useful to resolve the uncertainty. Even being difficult to quantify, the fishery-specific impact categories add valuable information for certification schemes and to a complete environmental assessment of the fishery (Emanuelsson et al., in review). If we had only included traditional LCA impact categories, the fishery would have a good environmental assessment, but the inclusion of stock information and biological impacts shows that there are problems with the sustainability of the stock that need to be taken into account.

4.3 Carbon footprint of sardine

The *S. pilchardus* carbon footprint from Portuguese purse seiners (0.36 kg CO_2 eq/kg) was almost half when compared with other purse seine fisheries, as for example purse seine fishery in Galicia (0.78 kg CO_2 eq/kg) (Iribarren et al. 2011) or horse mackerel purse seine (0.80 kg CO_2 eq/kg) (Vázquez-Rowe et al. 2010). Only purse seine fishery in Basque Country has lower carbon foot print (between 0.04 and 0.09 kg CO_2 eq/kg) (Ramos et al. 2011). Those fisheries included more inputs in the inventory such as cooling agents, not used in purse seine in Portugal, which represented 5 % of the total GWP (Vázquez-Rowe et al. 2010). They also included net production, an important contributor in Ramos et al. (2011) that represents 9 % of the GWP in Vázquez-Rowe et al. (2010), excluded from this study since it was considered a capital good with a long life span. Anyway, if we had done the same assumption as Tyedmers et al. (2007), that energy inputs to provide boats and gear would amount to 10 % of the direct fuel energy, the purse seine would still have been very efficient compared to the other fisheries. Their study, about the European pilchard fishery in UK, that operates with a similar gear and set the fish aboard into large tanks of refrigerated seawater (RSW tanks) and ice, gave a similar carbon footprint (0.25 kg CO_2 eq./kg) (Tyedmers et al. 2007). From these comparisons, we may realize that even the same fishing gear can have highly heterogeneous energy use and related emissions of fisheries.

Small pelagic fish species as sardine represent the largest catches and are the major group of species fished for non-food use globally (Tacon and Metian 2009). Given the relatively low environmental impact of this fishery increasing the amount of fish used for direct consumption should be a top priority (Jacquet et al. 2010). As other purse seine fisheries (Ramos et al. 2011), when compared to fisheries for other species (Ziegler et al. 2013), and even land-based animal production (Nijdam et al. 2012), sardine came out as one of the most energy-efficient types of animal protein available. If fisheries management takes into account stock information to sustainably exploited levels, Portuguese sardine will not only provide a healthy and highly valued traditional meal but also a sustainable source of food.

5 Conclusions

Large differences in environmental performance in the purse seine fishery were found between years, with indications that variability could be even larger between months within a year. The LCA results were driven by fuel production and combustion and all typical LCA impact categories closely followed GWP. No difference was found in fuel use between large and small vessels, and stock condition and energy efficiency were not directly correlated. Biological impact categories are an important complement to LCA to provide a more complete picture of the environmental impact of a fishery, without them the results of this study had been misleading. The carbon footprint of sardines landed in the studied purse seine fishery is low when compared to other fisheries, and a long-term management plan is needed to achieve a sustainable fishery.

Acknowledgments Cheila Almeida wishes to thank FCT for the financial support (SFRH/BD/60187/2009). Furthermore, the authors would like to thank the anonymous fishermen and organizations officers who kindly agreed to answer the questionnaires and give data (DGPA, PROPEIXE, APROPESCA, APARA, ANOPCERCO); people related with sardine research for the information gathered in reports or as personal communication (Vanja Karadzic. Sandra Farinha. Laura Wise. Ana Marcalo. Alexandra Silva); and Sara Hornborg and Andreas Emanuelsson for the contribution with fruitful discussions and endless inputs.

