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CHALLENGES AND BEST PRACTICE IN LCAS OF SEAFOOD AND OTHER AQUATIC PRODUCTS

The importance of using life cycle assessment in policy support to determine the sustainability of fishing fleets: a case study for the small-scale *xeito* fishery in Galicia, Spain

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Abstract

Purpose Drift net fishing activities have undergone a thorough revision at a European Union level, since authorities argue that several loopholes still exist in the legislation that allow small-scale fisheries to use these gears. High incidental catches, or the lack of selectivity, are some of the primary scientific criteria behind this discussion. This new framework is of particular interest in the region of Galicia (NW Spain) due to the social importance of small-scale fishing vessels using drift nets. In fact, over 400 vessels have a licence to capture European pilchard (*Sardina pilchardus*) with a fishing gear called *xeito*, which is a small-scale drift net.

Methods The main goal of this article is to provide stakeholders in the fishing sector with environmentally relevant results regarding the life cycle impacts linked to fishing practices performed by small-scale vessels using the *xeito* gear to target European pilchard. We hypothesize that environmental impacts computed with LCA will provide additional insights to the sustainability of the pilchard small-scale fishery in NW Spain, adding a series of criteria that may be useful for policy-makers to determine the consequences of forbidding this type of drift netting in the future.

Results and discussion Results show that environmental impacts across impact categories and operational activities do not differ much from that of other similar fishing fleets examined in recent years, with fuel for propulsion being the main environmental burden in most impact categories. When conducting a statistical analysis, no significant difference in energy use was identified between this small-scale fleet and purse seiners targeting pilchard in Galicia. Moreover, the results obtained demonstrate, in line with previous studies, that European pilchard is still an energy-efficient source of animal protein option as compared to demersal fish alternatives, crustaceans, or livestock.

Conclusions The results do not indicate that European pilchard landed with small-scale drift nets generates higher environmental life cycle impacts than pilchard landed by purse seiners in NW Spain. However, longer time frames for the analysis should be performed to attain results with lower uncertainty.

Keywords Drift net · Industrial ecology · LCA · NW Spain · Policy support · *Xeito* fishery

1 Introduction

The European Common Fisheries Policy (CFP) has undoubtedly transformed the fishing sector in Europe and through third-party agreements elsewhere (Churchill and Owen, 2010). Due to the existence of several erratic policies in

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previous formulations of the CFP, such as the lack of an ecosystem-based fisheries management (EBFM) or permissive regulations in terms of by-catch or discard, a reformed CFP was pushed forward in the period 2009–2013 and finally took effect on January 1, 2014 (Villasante et al. 2016a, 2016b). Most literature analysing the new CFP agree on highlighting a series of positive or ambiguous measures (Prellezo and Curtin 2015), although their effects in most cases are yet to be fully implemented. These changes in the CFP tend to generate important economic, social and environmental impacts in certain regions with strong economic dependence on fishing activities, such as the case of Galicia, in NW Spain (Salomon et al. 2014).

As of 2015, fishing landings in this region still represented roughly 1% of the gross domestic product (GDP), and directly employed a total of 21,305 people in the industry (Xunta de Galicia 2017a). The importance of the Galician fishing sector can be visualized at a European Union (EU) level, representing 9% of the total tonnage, comparable to that of France or Italy, and at a national scale within Spain (MAPAMA 2016). For instance, approximately 48% of fishing vessels registered in Spanish ports operate in Galicia (MAPAMA 2016).

Interestingly, despite representing such an overwhelming percentage of total fishing vessels, these translate only into 19% of national fresh landings. These values indicate that fishing in this region, in spite of the existence of industrial fleets, still maintains a strong traditional small-scale sector, with a variety of vessel sizes and gears operating along the coastline. These small-scale fleets are made up of a total of 3932 vessels, representing 89% of the total fleet of the region (Xunta de Galicia 2017ab). In fact, certain small-scale fisheries are still relevant sources of revenue for medium and small coastal towns in Galicia, as shown in Table 1. Additionally, it should be noted that the small-scale fishery in Galicia is characterized by using different fishing gears throughout the year. In this regard, skippers can combine different fishing gears (up to five) based on target species—including shellfish and fish—temporary bans and the state of stocks (Xunta de Galicia 2013).

From all the examples shown in Table 1, the *xeito* fishery has drawn attention by the media and politicians since mid-2014, due to the proposal at an EU level to ban this type of gear, together with all other drift nets in European waters (Sala 2016). Although large drift net gears have been banned in EU fishing vessels (even those operating beyond EU waters) since 1992 and several regulations have helped enforce these measures ever since, a considerable number of fisheries (45) using small-scale drift nets (SSDs) were excluded from these legislative measures. However, when the new CFP was being discussed and was finally passed in 2014, many difficulties persisted in terms of enforcing the regulations in many fisheries. Consequently, non-governmental organizations (NGOs) started advocating for a complete ban of drift nets in EU waters, a petition that soon reached European authorities and discussed for several months in the European Parliament until it was finally revoked (EP 2014; Senra-Rodríguez 2014; Juaristi-Abaunz 2014).

Xeito is an SSD that is only used in a few ports in Galicia, but is relevant from an economic and social perspective in

Table 1 Main socio-economic and fishing characteristics of Galician ports with an important reliance on small-scale fishing activities for year 2016

Port	Population[a]	Employment rate from direct fishing activities[a] (%)	Unemployment rate[a] (%)	Small-scale fleet[b]	Xeito fleet[b]	Total Vessels[b]	Total catches landed[b] (t)
Rianxo	11,295	11	21.3	198	116	320	518
Illa de Arousa	4909	46	15.8	417	47	563	712
Redondela	29,563	3	17.4	87	37	104	173
Boiro	18,871	10	19.8	90	24	231	311
Cangas	26,584	7	20.1	140	19	166	596
Moaña	19,458	6	20.8	104	16	168	174
Combarro - Poio	16,901	7	17.0	56	15	77	N/Av
Cambados	13,977	14	20.5	209	12	275	2147
Soutomaior - Arcade	7251	4	22.9	60	11	60	173
Fisterra	4737	12	21.1	73	10	75	642
Muros	8834	8	13.6	65	10	98	4402

N/Av not available

[a] Xunta de Galicia 2017a

[b] Xunta de Galicia 2017ab. The xeito fleet is included in the small-scale fleet. The remaining vessels that are not part of the small-scale fleet are mainly auxiliary vessels for the aquaculture industry and, to a lesser extent, purse seiners and trawlers that perform their activities within the Spanish EEZ (ICES subdivisions IXa and VIIIc)

these ports (see Fig. 1 and Table 1). The proposal to ban this gear was applauded by certain groups, mainly NGOs, which defended the need to reduce the amounts of incidental mortality of cetaceans, sea turtles or sharks, as well as other types of ghost fishing (EP 2014). However, Galician and Spanish authorities, as well as the stakeholders in this small-scale fishery, argued that this gear is strictly controlled by thorough regional legislation that include a series of technical norms that supervise the mesh size of the nets (i.e., 23–40 mm) or the fact that the net cannot lose physical contact with the vessel while fishing, among other regulations (Sala 2016; Galician Parliament 2014; Xunta de Galicia 2016), which makes this fishery selective to its target species: European pilchard (*Sardina pilchardus*).

The measure of how sustainable a fishery is has usually been linked to the evaluation of biological indicators in order to determine if a fishery is capable of maintaining its ability to spawn and endure recruitment and total biomass on an annual basis. While the objective of this study is not to reduce the importance of analysing these biologically driven parameters to assess the sustainability of fisheries, we argue that fishing fleets should also be evaluated in terms of the environmental impacts they may engender in terms of other environmental dimensions, other than fisheries depletion (e.g., CO_2 and other greenhouse gas (GHG) emissions, toxicity, and depletion of fossil fuels). In this context, an internationally standardised environmental management tool, named life cycle assessment (LCA), has steadily started to be applied to fisheries and fishing fleets worldwide with the aim of providing a holistic perspective regarding environmental impacts that may potentially arise from fishing activities (ISO 2006a, b; Vázquez-Rowe et al. 2012; Ziegler et al. 2016).

