Life Cycle Assessment of European anchovy (*Engraulis encrasicolus*) landed by purse seine vessels in northern Spain

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Abstract

Purpose The main purpose of this article is to assess the environmental impacts associated with the fishing operations related to European anchovy fishing in Cantabria (Northern Spain) under a life cycle approach.

Methods The Life Cycle Assessment (LCA) methodology was applied for this case study including construction, maintenance, use and end of life of the vessels. The functional unit used was 1 kg of landed round anchovy at port. Inventory data were collected for the main inputs and outputs of 32 vessels, representing a majority of vessels in the fleet.

Results and discussion Results indicated, in a similar line to what is reported in the literature, that the production, transportation and use of diesel were the main environmental hotspots in conventional impact categories. Moreover, in this case, the production and transportation of seine nets was also relevant. Impacts linked to greenhouse gas (GHG) emissions suggest that emissions were in the upper range for fishing species captured with seine nets and the value of Global Warming Potential (GWP) was 1.44 kg CO_2 eq per functional unit. The eco-toxicity impacts were mainly due to the emissions of anti-fouling substances to the ocean. Regarding fishery-specific categories, many were discarded given the lack of detailed stock assessments for this fishery. Hence, only the Biotic Resource Use category was computed, demonstrating that the ecosystems' effort to sustain the fishery is relatively low.

Conclusions The use of the LCA methodology allowed identifying the main environmental hotspots of the purse seining fleet targeting European anchovy in Cantabria. Individualized results per port or per vessel suggested that there are significant differences in GHG emissions between groups. In addition, fuel use is high when compared to similar fisheries. Therefore, research needs to be undertaken to identify why fuel use is so high, particularly if it is related to biomass and fisheries management or if skipper decisions could play a role.

Keywords: *Engraulis encrasicolus*; fuel efficiency; industrial ecology; Life Cycle Assessment; pelagic fisheries; purse seining

1. Introduction

Seafood is increasingly recognized as playing an important role in terms of food supply and security worldwide. In fact, the food versus feed debate is also highly related to capture fisheries given the dilemma of destining dwindling landings to direct or indirect human consumption (Fréon et al. 2014c). The beneficial effect of fish consumption on human health has been related to the high content of n-3 fatty acids, and it has been a recurring policy strategy to foster direct human consumption (Zlatanos and Laskaridis 2007). In this context, according to Zlatanos and Sagredos (1993), anchovy species are among the best sources of n-3 fatty acids.

European anchovy (*Engraulis encrasicolus*, Linnaeus, 1758) is a pelagic species belonging to the Engraulidae family. It is distributed along the Atlantic continental shelves of Europe and Africa, into the Mediterranean, Adriatic and Aegean seas and further into the Black Sea. It is a short-lived species, with individuals generally living between 3 and 5 years. Hence, population levels depend strongly on the incoming year-class strength, which is highly variable and largely dependent on environmental factors (Fréon et al. 2005).

Two different fleets fish for European anchovy in the Bay of Biscay, although they are spatially and temporally well separated. On the one hand, Spanish fleets operate mainly in Divisions VIIIc and VIIIb in the spring (Figure 1). On the other hand, French vessels operate in Division VIIIa in summer and autumn and in Division VIIIb in winter and summer (Pontes et al. 2015). Among all the existing fleets that target European anchovy, the purse seining fleet based in the region of Cantabria (Northern Spain) is the main anchovy catching fleet in the Bay of Biscay. In this context, anchovy represents the fifth most consumed seafood species in Spain, and the second most preferred in Cantabrian households (Eurofish 2012).

Figure 1. Geographical boundaries of the International Council for the Exploration of the Sea (ICES) subdivisions IV-VIII (Source: FAO, 2016).

The Spanish European anchovy fishery developed rapidly in the 1950s and began its decline in the early 1970s until the mid-1980s, when the French fishery developed (Villamor and Abaunza 2009). A couple of decades later, at the start of the new millennium, the fishery started to fail due to poor recruitment (Pontes et al. 2015). In fact, the fishery was closed on July 1st 2005 and reopened in 2006, but it was closed again in 2007 until the end of 2009. The fishery has remained open since June 2010 thanks to improved stock performance in the past few years (Pontes et al. 2015).

Cantabria is a small coastal region in the North of Spain where fishing and processing of anchovy is one of the main economic revenues in the food industry representing approximately 2% of Cantabria's Gross Domestic Product (GDP) (Ministry of Agriculture, Food and Environment 2015). Anchovy fishing operations started in the 1900s and reached peak captures in 1965 (82,000 metric tons) to decline dramatically in the 1970s and 80s due to overexploitation (García-Cobo 1998). Figure 2 shows anchovy captures from 2006 to 2015 by Cantabrian purse seining vessels. As shown, anchovy landings in 2006, when the fishery was closed, were very low. However, once the fishery reopened in 2010, the amount of anchovy landed and its economic value fluctuated to reach its highest value in 2015, with almost 6700 metric tons of anchovy landed in Cantabrian ports generating economic revenue of approximately 13 million euros at first sale.

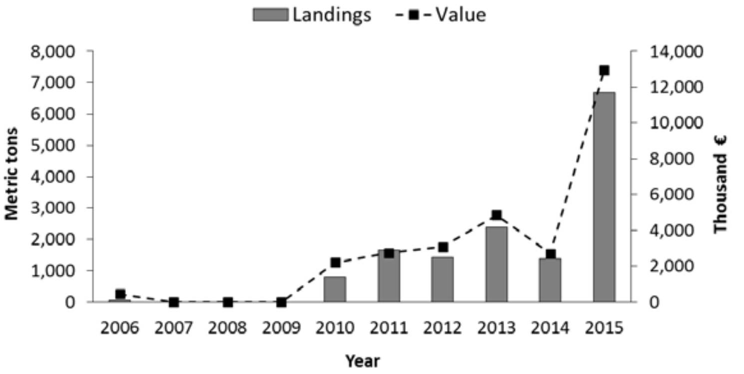

Figure 2. Anchovy landings in Cantabria ports and economic value in the period 2006-2015 (Data adapted from the Cantabrian Institute of Statics (ICANE). Grey bar represents anchovy captures and the dark points the value of these captures in thousands of €.

Approximately half of the anchovy landed in Cantabria is consumed fresh. The remaining 50% goes to factories where 25% is salted and the final 25% is canned (Magrama 2013). In fact, in Cantabria there are approximately 70 anchovy canning companies. In 2012, 13,267[1] metric tons of canned anchovies were produced, which translates into economic revenue that adds up to more than 91 million €. Moreover, the quality of the Cantabrian canned anchovy is world-renowned and it is considered a “gourmet product” by consumers due to its handmade and traditional manufacture (Laso et al. 2016b).

Despite the critical overexploitation of the European anchovy fishery, no environmental assessment of the industrial operations of this fleet exists in the literature. Although the direct link between an overexploited stock and the assessment of other environmental impacts may not be evident to the common public, recent studies have demonstrated that stock rebuilding can have an important role in fuel efficiency, which is usually the main carrier of GHG emissions and other environmental impact in fishing fleets (Ziegler and Hornborg, 2014; Parker et al., 2015). In this context, Life Cycle Assessment (LCA), a standardized framework used to quantify resource use and a broad set of environmental impacts of products through their supply chain (ISO 2006a and 2006b), is considered a consensus method to evaluate this sort of environmental impacts. In fact, the use of LCA as a method to quantify environmental impacts of seafood production systems has emerged rapidly over the 2000-2016 period (Ziegler et al. 2016). A comprehensive LCA of the Cantabrian anchovy fishery would be useful to complement

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[1] It should be noted that the region imports substantial amounts of European anchovy from other Spanish regions, France or Morocco, and other anchovy species from Peru (*Engraulis ringens*) and Argentine (*Engraulis anchoita*) to nourish the canning industry.

the recent studies regarding the processing of canned anchovies, as well as the management of anchovy residues throughout the canning process (Laso et al. 2016a, 2016b), as well as those linked to stock management (Pontes et al. 2015).

Previous fishery LCA studies, including studies of purse seining fisheries in the North Atlantic, have shown that conventional impact categories were heavily associated with fuel combustion in the fishery (Vázquez-Rowe et al. 2010; Ramos et al. 2011; Almeida et al. 2014). Studies for other similar pelagic fisheries elsewhere, such as Peruvian anchoveta, were recently developed by Avadí (2014a, 2014b, 2015) and Fréon (2014a, 2014b, 2014c). Hence, this study aims to evaluate the environmental impacts of the Cantabrian purse seining fishery for European anchovy for one year of operation (i.e., 2015). The LCA methodology was applied to quantify the overall environmental impact of the fishery. Although the study was not extended to other years of operation to assess the effect of stock size on environmental impacts due to lack of historical data, a statistical analysis was computed to analyze the variability of environmental impacts between vessels and ports.