References

Anderson J, Guillen J (2010) Scientific. Technical and Economic Committee for Fisheries. The 2010 Annual Economic Report on the EU fishing fleet. Joint Research Centre Scientific and Technical Reports doi:10.2788/29916

Anderson J, Guillen J, Virtanen J (2011) Scientific. Technical and Economic Committee for Fisheries. The 2011 Annual Economic Report on the EU fishing fleet (STECF-11-16). Joint Research Centre Scientific and Technical Reports doi:10.2788/18022

Anderson J, Carvalho N, Contini F, Virtanen J (2012) Scientific. Technical and Economic Committee for Fisheries. The 2012 Annual Economic Report on the EU fishing fleet (STECF-12-10). Joint Research Centre Scientific and Technical Reports doi:10.2788/40549

Baumann H, Tillman A (2004) A hitch-hikers guide to life cycle assessment. Studentlitteratur, Sweden

Borges T, Erzini K, Bentes L, Costa ME, Gonçalves JMS, Lino PG, Pais C, Ribeiro J (2001) By-catch and discarding practices in five Algarve (southern Portugal) métiers. J Appl Ichthyol 17(3): 104–114

Carrera P, Porteiro C (2003) Stock dynamic of the Iberian sardine (*Sardina pilchardus*. W.) and its implication on the fishery off Galicia (NW Spain). Sci Mar 67(S1):245–258

Ernest, Young (2009) Analyse de l'approvisionnement et de la commercialisation des produits de la pêche et de l'aquaculture dans l'Union Européenne. Tome 3 – Études de cas filières. European Commission. Directorate General for Maritime Affairs and Fisheries

Emanuelsson A, Ziegler F, Pihl L, Sköld M, Sonesson U (2013) Overfishing. Accounting for overfishing in life cycle assessment: new impact categories for biotic resource use. Int J Life Cycle Assess (in review)

Fishery Management Group (2012) Sardine fishery management plan—(2012–2015), Direcção Geral de Recursos Naturais, Segurança e Serviços Marítimos

Frischknecht R, Jungbluth N, Althaus HJ, 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. Duebendorf, Switzerland

Froese R, Pauly D (2012) FishBase. World Wide Web electronic publication. www.fishbase.org version. Accessed September 2012

Gonçalves J, Bentes L, Monteiro P, Coelho R, Corado M, Erzini K (2008) Reducing discards in a demersal purse-seine fishery. Aquat Living Resour 21:135–144

Guinée J, Gorrée M, Heijungs R, Huppes G, Kleijn R, de Koning A, van Oers L, Wegener A, Suh S, Udo de Haes HA (2001) Life cycle assessment—an operational guide to the ISO standards. Centre of Environmental Science, Leiden

Gutiérrez NL, Valencia SR, Trevor AB, Agnew DJ, Baum JK, Bianchi PL, Cornejo-Donoso J, Costello C, Defeo O, Essington TE, Hilborn R, Hoggarth DD, Larsen AE, Ninnes C, Sainsbury K, Selden RL, Sistla S, Smith ADM, Stern-Pirlot A, Teck SJ, Thorson JT, Williams NE (2012) Eco-label conveys reliable information on fish stock health to seafood consumers. PLoS ONE 7(8):e43765

Hornborg S, Belgrano A, Bartolino V, Valentinsson D, Ziegler F (2013) Trophic indicators in fisheries: a call for re-evaluation. Biol Lett 9(1)

Hough A, Nichols J, Scott I, Vingada J (2010) Portuguese sardine purse seine fishery. Public Certification Report. Moody Marine

ICES (2012) ICES Advice 2012. Sardine in divisions VIIIc and IXa. Book 7

INE (2011) Estatísticas da pesca 2010. Lisboa, 2011: Instituto Nacional de Estatística

INE (2012) Boletim Mensal da Agricultura e Pescas. Instituto Nacioanl de Estatística. ISSN-1647-1040

Iribarren D, Vázquez-Rowe I, Hospido A, Moreira MT, Feijoo G (2010) Estimation of the carbon footprint of the Galician fishing activity (NW Spain). Sci Total Environ 408(22):5284–5294

Iribarren D, Vázquez-Rowe I, Hospido A, Moreira MT, Feijoo G (2011) Updating the carbon footprint of the Galician fishing activity (NW Spain). Sci Total Environ 409(8):1609–1611

Jacquet J, Pauly D (2008) Funding priorities: big barriers to small–scale fisheries. Conserv Biol 22(4):832–835

Jacquet J, Hocevar J, Lai S, Majluf P, Pelletier N, Pitcher T, Sala E, Sumaila R, Pauly D (2010) Conserving wild fish in a sea of market-based efforts. Oryx 44(01):45–56