In the past decades, numerous publications have delved into the environmental impacts of industrial fleets across the globe (Avadí et al. 2014a; Ziegler et al. 2016), whereas a limited number of articles has analysed small-scale and artisanal fisheries (Ziegler et al. 2011, Avadí et al. 2014b; Parker and Tyedmers 2015). Nevertheless, some of the publications related to small-scale fisheries suggest that in many cases, the environmental impacts linked to these activities appear to be substantially lower than those for industrial fisheries (Ziegler et al. 2011), although in other cases, these tendencies are not as clear (Vázquez-Rowe et al. 2013). Moreover, recent studies have demonstrated that improved fishing stocks can be a main driver in terms of fostering fuel efficiency of fishing fleets (Ziegler and Hornborg 2014; Jafarzadeh et al. 2016),

The main goal of this article is to provide stakeholders in the fishing sector, especially policy-makers, with environmentally relevant results regarding the life cycle impacts linked to fishing practices performed by small-scale vessels using *xeito* to target European pilchard. We hypothesize that environmental impacts computed with LCA will provide additional insights to the environmental sustainability of the pilchard small-scale fishery in NW Spain beyond the health of the biological stock, adding a series of criteria that may be useful for policy-makers to determine the consequences of

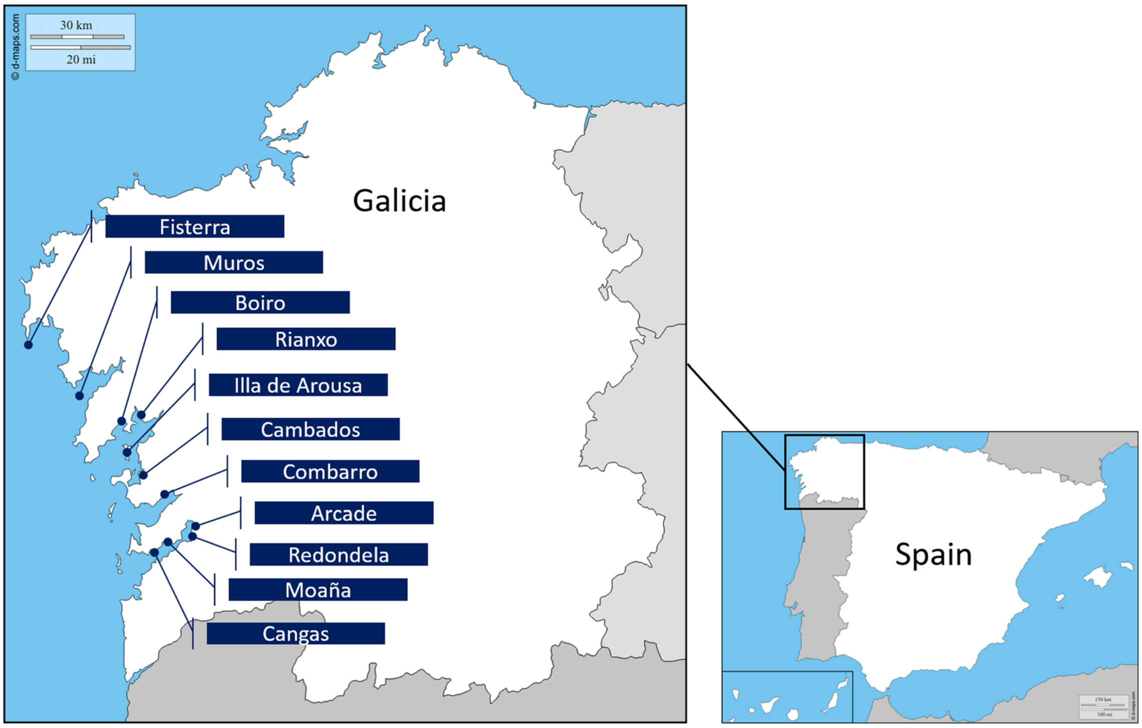

Fig. 1 Location of the main ports in Galicia with registered vessels using *xeito* to target European pilchard. Adapted from: d-maps.com, 2017

forbidding this type of drift netting in the future. Furthermore, a statistical analysis is provided to compare the environmental performance of this fleet to the Galician purse seining fleet, the latter representing approximately 99% of the total catch of pilchard in the region.

LCA studies have been known to support policy-making in several different sectors, including bioenergy, transportation or waste management (Hawkins et al. 2013; Vázquez-Rowe et al. 2014d; Astrup et al. 2015). It should be noted that concerns have also arisen regarding the methodological perspective of these advice studies (Plevin et al. 2014). However, in this case study, we argue that LCA-related information should be viewed as complementary to current fisheries management strategies. Hence, the target audience of the article is oriented to policy-makers at a regional, national and European level, seafood managers and other stakeholder throughout the pilchard supply chain.

2 Materials and methods

2.1 Description of the fishery

In 2016, the *xeito* fishery was made up of 419 small-scale vessels with a mean size of 6.40 m and an average gross tonnage of 1.87, constituting one of most important small-scale fisheries in Galicia (Xunta de Galicia 2017ab). As aforementioned, it is important to note that up to five gears can be used by small-scale fishing vessels throughout the year. However, many of these correspond to gears that land molluscs or crustaceans in coastal areas with strict temporal bans. Therefore, *xeito*, which targets mainly European pilchard (also named sardine), a small pelagic species abundant in Northern Portugal and NW Spain (Santos et al. 2011), tends to be used throughout the greater part of the year, usually above 50% of the allowed fishing days (Xunta de Galicia 2016).

Xeito is the main SSD that is still used by the Galician small-scale fishing fleet. It is made up of a series of rectangular nets that are placed in line up to a maximum length of 1000 m—100 m each piece— since that is the limit currently imposed by Galician legislation (Xunta de Galicia 2016). However, it should be noted that each individual piece is usually 70 m long and the width of the net can be up to 16 m. Interestingly, mesh size can vary from 23 to 40 mm. Varying mesh size is usually used by the fishermen to target pilchard at different times of the year, since the size of the individuals tends to increase from spring to summer. The gear is usually operated starting at nightfall until the early hours of the morning, when pilchard schools are more visible. It depends on the crew's criteria to define at what height in the water column should the 16-m-wide net be placed, since pilchard schools do not circulate at a defined depth. Figure 2 shows a graphical representation of how the vessels operate with this gear.

The stock management for European pilchard along the Atlantic coast of Spain and Portugal (i.e., ICES subdivisions IXa and VIIIc) is carried out jointly between the two nations. For instance, in 2016 they shared a fishing quota of 17,000 metric tons (BOE, 2016). *Xeito* is not the only fishing gear allowed to capture pilchard in these waters. In fact, preliminary quota distribution in 2016 among the different gears implied that purse seining accounted for a greater part of the landings, whereas only 175 t were linked to *xeito* operations in the area under Galician jurisdiction (Xunta de Galicia 2016). Moreover, the annual quota was distributed throughout the season, with the highest proportion of landings allowed in July and August (96 t, i.e., 55%), and a fishing ban enforced in November and December. However, the quota for the *xeito* fishery was finally increased to 210 t in July due to the scientific findings regarding the improving of pilchard stocks (BOE 2016). Finally, it is important to bear in mind that while purse seiners are not allowed to operate along the coastal areas in Galician waters, the small-scale fishery vessels using *xeito* are allowed to operate within the Galician *rias*, as illustrated in Fig. 3 (Xunta de Galicia 2011).

2.2 Goal and scope of the study

The main objective of the study, as abovementioned, is to obtain the environmental profile of pilchard landed by small-scale vessels using *xeito*. The main function of the production system is to land European pilchard (i.e., sardines) for direct human consumption in Galician ports. In fact, this function has been previously used in the literature to report the environmental impacts of pilchard landing in other fisheries throughout Atlantic Europe (Almeida et al. 2014; Vázquez-Rowe et al. 2014a; González-García et al. 2015). Consequently, the functional unit (FU) used to refer the environmental impacts was 1 metric ton of landed pilchard at a Galician port. The study was carried out in two non-consecutive years of operation: 2014 and 2016.