2. Materials and Methods

2.1. Goal and scope definition

The environmental analysis was based on LCA methodology and assumptions, following ISO 14040 specification. Moreover, the sampling of the purse seining vessels fulfilled PAS 2050-2 (PAS 2050-2, 2012) requirements specific to seafood and other aquatic food products.

The goal of this LCA study was to assess the environmental impacts associated with the fishing activity of European anchovy landings by the Cantabrian purse seining fleet. The functional unit (FU) considered was 1 kg of landed round anchovy by Cantabrian purse seining vessels in year 2015, reflecting the function of delivering raw material for further processing in local canning industries.

The system under study comprised the phases of a vessel's life cycle: construction, use, maintenance and end of life (EoL), including hull and engine production, diesel consumption, antifouling and lubricant oil emissions, net and boat paint production and vessel dismantling, as observed in Figure 3. Crew impact was limited to the emissions onboard (solid waste and wastewater), but excluding provision of food and transport (Fréon et al. 2014b). This assessment constituted a so-called cradle-to-gate study for the product (i.e., European anchovy) and a cradle-to-grave study for the main carrier of the fishing operations: the fishing vessels (Guinée et al. 2001). Landing operations at port were excluded from the system boundary (see Figure 3), 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 (Vázquez-Rowe et al. 2012c). Moreover, electronic devices were excluded from the analysis; however, a brief discussion on their environmental impact is included in the discussion section.

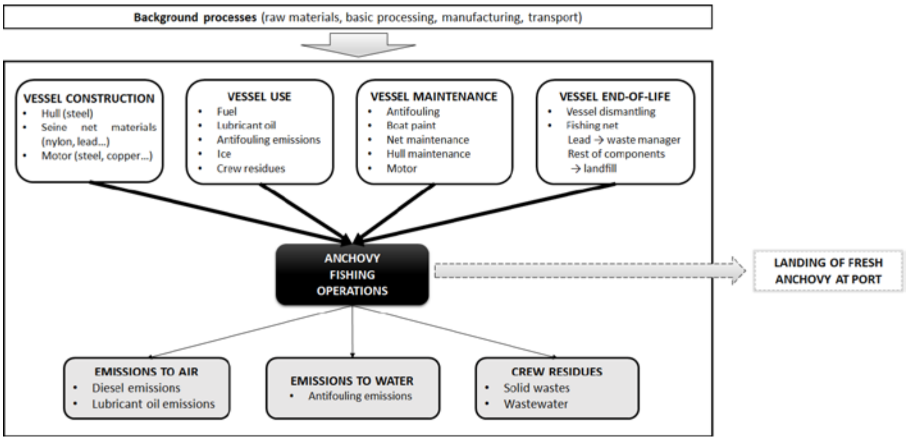

Figure 3. System boundary for the anchovy fishing fleet. Elements with dotted lines were excluded from the boundary.

2.2. Co-product allocation

The Cantabrian purse seining fleet performs its activities in a multispecies fishery. Therefore, direct and indirect inputs and outputs of the fishing operations, as well as the resulting environmental burdens, need to be allocated between European anchovy and the remaining landed by-catch (Ayer et al. 2007). In addition to European anchovy, the Cantabrian fleet catches tuna species (mainly *Thunnus alalunga*), European pilchard (*Sardina pilchardus*), Atlantic mackerel (*Scomber scombrus*) and Atlantic horse mackerel (*Trachurus trachurus*). For this particular study, three types of allocation were evaluated: mass, economic and energy (see Table 1 for details). No major differences between the three types of allocation were observed for the case of European anchovy, representing in all scenarios approximately 45% of total landings of the fleet. However, economic allocation was discarded based on the fact that landing sale prices in Galicia, a neighboring region in northern Spain, were used for the same period to compute this approach due to the lack of regional data (Xunta de Galicia 2016). Although the values could be used as a proxy of the situation in Cantabria, since landings in different Spanish regions tend to be influenced by common economic drivers (i.e., common geographic zone, common wholesales, common economic patterns), we were unable to determine the uncertainty behind this estimation. Similarly, although tuna is a large pelagic species which is usually sold at a much higher price, its landings are concentrated in a very specific window of time towards the end of the summer and beginning of the autumn months. Therefore, it is unlikely that seiners will target tuna species rather than small-pelagics throughout most of the year. Energy is another repeatedly used allocation perspective that has been traditionally applied in seafood LCA studies (Ayer et al. 2007; Pelletier and Tyedmers 2011). In fact, Pelletier and Tyedmers (2011) defend that seafood products are landed and processed based on a need to fulfil the human need for a minimum caloric intake and, therefore, the use of energy allocation constitutes a relationship that is causal from a biophysical and social perspective. However, based on the fact that the system boundaries were limited to the landing of the fish at port in this particular study, mass allocation was chosen as the most appropriate approach context since it is considered to better reflect reality over longer time periods and changing economic conditions and constitutes a clearer perspective to communicate to the stakeholders in this first stage of the supply chain.

Table 1. Mass, economic and energy allocation factors for the anchovy fishing fleet. Landings represent the average value in 2015.

Species	**Landings**		**Mass allocation**	**Value (€/kg)** (1)	**Economic allocation**	**Energy (MJ/kg)** (2)	**Energy allocation**
	Mass (kg)	SD					
European anchovy	196,634	±103,634	43.5%	1.54	44.3%	2.18	45.9%
Tuna (*Thunnus* spp.)	9,938	±42,157	2.2%	4.09	6.0%	2.42	2.6%
European pilchard	110,563	±89,560	24.5%	2.11	34.2%	2.11	24.9%
Atlantic mackerel	51,188	±12,545	11.3%	0.70	5.2%	2.05	11.2%
Atlantic horse mackerel	83,353	±103,240	18.5%	0.84	10.3%	1.72	15.4%

(1) Source: Xunta de Galicia (2015). http://www.pescadegalicia.gal/

(2) Peter Tyedmers, personal communication, September 2011)

2.3. Data acquisition

2.3.1. Primary activity data

Data were collected for year 2015 for a sample of 32 purse seining vessels out of a total of 41 belonging to the Cantabrian fishing fleet. These vessels represented 78% of this fleet, which allowed meeting the requirements recommended in the PAS 2050 document in terms of sample representativeness of vessels in a particular fleet (PAS 2050-2 2012). The percentage represents the number of fishing vessels that provided data for the study. Questionnaires on operational aspects and capital goods of the purse seine vessels were delivered to all skippers of the 41 vessels; therefore, the sample size also represents the response rate obtained. An average lifespan for each vessel of 30 years was considered (SUPERPROP 2012).

Primary data for fishing vessel operations were obtained from questionnaires filled out by skippers from the seven main purse seining ports in Cantabria: Colindres (P1), Santoña (P2), San Vicente de la Barquera (P3), Comillas (P4), Laredo (P5), Santander (P6) and Castro Urdiales (P7) (see Figure 4 for their geographical distribution). Vessel-specific data requested included the overall length, gross tonnage, vessel width, number of engines and their propulsive power, hull material and life span. For each vessel, operational data requested included the type and amount of fuel used, net consumption and dimensions, ice, lubricant oil, anti-fouling and paint, days at sea, crew size and annual catch data.

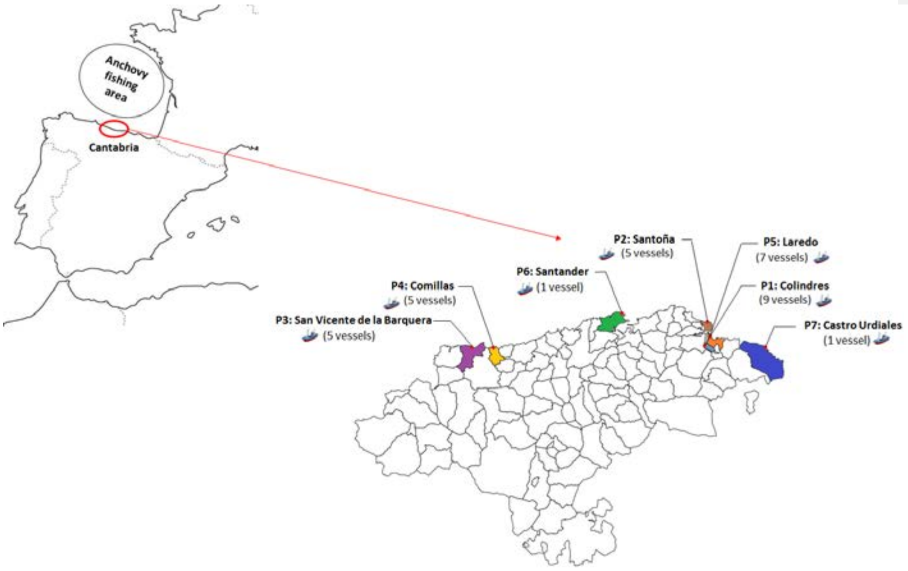

Figure 4. European anchovy fishing zone and Cantabrian ports.