Kelleher K (2008) Discards in the world's marine fisheries. An update. FAO Fisheries Technical Paper No.470

MSC (2013) Portuguese sardine fishery MSC certificate reinstated. http://www.msc.org/newsroom/news/portuguese-sardine-fishery-MSC-certificate-reinstated. Accessed April 2013

Nijdam D, Rood T, Westhoek H (2012) The price of protein: review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes. Food Policy 37(6):760–770

Nilsson P, Ziegler F (2007) Spatial distribution of fishing effort in relation to seafloor habitats in the Kattegat, a GIS analysis. Aquat Conserv 17(4):421–440

Parker R, Tyedmers P (2012) Life cycle environmental impacts of three products derived from wild-caught Antarctic Krill (*Euphausia superba*). Environ Sci Technol 46(9):4958

Pauly D, Christensen V (1995) Primary production required to sustain global fisheries. Nature 374(6519):255–257

Pauly D, Christensen V, Dalsgaard J, Froese R, Torres J (1998) Fishing down marine food webs. Science 279(5352):860–863

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

Pinsky M, Jensen OP, Ricard D, Palumbi S (2011) Unexpected patterns of fisheries collapse in the world's oceans. Proc Natl Acad Sci U S A 108(20):8317–8322

Ramos S, Vázquez-Rowe I, Artetxe I, Moreira MT, Feijoo G, Zufía J (2011) Environmental assessment of the Atlantic mackerel (*Scomber scombrus*) season in the Basque Country. Increasing the timeline delimitation in fishery LCA studies. Int J Life Cycle Assess 16(7):599–610

Silva A, Skagen D, Uriarte A, Massé J, Santos MB, Marques V, Carrera P, Beillois P, Pestana G, Porteiro C, Stratoudakis Y (2009) Geographic variability of sardine dynamics in the Iberian Biscay region. ICES J Mar Sci 66(3):495–508

SimaPro7 software (2007) PRé Consultants www.pre.nl

Stratoudakis Y, Marçalo A (2002) Sardine slipping during purse-seining off northern Portugal. ICES J Mar Sci 59:1256–1262

Svanes E, Vold M, Hanssen O (2011) Effect of different allocation methods on LCA results of products from wild-caught fish and on the use of such results. Int J Life Cycle Ass 16(6):512–521

Tacon A, Metian M (2009) Fishing for aquaculture: non-food use of small pelagic forage fish—a global perspective. Rev Fish Sci 17(3):305–317

Thrane M (2006) LCA of Danish fish products. New methods and insights. Int J Life Cycle Assess 11(1):66–74

Tyedmers P, Pelletier N, Garrett A (2007) CO2 emissions case studies in selected seafood product chains. Briefing paper. Dalhousie University and S. Anton Seafish

Vázquez-Rowe I, Moreira M, Feijoo G (2010) Life cycle assessment of horse mackerel fisheries in Galicia (NW Spain): comparative analysis of two major fishing methods. Fish Res 106(3):517–527

Vázquez-Rowe I, Hospido A, Moreira M, Feijoo G (2012a) Review: Best practices in life cycle assessment implementation in fisheries. Improving and broadening environmental assessment for seafood production systems. Trends Food Sci Tech 28:116–131

Vázquez-Rowe I, Moreira M, Feijoo G (2012b) Inclusion of discard assessment indicators in fisheries life cycle assessment studies. Expanding the use of fishery-specific impact categories. Int J Life Cycle Assess 17(5):535–549

Wise L, Ferreira M, Silva A (2005) Caracterização da Pesca de Cerco na Costa Oeste Portuguesa. Relatórios Científicos e Técnicos IPIMAR 24

Wise L, Silva A, Ferreira M, Silva M, Sequeira M (2007) Interactions between small cetaceans and the purse seine fishery. Sci Mar (Barc) 71(2):405–412

www.seafoodscotland.org (2011) Accessed August 2011

Ziegler F, Hansson P-A (2003) Emissions from fuel combustion in Swedish cod fishery. J Clean Prod 11(3):303–314

Ziegler F, Winther U, Hognes E, Emanuelsson A, Sund V, Ellingsen H (2013) The carbon footprint of Norwegian seafood products on the global seafood market. J Ind Ecol 17(1):103–116