2.3 System boundary

A *cradle-to-gate* perspective was assumed for the system boundaries, since it was limited to the fishing stage of the life cycle of seafood landing. Therefore, port activities, as well as all the remaining post-landing activities in the seafood supply, were omitted in this study. The rationale behind this methodological choice is justified on the basis that the only difference between this pilchard supply chain and that offered by other fleets resides in the fishing stage, although it should be noted that pilchard caught using *xeito* usually is considered of superior quality due to better general appearance. This difference in quality implies that the average sale price of pilchard at auction varies based on the gear used to target this species (Xunta de Galicia 2016; Xunta de Galicia 2017ab).

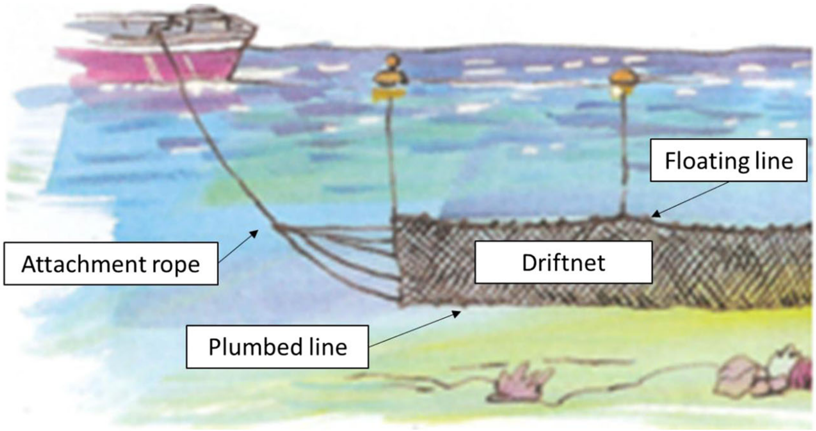

Fig. 2 Graphical representation of the use of the *xeito* gear by small-scale fishing vessels. Source: Xunta de Galicia (2017c)

Similarly, vessel construction materials were excluded from system limits. The differing materials used throughout small vessel hulls (e.g., wood, polyester and steel), together with the general lack of knowledge of fishermen regarding hull weight prevented using reliable inventory data. Furthermore, the implementation of the methodology proposed by Freon et al. (2014) to estimate ship construction materials was not used since this method is typically applied to vessels with lengths above 15 m. Figure 4 presents a graphical representation of the system boundaries.

2.4 Co-product allocation

Regarding the allocation of co-products, *xeito* is a relatively selective gear, since 85% of landings correspond to the target species: European pilchard (Xunta de Galicia 2016), while the remaining catches are other small pelagic species such as European anchovy (*Engraulis encrasicolus*). Moreover, discards are negligible (Sala 2016) and, unlike seiners, slipping is not a common practice (González-García et al. 2015). Mass allocation was conducted based on the fact that mass is the unit of reference for landings in the sector. Taking into account that the system boundaries only encompass the fishery, excluding the on-land supply chain once the catch is landed, this approach was considered the most appropriate as compared to other allocation perspectives (Table 2). Hence, economic allocation was disregarded due to the volatile prices that pilchard presents throughout the year (Xunta de Galicia 2017ab). Similarly, assigning weights based on the energy content of the different species was also discarded due to the fact that the

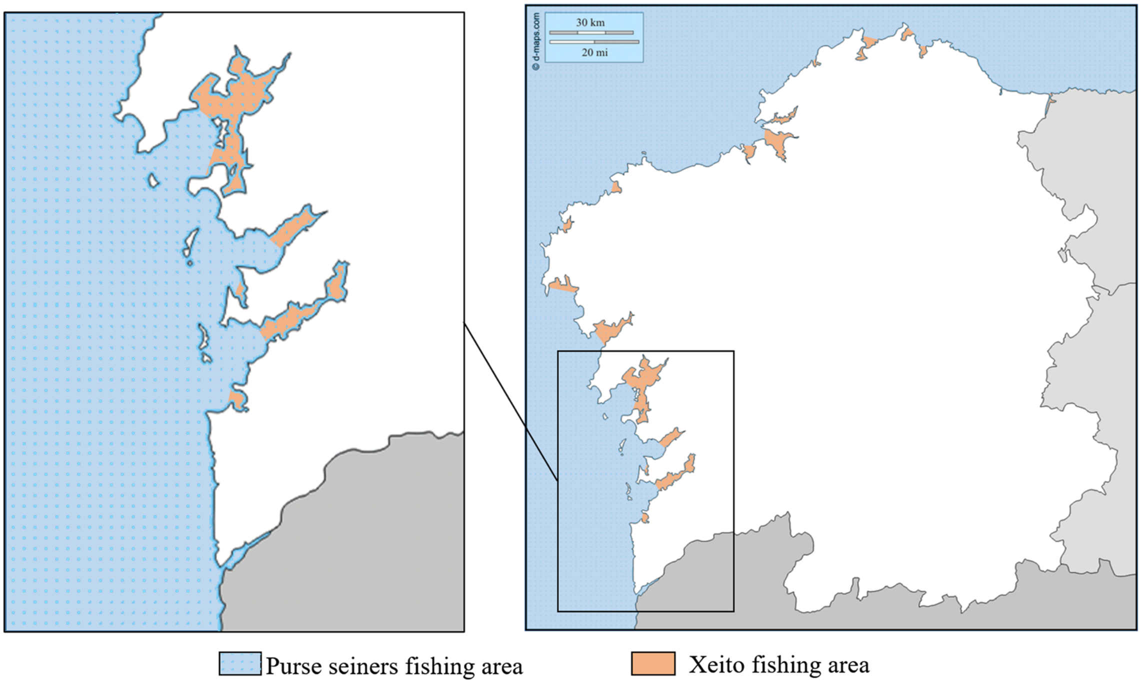

Fig. 3 Detail of the fishing areas allowed for the purse seining fishing fleet (only blue areas) and small-scale vessels using *xeito* (blue and orange areas). Therefore, *xeito* vessels are also allowed to fish outside their exclusive area. Adapted from: d-maps.com (2017)

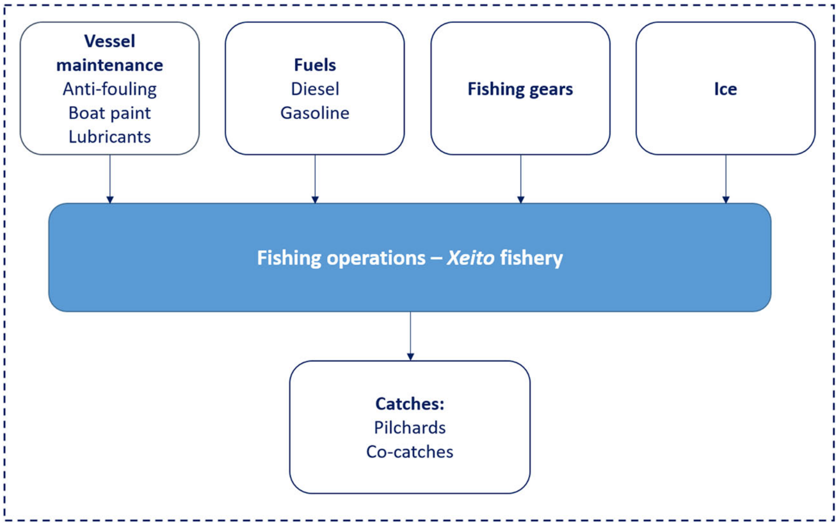

Fig. 4 Graphical representation of the system boundaries considered for European pilchard landings in the small-scale *xeito* fishing fleet

two species that represent close to 100% of the landings have identical maximum edible content of 62% and a mean protein content that ranges from 20.3 to 21% (Peter Tyedmers, personal communication, September 2011). Nevertheless, a sensitivity analysis was performed to identify the impact that the different allocation choices have on the environmental impact results (see Section 2.8).