Anti-fouling and paint were considered important in this study for two reasons: they tend to be linked to toxicity impact categories (Hospido and Tyedmers 2005) and skippers reported sending their vessels to the docks for maintenance once per year. The composition of the main paints and anti-fouling agents, as well as the emissions related to their production, was included in the inventory. These data were obtained from a leading world producer.

The production, transport and consumption of the seine nets were included within the system boundary due to the important percentage they represent in the total weight of the fishing vessels (Fréon et al. 2014b). Skippers reported that the production of nylon nets has shifted through the past years from Spain, which currently produces approximately 20% of total nets, to Portugal (20%) and the Philippines (60%). The composition of the nets was made up of nylon (50%), lead (28%), ethylene vinyl acetate (EVA) (20%) and polysteel (2%). These materials were produced in Canada, Valencia (Spain), Korea and Alicante (Spain), respectively, according to data reported by local retailers. Therefore, there has been an increase in transport that will be taken into account in this study as compared to previous studies in the literature (Vázquez-Rowe et al., 2010). Moreover, it was considered that the lifespan of seine nets was roughly 5 years. However, partial repairs are done annually, renewing at least 25% on an annual basis due to net losses at sea (Vázquez-Rowe et al. 2010). Another important operational input, ice, was produced at an ice-making factory. For this, data were obtained from a factory in Colindres, one of the fishing ports in the current study, which produced 2,000 metric tons per year. The factory reported using ammonia as the cooling agent in its operations.

Regarding vessel construction, only those impacts associated with the steel used in vessel hulls and engines were quantified. To estimate the weight of each vessel, the Light Ship Weight (LSW) as described by Freón et al. 2014b was used (Eq 1):

$$\textit{LSW (metric ton)} = -263.81 + 0.57 \bullet \textit{holding capacity} + 43.77 \bullet \textit{width} \qquad \text{(Eq.1)}$$

To apply this correlation, the holding capacity and the width data reported by the interviewed skippers were used. LSW is based on several statistical models that use the holding capacity and physical dimensions of the Peruvian vessels. Fréon and colleagues (2014b) found a high correlation between LSW and the following variables: holding capacity (m^3), gross tonnage (GT) (unitless index), length and height (m). However, collinearity was found between length and height. Moreover, GT was also excluded from the variables due to the high number of missing values. Scatter plots of LSW versus each of the tested variables showed linearity, which justifies the use of a linear model being the best regression equation (adjusted $r^2 = 0.79$) used in this work. It was considered that this correlation was valid for Spanish fleet due to the similarity in terms of holding capacity. Approximately 80% of the LSW value was assumed to correspond to the weight of the hull (steel), while 20% corresponded to the weight of structural elements and other systems that were not considered in this analysis. Moreover, it was assumed that 12% of the hull was replaced every two years for maintenance purposes (Fréon at al. 2014b).

The weight of the main and auxiliary engines was obtained from a leading world producer according to the power data facilitated by skippers (Guascor 2016). The composition modelled for these engines considered 65% cast iron, 34% chrome steel and 1% white metal alloys ($AlCuMg_2$), and they were replaced once over the lifetime of the vessel (Fréon et al. 2014b). It was assumed that 50% of the steel used in vessel hulls and engines was recycled. This assumption was based on data from the European Steel Association (Eurofer), which stated that 50% of the steel in the market was secondary steel (Bala et al. 2015).

2.3.2. *Secondary data*

Background data regarding the production of diesel fuel were obtained from the ecoinvent® v3.1 database (Ecoinvent 2016). The process data for diesel production include oil field exploration, crude oil production, long distance transportation, oil refining, regional distribution, etc. Additional processes where no direct data were available are linked to the production of supply materials, such as materials for vessel construction, seine nets, anti-fouling, paint and lubricant oil agents and electricity. To improve data quality and consider local conditions, the electricity mix provided by the ecoinvent® database was adapted to the characteristics of the Spanish electricity mix of 2013 (Vázquez-Rowe et al. 2015) for those processes occurring in Spanish territory. Finally, processes linked to the management of crew residues and fishing activity wastes, as well as the EoL of the vessel, were also taken from the ecoinvent® database.

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2.3.3. *Un-monitored emissions*

The emissions of carbon dioxide (CO_2) resulting from fuel combustion were calculated on the base of the EMEP-Corinair Emission Inventory Handbook of 2006 (EMEP-Corinair 2006), while remaining emissions, such as nitrogen oxides (NO_x), carbon monoxide (CO) and sulphur oxides (SO_x) were calculated on the base of the revised version of the handbook in 2013 (EMEP/EEA 2013). It is important to point out that, in the current study, CO_2 emissions resulting from the use of lubricant oil were considered and calculated on the base of the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006), as shown in the following equation:

$$\text{CO2 emissions} = LC \cdot CClubricant \cdot ODUlubricant \cdot 44/12 \qquad \text{(Eq. 2)}$$

where LC was the total lubricant consumption (TJ), $CC_{lubricant}$ was the carbon content of lubricants (20 metric tons C/TJ), $ODU_{lubricant}$ was the Oxidised During Use factor (0.2) and 44/12 was the mass ratio of CO_2/C. The loss of paint and anti-fouling to the marine environment was set as two thirds of the total employed, as assumed by Hospido and Tyedmers (2005). Finally, the environmental impacts linked to crew activities were modelled considering the number of crew members. Thereafter, the procedure identified by Fréon et al. 2014, which established that 120 L of wastewater is produced per crew member per working day and 0.2 kg of solid waste is generated per landed metric ton of fish, was followed. Approximately 38% of these solid residues were hazardous waste (mostly rags impregnated with lubricant oil), 26% plastic packaging, 20% other rags, 10% paper and 6% organic matter. In this study, it was considered that the hazardous wastes were deposited underground in a specialized landfill, whereas the non-hazardous wastes were deposited in a municipal landfill. Moreover, according to recycling data from Ecoembes, in Cantabria, 21% of the total plastic and 43% of the total paper was recycled in 2015 (Ecoembes 2015). The remaining residues, together with the organic matter, were assumed to be incinerated (Plan de Residuos de Cantabria, 2016). Finally, it was assumed that wastewater was collected and sent to a municipal wastewater treatment plant (WWTP). Data on the WWTP were obtained from Lorenzo-Toja et al. (2015). The selected plant was the WWTP from Ortigueira (Galicia) assuming that its technical and physical characteristics were similar to Cantabrian WWTPs.

2.4. *Life Cycle Inventory*

According to the questionnaires obtained, the 32 purse seining vessels landed a total of 14,454 metric tons of fresh fish, with European anchovy being the most captured species (6,292 metric tons). The average allocated inventory data are shown in Tables 2 and 3.

Table 2. Inputs for European anchovy landed in Cantabrian ports by purse seiners (data reported per functional unit: 1 kg of landed round anchovy in a Cantabrian port in year 2015).

Inputs (from the technosphere)			
Construction			
Materials and fuels	Unit	Value	SD
Steel (hull)	g	10.56	±3.43
Cast iron (motor)	g	0.336	±0.139
Chrome steel (motor)	g	0.178	±0.075
Aluminium alloy ($AlCuMg_2$) (motor)	g	0.005	±0.002
Nylon (fishing net)	g	5.172	±1.375
Lead (fishing net)	g	5.143	±0.888
Ethylene Vinyl Acetate (EVA) (fishing net)	g	2.128	±0.567
Polysteel (fishing net)	g	0.456	±0.080
Use			
Diesel	kg	0.34	±0.14
Lubricant oil	g	2.227	±0.788
Ice	kg	0.388	±0.225
Maintenance (replenishment, fixtures or replacements)			
Steel (hull)	g	0.633	±0.206

Cast iron (motor)	g	0.011	±0.004
Chrome steel (motor)	g	$5.89 \cdot 10^{-3}$	$\pm 2.21 \cdot 10^{-3}$
Aluminium alloy ($AlCuMg_2$) (motor)	g	$1.77 \cdot 10^{-4}$	$\pm 7.08 \cdot 10^{-5}$
Nylon (fishing net)	g	2.327	±0.620
Lead (fishing net)	g	2.314	±0.255
Ethylene Vinyl Acetate (EVA) (fishing net)	g	0.957	±0.399
Polysteel (fishing net)	g	0.205	±0.035
Anti-fouling	g	1.747	±0.573
Boat paint	g	0.354	±0.117
End of life (includes recycling during maintenance phase)			
Steel (hull and motor)	g	11.38	±3.64
Nylon (fishing net)	g	7.499	±1.993
Ethylene Vinyl Acetate (EVA) (fishing net)	g	3.085	±1.432
Polysteel (fishing net)	g	0.661	±0.923
Lead fishing net	g	7.457	±0.930

Table 3. Outputs for European anchovy landed in Cantabrian ports by purse seiners (data reported per functional unit: 1 kg of landed round anchovy in a Cantabrian port in year 2015).