2.5 Data gathering

Primary data were obtained from questionnaires that were distributed among skippers of the *xeito* fishery in the coastal towns of Rianxo (42° 38′ N 8° 49′ W), Cambados (42° 30′ N 8° 48′ W), Illa de Arousa (42° 33′ N 8° 51′ W) and Vilaxoán (42° 35′ N 8° 44′ W). Questionnaires were submitted to collect primary data in two different years: 2014 and 2016. There was also a willingness to collect data for the year 2015 by the research team. However, it was not possible to build up a sample in this particular year due to the political uncertainty in the *xeito* sector. Questionnaires were sent out to a total of 100 skippers, representing above 75% of vessels that report pilchard landings (Xunta de Galicia 2016). The response rate was approximately 30% in year 2014 and ca. 40% in 2016. However, due to data gaps in many questionnaires, only 10 and 16 vessels were included in the final sample in the years 2014 and 2016, respectively. Nevertheless, as shown in Table 3, the landings of sardine performed by the vessels included in the final sample represented 30 and 41% of the total European pilchard landed by the *xeito* fishery in 2014 and 2016, respectively.

For the year 2014, all vessels sampled were from the same port of origin (i.e., Rianxo), whereas in 2016 a total of seven vessels were from Rianxo and nine from the port of Cambados. For the former port, it must be noted that the sample in 2014 and 2016 is different. Moreover, the proportion of diesel- and gasoline-propelled vessels in this port differed in the 2 years of assessment, although there was certain equilibrium in both cases. In contrast, all vessels sampled in the port of Cambados used diesel fuel for propulsion. Despite the fact that all vessels are considered part of the Galician small-scale fleet, notable differences were identified between the vessels in Cambados and Rianxo. Firstly, the length of the vessels in Cambados is substantially greater (ca. 10 m) than those in Rianxo (approximately 6 m). In addition, the engine power of vessels in Cambados was an order of magnitude greater (208 hp on average), as compared to a range of 25–30 hp in Rianxo.

The questionnaires requested data regarding fishing operations for the small-scale fishing fleet that uses *xeito* as one of its allowed gears. Thus, fishing operational data included fuel and ice consumption, maintenance operations (i.e., lubricant oil, anti-fouling and paint) or the technical characteristics of

Table 2 Mass and economic allocation factors for the *xeito* fishing fleet. Landings represent the average values in 2014 and 2016. Different average auction prices were considered: the price for global pilchard landings and the price linked to xeito landings exclusively

	Catches (t)		Mass allocation (%)		Economic allocation (global landings) (%)		Economic allocation (*xeito* landings) (%)	
	2014	2016	2014	2016	2014	2016	2014	2016
European pilchard	61	179	85	91	83	83	90	90
European anchovy	11	17.5	15	9	17	17	10	10

Table 3 *Xeito* fishery vessels sample

Year	Number of vessels sampled			Total authorized vessels	Vessels reporting sardine landings	European pilchard landings[a] (%)
	Total	Rianxo	Cambados			
2014	10	10	–	426	166	30
2016	16	7	9	419	122	41

[a] Relative amount of landings refer to the total reported by the *xeito* fishing fleet in each year of assessment

the drift net. Additionally, vessel features (e.g., hull dimensions and material, life span and engine power), days at sea, crew size and landings were also requested. Background data for fuel production, lubricant oil, boat paints and gill net materials were retrieved from ecoinvent v3.2 database (Weidema et al. 2013).

2.6 Methodological assumptions

Gasoline-powered vessels can have two-stroke or four-stroke engines. Information regarding the nature of the engines in the vessels assessed was not available, despite this being important for modelling air emissions due to combustion. Therefore, it was assumed that 50% of gasoline-powered vessels have two-stroke engines and the other 50% four-stroke engines. Lubricants, anti-fouling and boat paint were allocated based on the length of *xeito* season during the year as a ratio of the total number of days in which the vessels went out to sea (Ramos et al. 2011). The average value was approximately 50% in each year, with small variations throughout the vessels sampled. The Spanish electricity production mix was adapted for the years assessed following the method proposed by Vázquez-Rowe et al. (2015) to model electricity linked to ice production (REE 2015, 2017). Direct emissions for fuel consumption emission factors were obtained from the EMEP-Corinair Emission Inventory Handbook 2013 (European Environment Agency 2013), and emissions derived from anti-fouling agent usage were retrieved from Hospido and Tyedmers (2005).

2.7 Life cycle inventory

Data acquired from skippers were combined with background datasets from the ecoinvent® database in order to construct the life cycle inventory (LCI), which is shown in Table 4 (detailed LCI data disaggregated per engine type and base port can be consulted in Section 1 of the Electronic Supplementary Material).

It should be noted that the ice used in vessels shown in Table 4 per FU presents a substantial swing between 2014 (39.2 kg) and 2016 (685 kg). The main reason behind this remarkable difference is the fact that in 2014, only 2 out of 10 vessels reported using ice on board, whereas in 2016, all vessels reported using ice. The main reason for this was the fact that not all vessels that provided data for 2016 sold their catch at the landing port. For instance, in the port of Cambados, many of the vessels send their catch to the port of Vigo for auction if the prize there is more competitive on a given day. Hence, these vessels will use extra ice for the catch to get to the port of sale in good conditions.

2.8 Assessment method

Potential environmental impacts were computed using the International Reference Life Cycle Data System (ILCD) assessment method (European Commission 2010). The selection of this method was based on the purpose of the study, which is oriented towards policy support at a European level. Table 5 depicts the impact categories considered for the life cycle impact assessment (LCIA) following the ILCD methodology guidelines. As detailed in Section 2.8, two other assessment methods, IPCC 2013 and ReCiPe midpoint-H, were run in the sensitivity analysis. Furthermore, edible protein energy return on investment (ep-EROI) was calculated for the fishery (Vázquez-Rowe et al. 2014b). For this purpose, the renewable and non-renewable energy embedded in the processes studied were taken into consideration throughout the calculation of the Cumulative Energy Demand (CED) v2 (VDI-Richtlinien 1997). SimaPro 8.2 was the software for the computational implementation of the life cycle inventories (PRè-Product Ecology Consultants 2016).

2.9 Sensitivity and statistical analysis

Uncertainties are an important issue to be taken into consideration in LCA studies. It should be noted that these can be divided into several subcategories depending on the source of the uncertainties. On the one hand, epistemic uncertainties in data quality and availability due to measurements errors or data misreporting by skippers constitute an important source of uncertainty. On the other hand, uncertainties linked to the functioning of life cycle assessment methods, methodological assumptions and databases have shown to be considerable in previous LCA studies (Lloyd and Ries 2007; Huijbregts et al. 2003).

Epistemic uncertainties are difficult to detect when collecting fisheries data directly from skippers. However, data gaps, as described in Section 2.6, were amended by using data from bibliography or databases. Nevertheless, a series of

Table 4 Life cycle inventory per functional unit (1 metric ton of European pilchard landed at port) for the small-scale fishing fleet targeting European pilchard using *xeito*. Data reported for years 2014 and 2016. Port base data reported for the years 2014 and 2016. SD: standard deviation

Inputs		2014		2016					
		Rianxo		Rianxo		Cambados		Average fleet	
		Average fleet							
From the technosphere	Units	SD		SD		SD		SD	
Fuel	GJ	8.37	±4.64	7.54	±2.98	15.26	±3.32	11.89	±5.01
Lubricant oil	kg	1.92	±2.40	0.94	±0.54	1.97	±0.71	1.44	±0.67
Boat Paint									
Xylene	kg	2.3E-02	±5.9E-02	1.2E-02	±5.9E-03	3.5E-02	±2.3E-02	2.4E-02	±1.7E-02
White Spirit	kg	2.3E-01	±5.9E-01	1.2E-01	±5.9E-02	3.5E-01	±2.3E-01	2.4E-01	±1.7E-01
Cobalt	kg	1.5E-04	±3.8E-04	8.0E-05	±3.8E-05	2.3E-04	±1.5E-04	1.5E-04	±1.1E-04
Anti-fouling									
4-methyl-2-pentanone	kg	5.3E-03	±3.9E-03	3.0E-03	±1.5E-03	6.7E-03	±5.0E-03	4.8E-03	±3.5E-03
Xylene	kg	4.5E-02	±3.3E-02	2.5E-02	±1.2E-02	5.6E-02	±4.2E-02	4.0E-02	±2.9E-02
White spirit	kg	6.2E-04	±4.6E-04	3.5E-04	±1.7E-04	7.8E-04	±5.8E-04	5.6E-04	±4.1E-04
Ethyl benzene	kg	1.3E-02	±9.1E-03	7.0E-03	±3.4E-03	1.6E-02	±1.2E-02	1.1E-02	±8.2E-03
Ethanol	kg	5.3E-03	±3.9E-03	3.0E-03	±1.5E-03	6.7E-03	±5.0E-03	4.8E-03	±3.5E-03
Copper oxide	kg	1.3E-01	±9.1E-02	7.0E-02	±3.4E-02	1.6E-01	±1.2E-01	1.1E-01	±8.2E-02
Zinc oxide	kg	6.2E-02	±4.6E-02	3.5E-02	±1.7E-02	7.8E-02	±5.8E-02	5.6E-02	±4.1E-02
Fishing gear	kg								
Nylon	kg	3.1E-01	±2.3E-02	1.4E-01	±1.4E-02	2.0E-01	±1.4E-02	1.7E-01	±1.4E-02
Lead	Kg	7.1E-01	±5.3E-02	3.1E-01	±3.1E-02	4.6E-01	±3.2E-02	3.8E-01	±3.3E-02
Cork	kg	3.9E-02	±2.9E-03	1.7E-02	±1.7E-03	2.5E-02	±1.8E-03	2.1E-02	±1.8E-03
Ice[a]	kg	39.18	±6.07	516.7	±234.1	813.6	±556.0	684.7	±480.4
Outputs									
To the technosphere									
Products									
European Pilchard	t	1.00		1.00		1.00		1.00	
Co-Products									
Anchovy	t	0.18		0.19		0.02		0.10	
To the environment									
Emissions to the atmosphere									
CO_2	kg	557.2	±853.1	415.6	±568.6	1102	±294.9	748.0	±659.0
CH_4	kg	0.13	±0.17	0.09	±0.18	0.06	±0.02	0.08	±0.15
NO_x	kg	5.28	±8.55	4.04	±4.69	13.49	±3.61	8.61	±6.25
CO	kg	44.75	±55.95	30.71	±64.39	6.95	±1.86	19.22	±52.61
NMVOC	kg	9.13	±11.60	6.30	12.86	2.62	±0.70	4.52	±10.74
TSP	kg	0.93	±1.38	0.68	±0.99	1.62	±0.43	1.13	±1.09
PM10	kg	0.93	±1.38	0.68	±0.99	1.62	±0.43	1.13	±1.09
NH_3	kg	0.95	±1.54	0.73	±0.83	2.46	±0.66	1.56	±1.12
Emissions to the ocean									
Lead	kg	7.1E-02	±5.3E-03	3.1E-02	±3.1E-03	4.6E-02	±3.2E-03	3.8E-02	±3.3E-03
4-Methyl-2-pentanone	kg	4.0E-03	±2.9E-03	2.3E-03	±1.1E-03	5.0E-03	±3.7E-03	3.6E-03	±2.6E-03
vXylene	kg	5.1E-02	+6.9E-02	2.8E-02	±1.4E-02	6.8E-02	±4.8E-02	4.8E-02	±3.5E-02
Zinc	kg	4.7E-02	±3.4E-2	2.6E-02	±1.3E-02	5.9E-02	±4.4E-02	4.2E-02	±3.1E-02
Copper oxide	kg	9.4E-02	±6.8E-02	5.3E-02	±2.5E-02	1.2E-01	±8.7E-02	8.4E-02	±6.1E-02
Ethanol	kg	4.0E-03	±2.9E-03	2.3E-03	±1.1E-03	5.0E-03	±3.7E-03	3.6E-03	±2.6E-03
[1]Cobalt	kg	1.1E-04	±2.9E-04	6.0E-05	±2.9E-05	1.7E-04	±1.1E-04	1.1E-04	±8.3E-05

[a] The mean and standard deviation for ice in the 2014 sample represents the average of the two vessels that reported the use of ice. The remaining vessels reported not using ice on board

scenarios were modeled to identify how different inventory data assumptions affect the final results of the study, as shown in Table 6.

Regarding the uncertainties linked to the computation of the assessment method, two different scenarios were considered (see Table 6). On the one hand, economic allocation scenario was computed, as mentioned in Section 2.4, to identify the influence on final results with respect to mass allocation.[1] On the other hand, results were computed with other assessment methods. More specifically, IPCC 2013 was used for global warming for the sake of comparison with

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[1] Energy allocation was excluded from the assessment due to the very similar energy and protein content of European pilchard and European anchovy, the two species that represented more than 98% of total landings of the fleet.

Table 5 Impact categories considered for life cycle impact assessment. Source: ILCD assessment method (European Commission 2010)

Impact category	Acronym
Climate change	CC
Ozone depletion	OD
Human toxicity, cancer effects	HT(cancer)
Human toxicity, non-cancer effects	HT(non-cancer)
Particulate matter	PMF
Ionizing radiation HH	IR
Photochemical ozone formation	POF
Acidification	AP
Terrestrial eutrophication	TE
Freshwater eutrophication	FE
Marine eutrophication	ME
Freshwater eco-toxicity	FET
Land use	LU
Water resource depletion	WD
Mineral, fossil and renewable resource depletion	MFD

the GWP indicator used in the ILCD, which is actually IPCC 2007, the previous version.

Finally, regarding the statistical analysis, a non-parametric test was conducted to assess whether the vessels in the abovementioned fishery show differences in environmental impact when compared to those of the Galician purse seining fleet sampled in 2008. The selected non-parametric test, named the Mann-Whitney-Wilcoxon was conducted based on the assumption that all the observations from the groups are independent of each other.

3 Results

3.1 Overall results

Table 7 shows the environmental impact values for all the impact categories assessed. Vessels from Rianxo in year 2014 showed an average climate change (CC) value of 866 kg CO_2eq per FU. However, this value was higher for vessels powered by diesel engines (+ 13%) in comparison to gasoline-powered vessels (812 kg CO_2eq). For year 2016, results were disaggregated firstly in terms of port of origin. In this sense, the average vessel in Cambados presented a value of 1.36 t CO_2eq per FU, whereas GHG emissions on average in Rianxo were 52% lower (655 kg CO_2eq). Moreover, if the results in the port of Rianxo are divided based on the source of energy, these were gasoline-powered vessels, in contrast to what occurred in 2014, that show higher environmental impact (+ 12%), as compared to diesel-fuelled vessels. Although the average CC results for Rianxo decreased from 2014 to 2016 (655 kg CO_2eq), when averaged with the vessels from Cambados, the mean value for 2016 was slightly higher (992 kg CO_2eq). Furthermore, these variations in terms of GHG emissions are strongly correlated to changes in energy use intensity. In fact, the environmental impact results show that fuel production and consumption, in line with most fishery-LCA studies conducted to date, is the main activity responsible for impacts, ranging from 58 to 99% depending on the impact category, except for human toxicity non-cancer (HTnc), freshwater eco-toxicity (FET) and mineral, fossil and renewable resource depletion (MFD), in both years of assessment.

Unlike most fishing fleets analysed in the LCA literature, the small-scale fleet using *xeito* to target European pilchard is made up of a mix of vessels, some powered by diesel engines, whereas others use gasoline for propulsion. Although a regular trend is that impacts per FU are slightly higher for gasoline-powered vessels in terms of particulate matter formation (PMF), these values are influenced by the engine types assumed in the study. Four-stroke engines generate an order of magnitude lower impact than two-stroke engines. In contrast, MFD, ionizing radiation (IR) and photochemical oxidant formation (POF) were three impact categories in which gasoline-powered vessels performed worse than diesel-propelled vessels (see Fig. 5).