Outputs (to the technosphere)		
Product	Unit	Value
European anchovy	kg	1
Residues	Unit	Value
Wastewater	m^3	$8.57 \cdot 10^{-4}$
Hazardous wastes	g	72.19
Non-hazardous wastes	g	37.99
Plastic	g	49.39
Paper	g	18.99

Organic matter	g	11.40

Outputs (to the environment)

Emissions to the ocean	Unit	Value
Zinc	mg	281
Copper	mg	462
Ethanol	mg	17.50
Ethyl-benzene	mg	41.20
Xylene	mg	148
4-Methyl-2-pentanone	mg	19.40
Emissions to the atmosphere	Unit	Value
CO_2 (diesel and lubricant oil)	kg	1.093
CO (diesel)	g	2.550
SO_2 (diesel)	g	11.90
SO_x (diesel)	g	6.890
NO_x (diesel)	g	27.70
NMVOC (diesel)	G	1.400

2.5. *Life Cycle Impact Assessment*

The Life Cycle Impact Assessment phase was carried out using a mix of impact categories from different assessment methods. This rationale was followed in order to account for the most relevant conventional impact categories commonly used in LCA studies, following the recommendations provided by the Joint Research Centre of the European Commission (ILCD 2011, Hauschild et al. 2013), but also to account for less conventional marine-related environmental impacts (Ziegler et al. 2016).

In the first place, the IPCC 2013 assessment method, 100-year time horizon, was used to compute the GHG emissions engendered by the analyzed production system (IPCC 2013). The reason for choosing this method is linked to the fact that it considers the most updated characterization factors for GHG emissions as recommended by the Intergovernmental Panel for Climate Change (IPCC 2013). Secondly, the CML-IA baseline method (Guinée et al. 2002) was selected to calculate acidification potential (AP) and eutrophication potential (EP). Thirdly, the ReCIPE midpoint (Goedkoop et al. 2009) was used to calculate impacts related to resource depletion: water depletion (WD), metal depletion (MD) and fossil depletion (FD). Particulate matter formation (PMF) and photochemical oxidant formation (POF) were also calculated using this assessment method. Finally, the USEtox method (Rosenbaum et al. 2008) was selected to calculate human and freshwater toxicity.

Regarding marine-related impact categories, the biotic resource use (BRU) impact category, as implemented by Parker (2011), was also used to monitor the primary production required (PPR) to sustain the European anchovy fishery (Pauly and Christensen 1995). The results were reported in terms of removed carbon. The selected unit to report PPR calculation was mass of carbon per live weight of fish (g C/kg fish, wet weight). The mean trophic level (TL) selected for European anchovy was set at 3.1 ±0.45 (Fishbase 2016; Vázquez-Rowe et al. 2012a).

$$PPR = [Catch/9] \times 10^{(TL-1)} \qquad \text{(Eq. 3)}$$

Lost Potential Yield (LPY), as defined by Emanuelsson et al. 2014, was not applied due to the lack of two important parameters to compute this impact category: maximum sustainable yield (MSY) and fishing mortality (F_{MSY}). However, the reports from ICES state that the limit reference point for spawning stock biomass (B_{lim}) is widely overpassed ever since the fishery was reopened for fishing activities in 2010 (ICES, 2014). Other marine-related impact categories that have been presented in the literature, such as seabed disturbance (Ziegler et al. 2009), the Global Discard Index (Vázquez-Rowe et al. 2012) or other categories used to monitor overexploitation or biomass removal (Langlois et al. 2014, 2015; Woods et al. 2016), were also excluded from the scope of the study. Finally, the indicator *edible protein energy return on investment* (ep-EROI) was also calculated in this study. For the computation of the ep-EROI results, renewable and non-renewable energy used to support the supply chains under examination were taken into consideration using the Cumulative Energy Demand (CED) v2.0 (Vázquez-Rowe et al. 2014a; Tyedmers et al. 2005). SimaPro 8 was the software used for the computational implementation of the inventories (Goedkoop et al. 2016).

2.6. Statistical and sensitivity analysis

A statistical analysis was conducted in order to determine whether there were any significant differences between vessels or groups of vessels in terms of GHG emissions. However, a first limitation that was encountered when conducting the statistical analysis, despite having sampled approximately 78% of the total population of vessels, was the fact that there were not enough purse seiners sampled per port in order to conduct a meaningful statistical test. Moreover, the samples at hand did not correspond to a proper experimental design, since there was no randomization in the analyzed vessels or ports. Nevertheless, the available dataset has been used to provide some insight on the distribution of GHG emissions. For this, an ANOVA test was proposed (equivalent to a T-test in the two-sample situation, in the sense that both test statistics are related), as well as the nonparametric equivalent: the Kruskal-Wallis (KW) test. It should be noted that for the results of the ANOVA test to be conclusive, the samples must meet homogeneity of variances, using the Levene test, and normality, using the Shapiro-Wilk test.

Comentado [J2]: Editor and Reviewer 2 (Comment 1)

To complement the statistical analysis, a sensitivity analysis was also performed. Input parameters required to describe the supply chain of this production process can generate uncertainty due to their reliance on several assumptions. This is the case for LSW, engine weight or the lifespan of vessels and seine nets, among other parameters. Therefore, two of these parameters, vessel lifespan and seine net replacement, were evaluated in order to identify how their variation can affect environmental impact values. For vessels, the average lifespan was modelled for 20 and 40 years, being 30 years the reference value assumed in the main inventory. In the case of seine nets, the 5 year replacement period was complemented with a 2 and 10 year analysis.

3. Results

3.1. Environmental performance of European anchovy fishery in Cantabria

According to the results shown in Table 4, the main stage that was responsible for the greater part of the environmental impacts was the vessel use stage except for MD and human toxicity-cancer (HT_c). More specifically, vessel use dominated the contribution to POF ($3.07 \cdot 10^{-2}$ kg NMVOC eq), PMF ($1.09 \cdot 10^{-2}$ kg PM_{10} eq), AP ($2.79 \cdot 10^{-2}$ kg SO_2 eq), GWP (1.32 kg CO_2 eq), FD ($4.35 \cdot 10^{-1}$ kg oil eq), EU ($3.83 \cdot 10^{-3}$ kg PO_4^{3-} eq), WD ($2.29 \cdot 10^{-3}$ m^3) and freshwater eco-toxicity FEP ($3.48 \cdot 10^{+1}$ CTUe). On the other hand, vessel construction and maintenance were also important contributors MD ($3.51 \cdot 10^{-2}$ and $3.98 \cdot 10^{-2}$ kg Fe eq, respectively). However, their contribution to the other categories was in all cases below 10%. The other subsystem included in the analysis, vessel EoL, presented contributions in all cases below 1%.

Impacts related to human toxicity and freshwater eco-toxicity can also be observed in Table 4. Vessel use accounted for 90% of the environmental impact for FEP, 56% for human toxicity – non-cancer (HT_{nc}) and 23% for HT_c. Vessel construction contributed to HT_c in 57% and to HT_{nc} in 13%, while vessel maintenance contributed 20% to HT_c and 31% to HT_{nc}. Environmental contribution for the different activities can be consulted in Figure S2 in Supporting Material (SM).

Table 4. Environmental impact of fishing 1 kg of European anchovy by purse seiners in Cantabria. GWP: global warming potential; AP: acidification potential; EU: eutrophication; WD: water depletion; -MD: metal depletion; FD: fossil depletion; POF: photochemical ozone formation; PMF: particulate matter formation; HT_c: human toxicity, cancer; HT_{nc}: human toxicity, non-cancer; FEP: freshwater ecotoxicity potential.

	Unit	Vessel Construction	Vessel Maintenance	Vessel Use	Vessel EoL
GWP	kg CO_2 eq	$4.93 \cdot 10^{-2}$	$7.70 \cdot 10^{-2}$	1.32	$5.52 \cdot 10^{-4}$
AP	kg SO_2 eq	$3.02 \cdot 10^{-4}$	$6.76 \cdot 10^{-4}$	$2.79 \cdot 10^{-2}$	$4.27 \cdot 10^{-6}$
EU	kg PO_4^- eq	$1.20 \cdot 10^{-4}$	$2.76 \cdot 10^{-4}$	$3.83 \cdot 10^{-3}$	$4.86 \cdot 10^{-6}$
WD	m^3	$1.06 \cdot 10^{-3}$	$1.93 \cdot 10^{-3}$	$2.29 \cdot 10^{-3}$	$6.81 \cdot 10^{-6}$
MD	kg Fe eq	$3.51 \cdot 10^{-2}$	$3.98 \cdot 10^{-2}$	$1.65 \cdot 10^{-2}$	$4.87 \cdot 10^{-41}$
FD	kg oil eq	$1.47 \cdot 10^{-2}$	$2.70 \cdot 10^{-2}$	$4.35 \cdot 10^{-1}$	$1.56 \cdot 10^{-4}$
POF	kg NMVOC	$1.84 \cdot 10^{-4}$	$3.00 \cdot 10^{-4}$	$3.07 \cdot 10^{-2}$	$2.77 \cdot 10^{-6}$
PMF	kg PM_{10} eq	$1.25 \cdot 10^{-4}$	$1.82 \cdot 10^{-4}$	$1.09 \cdot 10^{-2}$	$1.61 \cdot 10^{-6}$
HT_c	CTU_h	$2.43 \cdot 10^{-8}$	$8.47 \cdot 10^{-9}$	$9.67 \cdot 10^{-9}$	$1.37 \cdot 10^{-10}$
HT_{nc}	CTU_h	$8.08 \cdot 10^{-8}$	$1.92 \cdot 10^{-7}$	$3.43 \cdot 10^{-7}$	$2.36 \cdot 10^{-9}$
FEP	CTU_e	1.14	2.52	$3.48 \cdot 10^{+1}$	$5.89 \cdot 10^{-2}$

As abovementioned, vessel use was the main contributor to most impact categories. However, when looking at the results in more detail (see Figure 5), it appears that most environmental burdens generated were due to fuel consumption for all impact categories, except for WD, MD, HT_{nc} and FEP. For the rest of impact categories, its contribution was in all cases above 88%. Seine net production and transport contributed to 7% in GWP, whereas ice production and antifouling and lubricant oil production and emissions showed contributions below 1%. In WD and MD the production of the seine net had a relevant contribution, 40% and 20% respectively, while the production and use of diesel presented the highest contribution to FD, 89%. The production and emissions of antifouling were relevant to HT_{nc} (55%) and FEP (83%). Production of steel for the construction and maintenance of vessels and motors presented low contributions in all impact categories, except in terms of MD (31%). The management of on board residues presented contributions below 10% in GWP, AP, EU, FD and HT_{nc}, whereas these were higher for WD (11%), MD (13%) and FEP (10%).

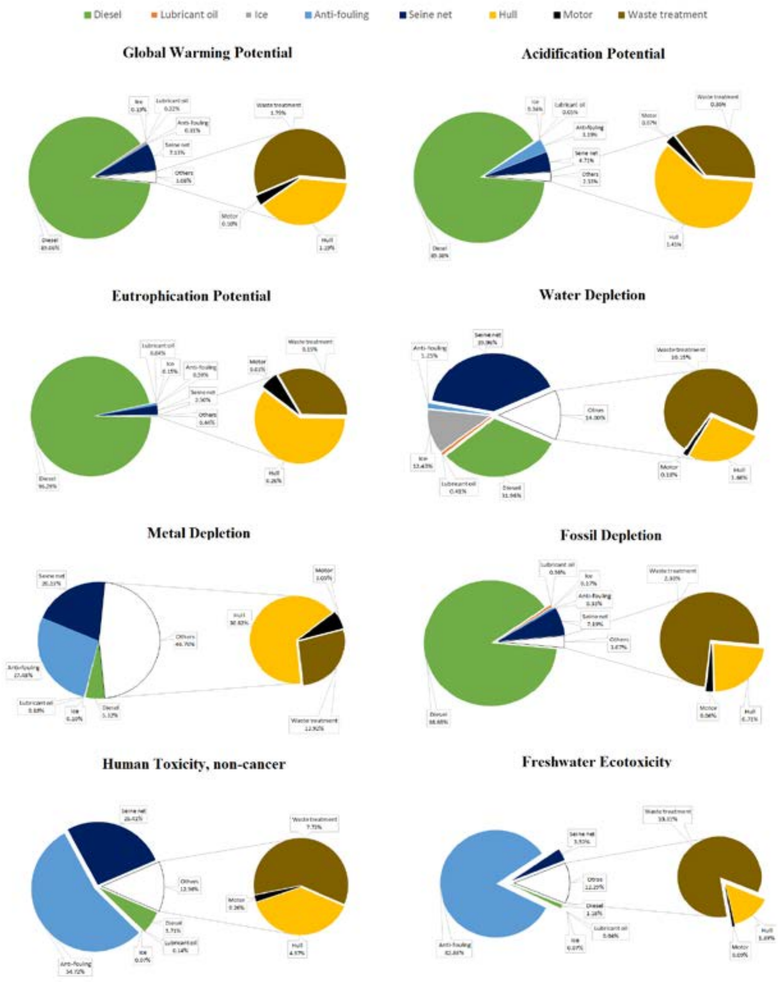

Figure 5. Environmental impact potential for the selected conventional impact categories for the average vessel per functional unit.

Comentado [J3]: Reviewer 2 (Comment 4)

3.2. *Biotic Resource Use (BRU)*

The BRU value obtained for European anchovy was 13.99 g C/kg fish. This value is relatively low, in line with other small-pelagic species in the literature considering that European anchovy does not have a high TL (Parker and Tyedmers 2012). Figure 6 represents the PPR value of European anchovy as compared to the other anchovy species that are used in the canning industry in Cantabria. Data on TL were taken from FishBase (2016):

European anchovy (*Engraulis encrasicolus*) 3.1±0.45; Peruvian anchovy (*Engraulis ringens)* 2.9±0.38; and Argentine anchovy (*Engraulis anchoita)* 2.5±0.00[2]. European anchovy shows a higher PPR value than the other species, which, according to Coll et al. (2006), is based on its feeding patterns, more reliant on mesozooplankton, whereas Peruvian anchoveta, for instance, feeds mainly on phytoplankton. Nevertheless, it should be noted that European anchovy also presents a higher standard error in its PPR values.

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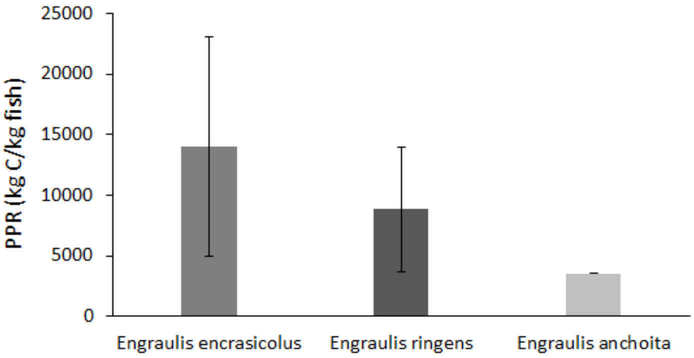

Figure 6. Primary Production Required (PPR) value of the European anchovy (*Engraulis encrasicolus*), Peruvian anchovy (*Engraulis ringens*) and Argentine anchovy (*Engraulis anchoita*). Data on trophic level (TL), including standard error, were taken from FishBase (2016): European anchovy (*Engraulis encrasicolus*) 3.1±0.45; Peruvian anchovy (*Engraulis ringens)* 2.9±0.38; Argentine anchovy (*Engraulis anchoita)* 2.5±0.00

3.3. *Edible Protein energy return on investment (ep-EROI)*

The current study assessed the ep-EROI value for the anchovy captured by purse seining fishing vessels in Cantabria. The energy provided by anchovy was fixed at 2.18 MJ/kg anchovy (Peter Tyedmers, personal communication, September 2011) and the average value of CED was 22.5 MJ. The ep-EROI value was calculated for each vessel of the sample and the results indicated an average value of 12.2%, with a minimum value of 3.3% (P5.2) and a maximum value of 30.3% (P4.1).

4. Discussion

4.1. *Identification of environmental hotspots*

The environmental performance of the European anchovy fishery off the coast of Cantabria led to a first finding that the most important environmental impact associated with the operation of the fleet was linked to the

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[2] A standard error of 0.00 was computed for *Engraulis anhcoita*, according to the data provided by FishBase (2016). This value is probably linked to the lack of multiple data points measuring the trophic level of this species.

production, transportation and direct combustion of diesel. This result is not new in fisheries LCA studies, since most of the available literature highlights the direct use of fuels by vessels as the main environmental carrier in most impact categories (e.g., GWP, ODP, FD…). For instance, Fréon et al. (2014) previously presented similar results for the Peruvian anchoveta purse seining fleet, showing that the steel fleet presented the lowest fuel use intensity worldwide, although fuel production and use remained the main contributing operation. Hull construction and maintenance was the second item that contributed the most to environmental impacts. Moreover, other authors have also reported similar results for different small pelagic fish species: European pilchard (Almeida et al. 2014), Atlantic mackerel (Ramos et al. 2011), or horse mackerel (Vázquez-Rowe et al. 2010), but also for some large pelagic fish species, such as tuna or swordfish (Hospido and Tyedmers, 2005; Parker et al. 2015).