Anti-fouling paint presented a significant impact contribution for HTnc (47%) and FET (46%), being the operational activity that contributed the most to these impact categories in both years of assessment. Anti-fouling also presented a relevant contribution in terms of freshwater eutrophication—FE (28%). The impact contribution of the production of the gear for MFD was above 65% in both years of operation, whereas in terms of HTnc, the contribution range was ca. 20%. Ice production was

Table 6 Scenarios considered for sensitivity analysis

Scenario	Brief description
ReCiPe assessment method	Different characterization results based on assessment method
IPCC 2013 characterization factors	New characterization factors for IPCC 2013 methodology
Economic allocation	Two different economic allocation approaches based on pilchard origin
Fishing gear life span	Characterization results variation due to *xeito* gear life span fluctuation.
Base port influence	*Xeito* fleet assessment divided by base port
Gasoline engine type	4-stroke and 2-stroke engines disaggregated

Table 7 FUI, ep-EROI and LCIA characterization results per FU (1 ton of fish landed at port) for the *xeito* fishery during 2014 and 2016

		2014			2016				
		Rianxo			Rianxo			Cambados	Average fleet
	Units	Average fleet	*Diesel engine*	*Gasoline engine*	Average Rianxo fleet	*Diesel engine*	*Gasoline engine*	*Diesel engine*	
Fuel Use Intensity (FUI)[a]	L fuel/t fish	–	*309*	*224*	–	*226*	*231*	*426*	–
epEROI	%	**20.53**	*15.24*	*29.13*	**25.29**	*21.84*	*31.15*	*10.09*	**14.69**
LCA IMPACT CATEGORIES									
CC	kg CO2 eq	**865.8**	*923.9*	*812.2*	**655.0**	*619.1*	*709.2*	*1359.1*	**991.9**
OD	kg CFC-11 eq	**9.9E-05**	*1.2E-04*	*8.3E-05*	**7.53E-05**	*7.8E-05*	*7.3E-05*	*1.7E-04*	**1.2E-04**
HT(cancer)	CTUh	**5.0E-06**	*7.5E-06*	*3.0E-06*	**4.72E-06**	*5.9E-06*	*3.3E-06*	*1.2E-05*	**8.3E-06**
HT(non-cancer)	CTUh	**5.9E-05**	*7.4E-05*	*4.6E-05*	**4.01E-05**	*4.8E-05*	*3.1E-05*	*9.3E-05*	**6.6E-05**
PMF	kg PM2.5 eq	**1.30**	*1.60*	*1.05*	**0.97**	*1.04*	*0.90*	*2.31*	**1.61**
IR	kg U235 eq	**26.10**	*18.44*	*32.34*	**40.78**	*36.80*	*46.37*	*63.24*	**51.48**
POF	kg NMVOC eq	**17.18**	*12.48*	*20.99*	**12.32**	*8.08*	*17.87*	*17.95*	**15.00**
AP	molc H+ eq	**5.33**	*8.88*	*2.33*	**4.26**	*5.95*	*2.17*	*13.06*	**8.48**
TE	molc N eq	**24.10**	*42.49*	*8.63*	**18.65**	*27.53*	*7.59*	*61.17*	**39.05**
FE	kg P eq	**2.5E-02**	*3.4E-02*	*1.8E-02*	**2.5E-02**	*3.0E-02*	*2.0E-02*	*5.8E-02*	**4.1E-02**
ME	kg N eq	**2.21**	*3.89*	*0.79*	**1.71**	*2.52*	*0.70*	*5.60*	**3.57**
FET	CTUe	**629.0**	*746.2*	*527.8*	**618.6**	*680.2*	*548.0*	*1268*	**929.3**
LU	kg C deficit	**1792**	*2572*	*1132*	**1575**	*1911*	*1167*	*4066*	**2769**
WD	m3 water eq	**8.5E-02**	*1.8E-01*	*4.8E-03*	**1.5E-01**	*2.1E-01*	*7.3E-02*	*3.9E-01*	**2.6E-01**
MFD	kg Sb eq	**4.0E-03**	*3.3E-03*	*4.7E-03*	**2.8E-03**	*2.6E-03*	*3.1E-03*	*4.2E-03*	**3.5E-03**

[a] Fuel use intensity (FUI) is only reported for samples with the same energy carrier

highly dependent on the year of assessment. Taking into consideration that the samples in the 2 years of assessment were different, it was observed that ice used per landed metric ton of pilchard was 39.2 kg in 2014 and 685 kg in 2016. Hence, ice production environmental impacts were negligible in 2014 for all impact categories except for water depletion—WD (ca. 5%), whereas in 2016, these impacts were 58% in terms of IR, 41% for WD and 31% for MFD and FET. Finally, environmental impacts linked to boat paint and lubricant oil were not relevant in any impact category analysed.

Regarding the ep-EROI ratio, the average value for the fleet in 2014 was 20.5% (see Table 7). Considering only vessels from Rianxo, this value increased to 25.3% in year 2016. However, the mean value for the port of Cambados in 2016 was considerably lower (10.1%). Moreover, in accordance with the values obtained in terms of FUI and CC, there is a difference between diesel-powered vessels and boats that use gasoline for propulsion. When vessels are analysed separately based on the type of fuel used, gasoline vessels attain higher values (29.1% in 2014 and 31.2% in 2016) than diesel vessels (15.2% in 2014 and 21.8% in 2016). Complete data regarding CED assessment and edible protein embedded in European pilchard can be consulted in Table SM2.7 in the Electronic Supplementary Material.

4 Discussion

4.1 Environmental hotspots and statistical analysis: Contextualizing the results obtained

As shown in the results section, the distribution of environmental impacts across impact categories and operational activities does not differ much from that of other similar fishing fleets examined in recent years. In fact, when the *xeito* fishery is compared to other published studies, similar hotspots can be observed: fuel production and consumption, anti-fouling paint and ice production depending on the impact category evaluated (Hospido and Tyedmers 2005; Vázquez-Rowe et al. 2010). Fuel production and consumption during fishing operations involving the use of *xeito* proved to be the main source of environmental impact regardless of the type of fuel burned or the year analysed. This result is no surprise and is in line with other examined fishing fleets, which highlight direct and indirect fuel emissions as the most important carrier of GHG

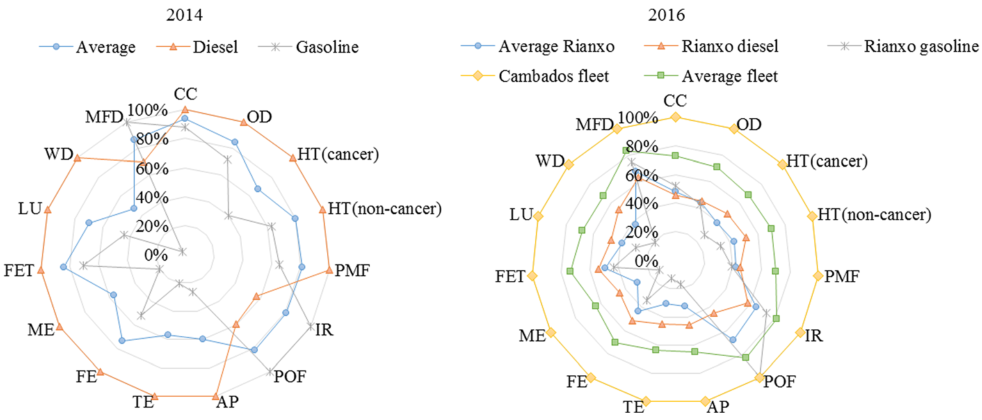

Fig. 5 Relative environmental profile linked to average European pilchard landings in the *xeito* fishing fleets in years 2014 and 2016, as well as landings performed by diesel- and gasoline-powered vessels

emissions, as well as other environmental impacts, such as eutrophication, particulate matter formation or acidification (Ziegler et al. 2016).

When analysing the environmental impacts as a whole, a recent study by Laso et al. (2017) shows that the purse seining fleet targeting European anchovy in the Cantabrian Sea presented a similar range of environmental impacts. More specifically, if the GHG emissions are analysed in detail, it can be observed that the range between 619 kg CO_2eq and 1.36 t CO_2eq per metric ton of landed pilchard is in line with the range observed for the landing of small pelagic species (including pilchard) by purse seiners along the Spanish Atlantic continental platform (see Table 8).