However, despite the fact that the consumption of diesel was the main hotspot of these analyzed studies, the consumption of diesel per kilogram of landed fish was very different (Table 5). Fréon et al. (2014) reported the lowest value, 15.6 g diesel/kg of landed fish for anchoveta for the period 2008-2011, while Hospido and Tyedmers (2005) reported a value very similar to the one reported in the current study, 364 g diesel/kg fish landed. However, it should be noted that in the case of Hospido and Tyedmers, landings were performed by large industrial vessels operating in open sea, whereas in the current study purse seiners were smaller in size, landed less amount of catch and operated in the Spanish Exclusive Economic Zone (EEZ) along the continental shelf. In the other studies, Vázquez-Rowe et al. (2010) reported a value of 176 g diesel/kg fish landed, Almeida et al. (2014) 92 g diesel/kg fish landed and Ramos et al. (2011) 27 g diesel/kg fish landed. Pelagic species targeted by trawlers presented a much stronger dominance of energy use. Therefore, it appears as if the European anchovy fleet is located in the upper range of pelagic species in terms of fuel use intensity (FUI), but still substantially lower than trawling fleets targeting pelagics. The data collected for the current study only allowed analyzing one year of operation, making it difficult to hypothesize the causes behind this relatively high FUI value. However, previous studies have suggested that relevant fuel efficiency improvements can be attained following stock rebuilding (Ziegler and Hornborg 2014). Therefore, considering the volatility of the European anchovy fishing stock in the Bay of Biscay in the past decade, future research should delve into the role of recruitment, stock size and size of individuals to determine whether the apparent recovery of the fishery is gradually translating into fuel savings.

Table 5. Diesel consumption of other pelagic species fisheries reported in the literature.

Species	Unit	Fishing gear	Value	Reference
European anchovy	g diesel/FU	Purse seining	340.0	Current study
Anchoveta	g diesel/FU	Purse seining	15.6	Fréon et al. 2014
Sardine	g diesel/FU	Purse seining	91.5	Almeida et al. 2014
Atlantic mackerel	g diesel/FU	Purse seining	26.9	Ramos et al. 2011
Horse mackerel	g diesel/FU	Purse seining	176.0	Vázquez-Rowe et al. 2010
Tuna	g diesel/FU	Purse seining	364.3	Hospido and Tyedmers 2005
Tuna	g diesel/FU	Purse seining	306.4	Parker et al. 2015b
Atlantic mackerel	g diesel/FU	Trawling	496.0	Vázquez-Rowe et al. 2010
Common octopus	g diesel/FU	Trawling	1287.0	Vázquez-Rowe et al. 2012b
Pelagic species	g diesel/FU	Trawling	354.0	Jafarzadeh et al. 2016
Small pelagic species (Europe)	g diesel/FU	Trawling	149.0	Parker and Tyedmers 2015
Pelagic species	g diesel/FU	Coastal seining	56.0	Jafarzadeh et al. 2016

An important limitation of this study is the fact that most operational activities, including the use of diesel, were reported on an annual basis. Therefore, it was not possible to disaggregate fuel use per landed species, despite the fact that the purse seining fleet from Cantabria has a fairly delimited season for each one of the main species it lands. Based on this assumption, it could be hypothesized that different operations and skipper behavior when targeting different species throughout the year could translate into an important source of uncertainty in this study.

Anti-fouling emissions to the ocean generated reduced burdens for most impact categories, but its contribution to freshwater toxicity is relevant due to the emissions of copper and zinc. However, it should be noted that corrosion from vessels is an unexplored impact in seafood LCA studies that may cause certain environmental impacts, especially in terms of eco-toxicity.

The management of non-hazardous wastes had also an important contribution to human and freshwater eco-toxicity due to the emissions produced in the incineration process, as well as to water and metal depletion. Regarding water depletion, however, it should be noted that the impact category used considers a raw calculation of the amount of water used in the production system, without taking into account geographical/regional availability or scarcity (Goedkoop et al. 2009). In fact, water footprint has been a repeatedly overlooked impact category in fisheries LCA through the years. Results shown in this study demonstrate that total water use (5.29·10-

3 m3/FU) represents a relatively low value as compared to most agricultural products (Vázquez-Rowe et al. 2016; Lovarelli et al. 2016). However, as shown in Figure 6, WD is distributed evenly throughout several subsystems (e.g., seine net production, diesel, ice, waste treatment, etc.). Therefore, considering the variety of water sources included in the inventory, the use of more refined water-related characterization factors, as those recently released in the AWARE method, may provide interesting insights linked to the water footprint of seafood products (Boulay et al., 2015; WULCA, 2016).

Vessel and seine net EoL did not represent relevant contributions to the product systems' environmental burdens. This fact leads to the apparent conclusion that EoL may not be key subsystem compared with others. Nonetheless, it should be studied in depth, since the study of the EoL of vessels constitutes a major gap in LCA. Only some authors have reported some results. For instance, Gilbert et al. (2016) compared two ships under an LCA approach analyzing two EoL scenarios: (i) reusing the hull as a whole and (ii) decommissioning the hull. Choi (2016) determined the economic feasibility and environmental impacts of three examples of EoL: standard ship recycling, substandard ship recycling and reefing. On the other hand, Ko and Gantner (2016) performed an environmental and economic analysis to calculate the imbalance in the distribution of the added value and the harm to the environment over the lifetime of a ship employing the dismantling as EoL.

It is important to highlight that in this study electronic components (i.e., radars, sonars, computers, screens, etc.) of vessels were not considered. However, these electronic products contain many materials requiring special EoL handling, such as lead, mercury, arsenic, chromium, cadmium and plastics capable of releasing, if not managed adequately, compounds such as dioxins or furans (Sthiannopkao and Wong 2013). The European Union has been adopting a number of community level regulations related to commonly known as e-waste (European Commission 2012; European Commission 2011). These measurements include dismantling of parts and recyclability of materials, proper collection systems that support separate collection of e-waste (also referred to as "waste of electrical and electronic equipment" – WEEE) to reduce disposal in common municipal waste streams, and best practices for treatment, recovery and recycling of e-waste (Kahhat et al. 2008). Some authors have studied the environmental impact of e-waste treatment via LCA. Song et al. (2012) demonstrated that the recovery of metals, glass and plastic from e-waste can generate environmental benefits. Niu et al. (2012) compared three scenarios (incineration, manually dismantling and mechanical dismantling) using LCA. Their results showed that incineration has the greatest impact, followed by mechanical dismantling. Moreover, incineration has a poor reputation because of its emissions of greenhouse gases, acid gases, and dioxins and furans (Margallo et al. 2014).

For the BRU impact category it can be observed that the Cantabrian purse seining fleet shows relatively low BRU values (Table 6), due to the fact that European anchovy is a species that is situated in a lower TL than most fish species landed in Spain (Vázquez-Rowe et al. 2012a). Interestingly, many fisheries worldwide that capture species similar to European anchovy send their landing to reduction to produce fishmeal or fish oil (Fréon et al. 2014c). In fact, clear examples of this are the Peruvian anchoveta and US menhaden fisheries, sending over 99% of their catch to reduction (Cashion et al. 2016). However, the European anchovy captured by Cantabrian purse seining vessels is used exclusively to process products for direct human consumption – DHC (Laso et al. 2016a and 2016b). Other low TL species are destined to DHC in Spain, such as European pilchard (Vázquez-Rowe et al., 2014), tend to be used elsewhere for reduction. There use as DHC demonstrates that there can be a potential market as DHC for these species, rather than sending them to more complex, and usually more intensive in terms of energy and biotic impact, food supply chains (Cashion et al. 2016).

Table 6. Biotic Resource Use (BRU) values for other fish species collected in the literature.

Specie	Unit	BRU	Reference
European anchovy	kg C/kg fish	13,988	Current study
Peruvian anchovy	kg C/kg fish	5,786	Avadí and Fréon 2015
Gulf menhaden	kg C/kg fish	1,721	Parker and Tyedmers 2012
Antarctic krill	kg C/kg fish	1,761	Parker and Tyedmers 2012
Atlantic herring	kg C/kg fish	18,869	Parker and Tyedmers 2012
Blue whiting	kg C/kg fish	133,699	Parker and Tyedmers 2012

The ep-EROI results provide valuable information regarding energy requirements of the Cantabrian purse seining fishing fleet. As observed in Table 7, the value obtained in this study, 12.2%, is similar to those obtained in other purse seining fisheries (Vázquez-Rowe et al. 2014a; Ramos et al. 2011), although substantially lower than some collected in the literature (Tyedmers 2001). Therefore, despite the values for this fishery being in the lower range for pelagic species landed by purse seiners, its results are still considerably better as compared to trawlers.

Table 7. Edible protein energy return on investment (ep-EROI) values for other pelagic species.