If other environmental indicators are analysed, including FUI and ep-EROI, but also other LCA impact categories (see Table 8), results confirm that the small-scale fleet that uses *xeito* as a gear to catch European pilchard does not offer relevant differences in environmental impact as compared to the fishing fleet that represents the greater proportion of small pelagic landings, including 99% of European pilchard: purse seiners. Nevertheless, for these results to be conclusive, both fleets should be compared in the same year of assessment, which is not the case in this study, since the available data for the Galician purse seining fleet are from 2008.

Despite this limitation, the Mann-Whitney-Wilcoxon statistical analysis test allows detecting differences between two populations that are independent of each other. Hence, the two annual samples used in the current study were compared individually to the sample of purse seiners used in Vázquez-Rowe et al. (2010). In order to avoid constraints in terms of comparability of the populations, the comparison was not performed in terms of the GHG emissions or any other environmental indicator, but rather on the basis of the amount of energy, measured in MJ, used to power the vessels per FU.

The rationale behind this assumption is linked to the fact that based on observations performed in studies elsewhere, there has been some discussion of the drivers that lead an industrial fleet to improve or worsen its environmental impact (Ziegler et al. 2016). These trends have been bound to improvements in technical efficiency (Eigaard et al. 2014) or attributed to changes in fishermen behaviour, i.e., the so called "skipper effect" (Branch et al. 2006). Similarly, Ziegler and Hornborg (2014) found that stock size matters when it comes to improving FUI and LCA results. In other words, the authors identified that rebuilding of demersal stocks in Sweden was directly correlated to an improvement in fuel efficiency and, therefore, in environmental impacts. Another study presented by Ramos et al. (2011) analysed the Basque purse seining fleet targeting Atlantic mackerel (*Scomber* spp.) along the Cantabrian coast. In this particular study, a certain correlation was identified between years with low spawning stock biomass (SSB) and higher environmental impacts.

Results of the Mann-Whitney-Wilcoxon suggest that vessels from Cambados present a distinct behaviour in terms of their FUI as compared to the vessels in Rianxo as described in Section 2.5. In this sense, there is no evidence for a significant difference between the *xeito* sample in the year 2014 and the seiners for a confidence interval of 95%. Although it could be argued that diesel- and gasoline-powered vessels should be treated as independent samples, this was not considered given the fact that these vessels coexist in the port of Rianxo under similar conditions in terms of vessel size, horse power of the engines, fishing grounds and landing ports. For the year 2016, the sample was disaggregated into two smaller samples based on the port of origin. In this case, the Mann-Whitney-Wilcoxon test suggests that that there is no evidence for a significant difference between seiners and *xeito* vessels in the port of Rianxo in 2016, confirming the results presented above for the year 2014. However, in the case of the vessels from Cambados, the result is significant at a 2% level.

While there may be port-specific variability, the information in Table 8 and the results of the statistical comparison of MJ per FU do not indicate that there are obvious differences in fuel-based environmental impacts between seiners and small-scale vessels. In this sense, future research should focus on enhancing the temporal robustness of this observation. Moreover, the fact that the larger vessels from Cambados showed a different behaviour to those from Rianxo, regardless

Table 8 Comparative results for fuel use intensity (FUI), edible protein energy return on investment (ep-EROI) and global warming potential (GWP) with other studies available in the literature. Results are linked to 1 metric ton of landed fish, assuming mass allocation. GWP results were computed with a series of different assessment methods (i.e., ReCiPe midpoint-H, CML-IA, ILCD and IPCC 2007 and 2013); no homogenization of the results based on the assessment method was performed based on the assumption that differences are negligible

Species	Fishing gear	Reference year	Fishing area	ep-EROI (%)	FUI (L/metric ton)	GWP (kg CO_2eq)
European pilchard	*Xeito*	*2014*	*Current study (average fleet)*	*20.5*	*229*	*866*
European pilchard	*Xeito*	*2016*	*Current study (Cambados diesel-fueled fleet)*	*10.1*	*422*	*1359*
European pilchard	*Xeito*	*2016*	*Current study (Rianxo diesel-fueled vessels)*	*21.8*	*228*	*619*
European Pilchard[a]	Purse seining	2011	Portuguese coast	N/A	118	510
European Pilchard[b]	Purse seining	2008	Galician coast—Spain	18.3	196	790
Atlantic mackerel[b]	Purse seining	2008	Galician coast—Spain	17.8	196	790
Horse mackerel[b]	Purse seining	2008	Galician coast—Spain	14.9	196	790
European anchovy[c]	Purse seining	2015	Cantabria—Spain	12.2	340	1320
European hake[b]	Drift net	2008	Galician coast—Spain	N/A	123	N/A
European hake[b]	Trawling	2008	Galician coast—Spain	5.7	557	2290
Senegalese hake[b]	Trawling	2009	Mauritanian EEZ	1.5	1939	7750
Patagonian grenadier[b]	Trawling	2010	FAO area 87 (Chile)	10.4	469	2700
Octopus[b]	Trawling	2009	Mauritanian EEZ	2.1	1939	7750
Norway lobster[b]	Trawling	2008	Northern stock—Galician fleet	0.8	2363	8800
Atlantic mackerel[b]	Trawling	2008	Galician coast—Spain	7.3	557	2290
Tuna[b]	Long-lining	2005–2008	Azores	2.8	1200	N/A
Global fisheries[d]	Varied	N/A	N/A	8	N/A	N/A

N/Av not available

[a] González-García et al. 2015

[b] Vázquez-Rowe et al. 2010, 2014b, c

[c] Laso et al. 2017

[d] Tyedmers et al.,2005

of the energy carrier for propulsion, suggests that segmentation within the Galician small-scale fleet in terms of capacity, size or engine power, in a similar way to what was done by Avadí et al. (2014) for the *anchoveta* fleet in Peru, could provide useful insights regarding the variability of this fleet subdivision. Complete data regarding the Mann-Whitney-Wilcoxon statistical test can be consulted in Table SM 3.1 in the Electronic Supplementary Material.

4.2 Linking LCA environmental impacts and stock size

The stock size of European pilchard was analysed for the past decade in divisions VIIIc and IXa, which correspond to the fishing area of vessels targeting this species in Galician waters (both seiners and small-scale vessels using *xeito*). As shown in Table 9, the biomass of pilchard has been cut by half in the past decade (ICES 2016). Fishing mortality (F) doubled in the period 2008–2011 as compared to a relatively low *F* value below 0.25 in the period 2002–2007. In addition, ICES advice was ignored for every single year of operation after 2007 except for 2013 (see Table 9). The main consequence of the mismanagement of the sardine stock is the fact that the cyclic boom in recruitment, which tends to be critical in small pelagic fish to guarantee a robust SSB in short lifespan species, is yet to occur since 2004, when the last pulse of good recruitment occurred (Santos et al. 2011).

Hence, it could appear plausible to hypothesize that environmental impacts in the seining fleet would also be high for the years 2014 and 2016, since stock abundance was in a healthier state in 2008. However, when analysing the data published in Vázquez-Rowe et al. (2010), it must be noted that seiners in Galicia do not target one single species, but rather land a variety of small pelagic fish, mainly pilchard, Atlantic mackerel (*Scomber scombrus*) and Atlantic horse

Table 9 Stock assessment summary for the European pilchard (*Sardina pilchardus*) stock in Divisions VIIIc and IXa. The last column represents the proportion of landings attributable to the *xeito* fishery. Source: ICES (2016)

Year	Biomass 1+ (tonnes)	*F*	Recruitment—age 0 (thousands)	Landings (tonnes)	Adviced catch (tonnes)	% over advice	% of catch *xeito* fishery
2008	378,483	0.354	5,706,010	101,000	92,000	9.8	N/Av
2009	285,870	0.399	6,660,540	87,000	71,000	22.5	N/Av
2010	228,887	0.540	3,295,820	90,000	75,000	20.0	N/Av
2011	198,134	0.610	3,152,300	80,001	75,000	6.7	0.34
2012	146,805	0.464	3,664,570	55,000	36,000	52.8	0.31
2013	158,020	0.418	4,781,900	46,000	< 55,000	Below advice	0.35
2014	135,106	0.244	4,009,410	27,937	< 17,000	64.3	0.71
2015	168,221	0.145	4,655,210	20,595	< 16,000	28.7	0.78
2016	199,264	N/Av	4,005,000		< 12,000		N/Av

N/Av not available

mackerel (*Trachurus trachurus*). Although all small pelagic species, they do present species-specific behaviours, an issue that has an influence on the efficiency of the fishery (Ziegler et al. 2016). The lack of disaggregated data for individual days in which vessels target different species is a significant limitation when it comes to drawing conclusions regarding these trends.