Species	Fishing gear	ep-EROI (%)	Reference
European anchovy	Purse seining	12.2	Current study
Atlantic mackerel	Purse seining	68.6	Tyedmers 2001

Atlantic mackerel	Purse seining	17.8	Vázquez-Rowe et al. 2014a
Tuna	Purse seining	14.0	Ramos et al. 2011
Horse mackerel	Purse seining	14.9	Vázquez-Rowe et al. 2014a
European pilchard	Purse seining	18.3	Vázquez-Rowe et al. 2014a
European hake	Trawling	5.6	Vázquez-Rowe et al. 2014a
Horse mackerel	Trawling	6.1	Vázquez-Rowe et al. 2014a
Atlantic mackerel	Trawling	7.3	Vázquez-Rowe et al. 2014a

Other fishery-specific impact categories, such as the seafloor impact potential (SIP) proposed by Nilsson and Ziegler (2007), were not applied to this fishery because it was assumed that purse seining was a fishing gear that caused negligible direct damage on the seafloor according to the SIP index due to the lack of contact with the seabed (Hornborg et al. 2012; Langlois et al. 2015; Ziegler and Valentinsson 2008). However, lost nets can potentially create ghost fishing, that is to say, the mortality of fish and other species that takes place after all control of fish gear is lost by a fisher (Brown and Macfadyen 2007). Similarly, discards in this fishery were considered minimal and were not computed (Pelletier et al. 2007; Vázquez-Rowe et al. 2011b).

4.2. Global Warming Potential of the whole life cycle of canned anchovy

As abovementioned, most European anchovy landed in Cantabria is sent to canning factories. The most common final product destined to DHC is a 150 g aluminum can that contains 30 g of processed anchovy and 20 g of olive oil. It should be noted that during anchovy processing approximately 60% of the wound weight of the individuals is lost, including heads, spines and broken anchovies, which are valorized into fishmeal and anchovy paste (Laso et al, 2016a). Figure 7 presents the relative GHG emissions emitted in each phase of the life cycle of one 50 g can of European anchovy in olive oil. The GWP related to the processing, wholesale and retail, use and end of life of canned anchovies was taken from Laso et al. (2016b). For the post-processing stages, it was considered that the canned anchovies were transported from the canning plant to a logistic hub, and then to a supermarket, and consumed as ready-to-eat products that do not required any cooking. Finally, in the EoL the packaging materials were disposed of in a landfill (Laso et al. 2016b).

Results show that the anchovy fishery would account for 44% of the total GHG emissions, whereas the processing stage would represent 45% of total impacts. A previous study in the literature, developed for canned sardines in Galicia, established that the processing stage to produce canned sardines represented approximately 77% of total GWP while the sardine fishery accounted 5% of the total GHG emissions (Vázquez-Rowe et al.

2014b). Nevertheless, it should be noted that the processing of canned sardine has additional steps, such as cooking or sterilization (Vázquez-Rowe et al. 2014b). Therefore, the energy demand of the canned sardines was higher.

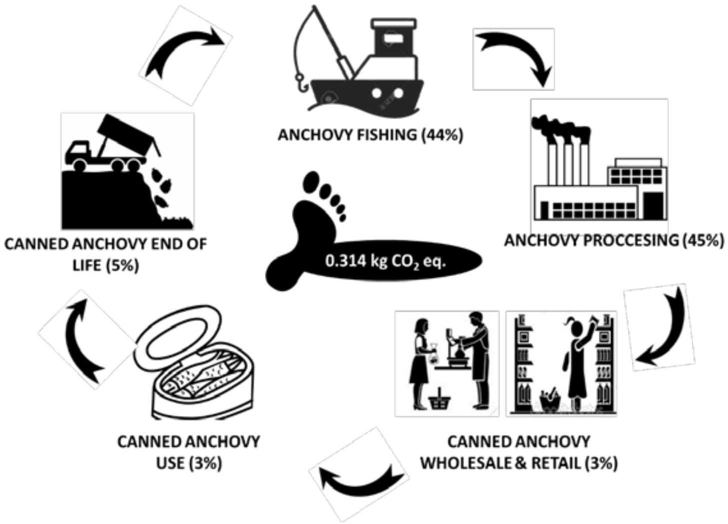

Figure 7. Global Warming Potential of the life cycle of one can of canned anchovies in olive oil.

4.3. *Trends between ports and vessels*

When the GWP is analyzed per port, as shown in Figure 8, the values range from 0.82 kg CO_2 eq (P4) to 1.91 kg CO_2 eq (P3). However, it should be noted that ports P6 and P7 only reported one vessel each; therefore, the samples for these two ports were not representative. It was expected that ports that were situated in the same zone presented similar values of GWP. Interestingly, this fact did not occur. P3 and P4 were situated in West Cantabria and they had very different GWP values: 1.91 kg CO_2eq and 0.82 kg CO_2eq, respectively. Similarly, P1, P2 and P5, which are located in Cantabria, presented a wide range of average GHG emissions per FU: 1.21 kg CO_2eq, 1.48 kg CO_2eq and 1.86 kg CO_2eq, respectively. Therefore, no trend was observed between ports in terms of vicinity or based on their proximity to the fishing ground.

Figure 9 shows the GHG emissions for each of the 32 vessels studied. In this case, the environmental impact ranged from 0.55 kg of CO_2eq (P4.1) to 4.42 kg of CO_2eq (P5.2). It was observed that vessels belonging to the same port presented similar values of GWP, i.e. P1, P3 and P4, although there were some vessels that had substantially higher GWP values than the average of their ports (e.g., P2.2, P5.2 or P5.6).

These results suggest the existence of certain differences between vessels in terms of their operational activities. In fact, this variability could be caused by a series of differences in vessel characteristics, such as size, age, engine power or tonnage, geographical distribution of the vessel, including landing and base port, technological improvements, and a set of operational issues relating to the use of resources, such as gear, fuel or ice use (Basurko et al. 2013; Vázquez-Rowe and Tyedmers 2013). In this study, the sample studied was very homogeneous, the age of the vessels ranged from 11 to 20 years, the size of the vessels and the engine power were very similar and the materials used in vessel construction were practically the same. Moreover, the distance from the ports to the fishing zone was between 100 and 150 miles in all cases. Therefore, the technical differences between the units assessed appeared to be relatively low. Data gaps and misreporting were also considered to be minimal, since data were supplied directly by the skippers. Finally, illegal, unreported and unregulated (IUU) fishing were also considered to be low, given the strict controls from authorities and certification agencies (González-García et al. 2015). Consequently, these results may be linked to the skill of the skipper and other members of the crew to sense where the catch will be available. This fact, usually named as the "skipper effect", has generated high controversy and interest in the literature (Russell and Alexander 1996; Ruttan and Tyedmers 2007). Several studies reported the fact that the "skipper effect" tends to be more noticeable in seining fleets than in other industrial fleets, such as trawlers or long liners (Gaertner et al. 1999). For instance, strong correlations between the "skipper effect" and vessel efficiency were identified in the US menhaden purse seining fleets (Ruttan and Tyedmers 2007; Vázquez-Rowe and Tyedmers 2013).

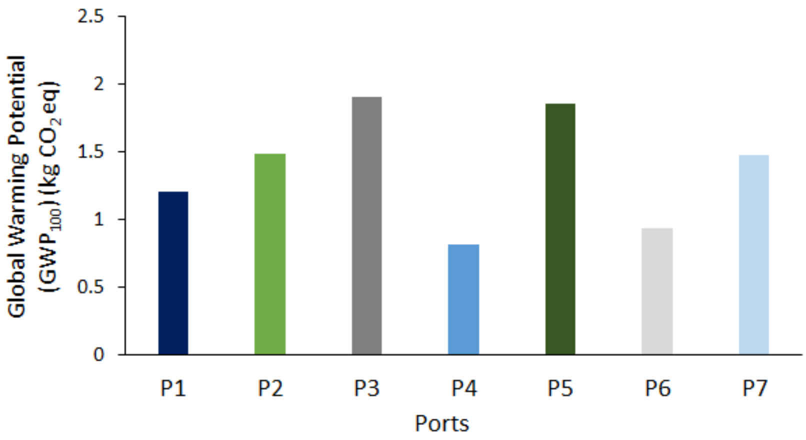

Figure 8. Global warming potential (GWP) average value of each Cantabrian port. P1: Colindres; P2: Santoña; P3: San Vicente de la Barquera; P4: Comillas; P5: Laredo; P6: Santander; P7: Castro Urdiales.