Another point of discussion is the fact that the two fishing fleets (i.e., seiners and small-scale vessels) have to share the pilchard quota of the same biological stock. However, the area of operations slightly differs for the two fleets as shown in Fig. 3, with vessels with *xeito* license allowed to operate within the inner area of the Galician *rias*. Nevertheless, the distribution dynamics of European pilchard in the area are yet to be fully understood. In fact, previous studies have noted the lack of scientific research linked to coastal fisheries in Galicia (Pita et al. 2016).

Regardless of the operational differences in the way in which European pilchard is captured off the Galician coast, it remains evident that this species, used mainly for direct human consumption in the region, is still an energy-efficient way to produce food when compared to most sources of animal protein (Noya et al. 2017). In fact, a study performed by Vázquez-Rowe et al. (2014a), which analysed the entire supply chain of sardines arriving from the local seining fleet, demonstrated that its environmental impacts, provided it is not canned in tin containers, are very low as compared to demersal fish. Moreover, a recent study by Clune et al. (2017), which reviewed the global warming potential (GWP) values for 168 types of fresh food products, suggests that pilchard consumption would entail substantially less GHG emissions per consumed kilogram than livestock, dairy products and a majority of other fish species.

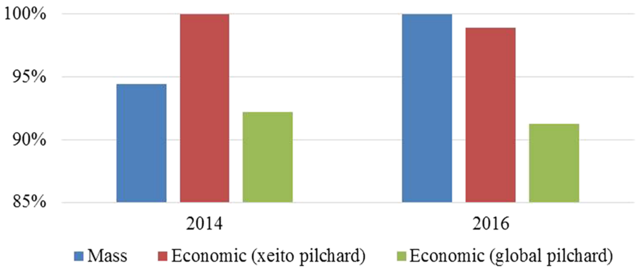

Fig. 6 Comparative relative environmental impacts for the allocation perspectives evaluated (applicable to all impact categories assessed)

4.3 Sensitivity analysis

Alternative assessment methodologies and allocation approaches were explored for the sensitivity analysis (see Section 3 in the SM for numerical details). Firstly, ReCiPe midpoint-H and IPCC 2013 methodologies were computed with the aim of identifying the fluctuation in environmental burdens based on method and characterization factors. Thus, for those impact categories which share reference units with ILCD, the ReCiPe results shows similar impact figures for

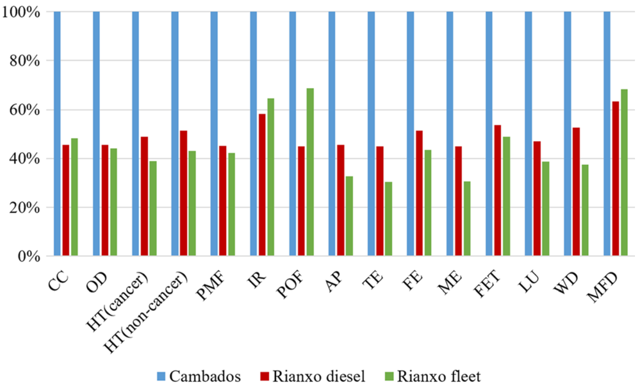

Fig. 7 Relative environmental impact performance of European pilchard landings by the small-scale fishing fleet using *xeito* dividied by base port. Results are reported for year 2016

CC, OD, FE, POF and IR, except for ME and WD. The underlying factors behind the latter are related to the different characterization factors of both methods for ME and WD. Similarly, the GWP indicator does not differ much when the IPCC 2013 method is implemented, being 2% lower for IPCC 2013, which is mainly attributable to the lower characterization factor of dinitrogen monoxide (i.e., 265) that has been more recently recommended. More detailed data for sensitivity analysis can be consulted in the SM. Secondly, two economic allocation approaches were explored based on the level of detail available for European pilchard prices once landed. Hence, two different average auction prices for years 2014 and 2016 were considered: (i) the price for global pilchard landings (which include that of purse seiners, *xeito* and incidental catches from other gears), on the one hand, and (ii) the price linked to *xeito* landings exclusively, on the other. Traditionally, due to better visual appearance and flesh texture, pilchards caught by the *xeito* fleet achieve higher auction values than those caught by seiners. Figure 6 depicts that using economic allocation has little influence on impact results—less than 10% variation for both perspectives. In addition, it should be remarked that there is minimal difference between mass and economic allocations, which reinforces the selection of mass allocation for *xeito* vessels and the selectivity of this gear, since we consider that mass allocation better reflects the reality of this species due to volatile prices (Laso et al. 2017). Thirdly, the influence of assumptions made for LCI was explored for fishing gears. Skippers reported complete material substitution every 5–6 years, being 6 years the life span selected for this study. Nonetheless, two different schemes were assessed to evaluate possible impact fluctuations when the life span is either increased or decreased. However, the latter variations only affected significantly the impacts in terms of HT (non-cancer) and MFD (see Table SM3.4 in the Electronic Supplementary Material). Finally, the influence on environmental impacts of the characteristics of gasoline engines was evaluated. Two schemes were assessed taking into account that gasoline-fuelled fleet is either made up of 2-stroke or 4-stroke engines, exclusively. Thus, whilst 4-stroke engines increased the impact considerably for AP, TE and ME, due to higher emission values of ammonia, carbon monoxide or nitrogen oxides, 2-stroke engines presented higher impacts for PMF and POF, linked to increased particulate matter and non-methane volatile organic compounds (NMVOC), respectively (see Table SM3.5 in the Electronic Supplementary Material).

Interestingly, the environmental performance of vessels varies taking into account the base port (Fig. 7). In this regard, vessels based in Rianxo present significantly lower environmental impacts per FU (47% on average) for all impact categories when compared to vessels from Cambados. The reason behind these differences is related to two main issues. Firstly, the length of the vessels in Cambados is substantially higher (ca. 10 m) than those in Rianxo (approximately 6 m). Secondly, the engine power of the vessels in Cambados was an order of magnitude higher (208 hp on average), as compared to a range of 25–30 hp. in Rianxo. Nevertheless, other factors such as the distance to fishing areas or the “skipper effect” could be underlying issues that should be explored further in future research (Vázquez-Rowe and Tyedmers 2013).

5 Conclusions

From a life cycle perspective, results do not indicate that the EU-proposed ban on SSDs that target pilchard in Galician waters would imply substantial environmental benefits, since the main impact categories show similar value ranges to those observed in other fisheries targeting small pelagic fish in NW Spain. Having said this, it must be noted that LCA outcomes cannot be considered as the single criteria to assess the convenience of banning a specific gear or not. However, it does add to a series of integrated assessment methods that have been steadily included in fisheries management to account not only for the biological stock assessment of a single species, but also for a set of economic, social and environmental indicators. More specifically, LCA allows assessing global-scale environmental impacts linked to the industrial nature of the small-scale fishery assessed, providing additional information in terms of energy flows and environmental burdens, which can ultimately be of utility in policy support.

Small-scale fishing vessels that use *xeito* for landing pilchard rely on this gear to subsist economically throughout the greater part of the fishing year. Moreover, these vessels constitute a substantial source of revenue in several port towns along the Galician coast. In this sense, we hypothesize that banning the use of *xeito* may lead to a reduction in the number of fishermen in coastal Galician towns, since the remaining authorized licences of these vessels, mainly to capture shellfish and other pelagic species, would barely guarantee sufficient economic revenue throughout the year. Hence, future actions should focus on the social and economic sustainability of this fleet. In this context, social life cycle assessment (SLCA) and life cycle costing (LCC) may provide additional insights regarding the sustainability of *xeito*.

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