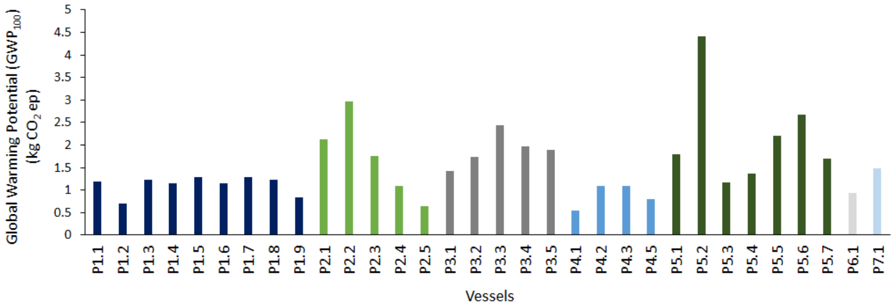

Figure 9. Global warming potential (GWP) of the 32 vessels studied. The letter P followed by the first digit represents the port of origin for each vessel, P1: Colindres; P2: Santoña; P3: San Vicente de la Barquera; P4: Comillas; P5: Laredo; P6: Santander; P7: Castro Urdiales. The second digit represents the number of each vessel within its port of origin.

The results obtained from the statistical analysis showed that when plotting the entire data sample on a histogram (see Figure S1 in the SM) a clear asymmetry is identified in the distribution of the results. This is also highlighted by the inclusion of a kernel density estimator, also shown in Figure S1. Therefore, the sample of 32 vessels was divided into two groups based on the average GHG emission results per port, as a proxy of the fuel used for propulsion. In other words, each vessel was assigned to a high-GWP port group or a low-GWP port group on the basis of the GHG emissions port average. In other words, if a certain vessel belongs, for instance, to a low fuel consumption/production port, it does not mean that its own GWP value is "low". Hence, the statistical analysis conducted allows determining the homogeneity of vessels in terms of GWP with respect to the port classification. For that purpose, and bearing in mind that the considerations described in section 2.6 must be taken into account when interpreting the results, two procedures were run: an ANOVA test and a Kruskal-Wallis test. The two groups were generated using a cut-off criteria at 1.46 kg CO_2 eq, obtaining balanced samples (i.e., 15 units for <1.46 kg CO_2 eq and 17 units for >1.46 kg CO_2 eq; see Figure S2 in the SM). Another cut-off point had been set previously at 1.50 kg CO_2 eq, but it was finally discarded due to a higher number of atypical values in the sample (see Figure S3 in the SM). Hence, the hypotheses were redefined in order to determine whether: i) the average GWP values were the same for both groups; and ii) if distribution of values in both groups was the same.

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The first hypothesis was tested using an ANOVA procedure, whereas for the second problem the U Mann-Whitney test was run. Nevertheless, considering that there are only two groups in the analysis, the use of an ANOVA is equivalent to a T-test. For the ANOVA procedure, normality and homogeneity of variances in the groups must be assessed in advance. For that purpose, Shapiro-Wilk and Levene tests were applied, respectively.

Results, presented in Table S2 in the SM, demonstrate that there is no evidence to reject the hypothesis of normality and homogeneity of variances (with p-values above the usual significance levels of 5% or 1%). Therefore, the samples meet the prerequisites to conduct an ANOVA test, as long as a 1% significance level is set for the homogeneity of variances. The output of the ANOVA provided a p-value below the usual significance levels, indicating that the means in the two groups are different. Similarly, the U Mann-Whitney test shows a p-value under the significance level, which also indicates that there is a significant difference between the distributions of the values in both samples. That is, not only the mean GWP values are different, but also their distributions (see Figure S2 in the SM).

It should be noted that results suggest a significant difference between the two groups of vessels, but not of each port individually given the low sample size per port. The sample size and the detail of data for the vessels were a limitation to conduct more detailed statistical analyses on the purse seining fleet. However, considering that the similarity of the sample in terms of vessel size, captured species or fishing areas is remarkable, we hypothesize that the differences could be due to the type of engine that is been used, or due to the skill of the skipper/crew. In fact, the “skipper-effect”, although not directly analyzed in this study, has been pointed out as a critical issue when considering differences in behavior among vessels (Vázquez-Rowe and Tyedmers 2013; Ruttan and Tyedmers 2007; González-García et al. 2015).

Regarding the sensitivity analysis, Figure 10 displays the GWP, WD, MD and HT_c per functional unit when the estimated lifespan of the vessels and the seine nets were varied. In terms of GWP and WD, the vessels lifespan showed very low variation, whereas the seine nets lifespan presented a variation of WD from $7.74 \cdot 10^{-3}$ m^3 (2 years) to $4.47 \cdot 10^{-3}$ m^3 (10 years). In terms of MD and HT_c, the variation of both vessels and seine nets lifespan resulted in a change in the environmental impact. In particular, MD and HT_c decreased 22% and 33%, respectively, when vessels lifespan varied from 20 to 40 years. On the other hand, when seine nets lifespan ranged from 2 to 10 years, MD and HT_c decreased 21% and 17%, respectively.

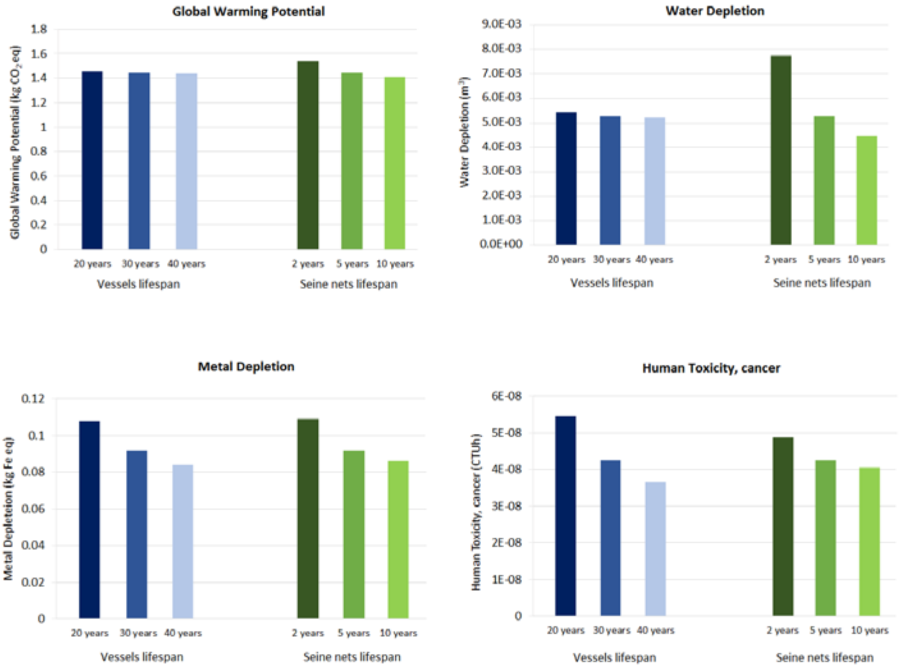

Figure 10. Graphical representation of the sensitivity analysis. Variation in Global Warming Potential, Water Depletion, Metal Depletion and Human Toxicity - cancer per functional unit based on changes in the estimated lifetime of the vessels and seine nets.

5. Conclusion

The European anchovy purse seining fleet in northern Spain represents an emblematic and high value-added fishery. Its closure due to overexploitation at the beginning of the century is probably the cause of the lack of a previous LCA study, since every other major pelagic species caught throughout the Spanish northern coast has already been reported in the seafood LCA literature. Therefore, this study aimed at filling that gap. For this, data on 32 vessels, representing roughly 75% of this fleet, were obtained to elaborate an exhaustive inventory, which collected the main inputs and outputs of the construction, use, maintenance and EoL of each vessel.

The LCA results were driven by diesel production, transportation and use in most conventional impact categories. In fact, FUI values appear to be in the upper range for small pelagic species when compared to previous fuel intensity studies elsewhere, despite the fact that distances to the fishing grounds are relatively short. The use of anti-fouling paints was identified as the main hotspot in toxicity potential, due to the emissions of zinc and copper, whereas the remaining activities, as well as the construction and EoL of the vessel presented lower relative contributions. However, we argue that for the latter the repeated exclusion of certain capital goods, such as electronic equipment, or a more detailed inventory in terms of vessel construction may hide certain environmental impacts, especially in terms of waste generation and treatment.

A statistical analysis was also carried out to identify the significance of the differing values obtained between ports and vessels. However, given the low amount of vessels in the fleet, analysis at a port level was discarded. When several ports were aggregated based on the average GHG emissions of their vessels per FU, results suggest that there is a significant difference between the ports. Unfortunately, available data were not enough to identify the causes of this difference, although we hypothesize that mechanical or temporal characteristics of the motors, or the so called "skipper effect" could well explain these trends.

Future research in the frame of the same project will include the combination of LCA with Data Envelopment Analysis, a linear programing management tool, with the aim of identifying the best performing fishing vessels in the fleet in terms of environmental efficiency, as well as the sources of inefficiency among the inventoried sample. In addition, future progress will be needed in the stock management of the European anchovy fishery in order to attain more meaningful assessments in terms of biotic impacts.

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