Int J Life Cycle Assess (2015) 20:1415–1428
DOI 10.1007/s11367-015-0943-2

Life cycle assessment of Ecuadorian processed tuna

Angel Avadí[1,2] · **Carolina Bolaños**[3] · **Isabel Sandoval**[4] · **Carla Ycaza**[4]

Received: 14 May 2015 / Accepted: 20 July 2015 / Published online: 30 July 2015

Abstract
Purpose Ecuador is an important player in the global tuna fishing and processing industry: The Ecuadorian industrial tuna fleet represents 17 % of the global tuna purse seiner fleet, and it is the second largest tuna processing country after Thailand. The fishing and processing operations of one of the largest vertically integrated tuna processing firms in Ecuador were evaluated regarding their environmental impacts and assumed representative of the Ecuadorian tuna processing industry. Results were compared with those of other international fish processing and other sources of animal protein for human consumption. Directions are finally identified toward reducing environmental impacts of both the tuna fishery and processing industry.
Methods Detailed operational fishery and processing data was collected from a representative Ecuadorian tuna processing firm, and the life cycle assessment framework applied to it for hotspot identification. Two functional units were used: 1 t of final product (for canned, pouched, vacuum bagged and mean products) and 1 t of "fish in product", which includes all process losses and normalises the final product/raw fish ratios among the different processing routes analysed. The ReCiPe impact assessment method was used.
Results and discussion In the period 2012–2013, the studied sub-fleet featured a fuel use intensity of 835 L per landed tonne, which was 235 % higher than reported values for all tuna landings in the Pacific Ocean in 2009. Reasons for such underperformance may include inter-annual variations in tuna catchability and the fact that fuels are generally subsidised in Ecuador, and thus skippers perhaps do not apply sufficient fuel-saving strategies. The main contributors to impacts associated with tuna processing were the provision of tinplate cans (58.0 % of the ReCiPe single score) and fuel use by the fishery (22.6 %). Ecuadorian tuna products feature environmental impacts generally higher than those of other fish processing industries worldwide, yet lower than those of many alternative sources of fish and land animal protein.
Conclusions Efforts to reduce environmental impacts of Ecuadorian tuna processing should focus on the fuel performance of the providing fleet, and on the container technology. Increased use of larger tinplate cans, aluminium cans, or other non-metal container technologies (e.g. pouches and retort cups) would decrease environmental impacts of tuna processing. The sources of relative inefficiency observed for the Ecuadorian tuna fleet should be thoroughly investigated. Possible solutions could involve applying fuel-saving strategies.

Keywords Canning · Ecuador · Fuel use intensity · Tuna

Responsible editor: Ian Vázquez-Rowe

Electronic supplementary material The online version of this article (doi:10.1007/s11367-015-0943-2) contains supplementary material, which is available to authorized users.

✉ Angel Avadí
angel.avadi@rennes.inra.fr

1 INRA, UMR1069 Sol Agro et hydrosystème Spatialisation, 35000 Rennes, France

2 AGROCAMPUS OUEST, UMR1069, 35000 Rennes, France

3 Negocios Industriales Real S.A. (NIRSA), Av. Carlos Luis Plaza Dañín y Democracia, Guayaquil, Ecuador

4 Soluciones Ambientales Totales S.A. (SAMBITO), Centro de Convenciones "Simón Bolívar", Oficina 19, Guayaquil, Ecuador

1 Introduction

Ecuador is one of the top ten tuna fishing countries in the world, and the second largest tuna processing country—after

Thailand—accounting for almost 12 % of global annual production with 362,400 t produced in 2008 (Miyake et al. 2010; Hamilton et al. 2011). After cultured shrimp, tuna products represent the second most traded fisheries and aquaculture product of Ecuador. The fisheries and aquaculture sector represented 12 % of total trade for the country in 2012, ranking second after petroleum (FAO 2013).

The Ecuadorian tuna-targeting industrial fleet, featuring 107 purse seiners as of 2013 with holding capacities between 46 and >425 m^3 and a cumulative capacity of 84 721 m^3, is the main Ecuadorian industrial fleet (Pacheco Bedoya 2013). This fleet represented in 2008 roughly 44 % of the Eastern Pacific Ocean (EPO) purse seiner fleet and 17 % of the global tuna purse seiner fleet (Hamilton et al. 2011). In 2013, the Ecuadorian fleet represented 38 % of the EPO tuna fleet and landed 42 % of that year's 554,000-t captures in the EPO (IATTC 2014). It targets three main tuna species: yellowfin ("aleta amarilla", *Thunnus albacares*), skipjack ("barrilete", *Katsuwonus pelamis*) and bigeye ("patudo" or "ojo grande", *Thunnus obesus*). Tuna is captured both in Ecuador's exclusive economic zone, which includes the Galapagos Islands, and in international waters (26 and 74 % of captures, respectively). Ecuadorian fishing operations by purse seiners are based on three types of sets: non-associated with other species (35 %), using fish aggregation devices (FADs, 60 %) and associated with dolphins (5 %) (Pacheco Bedoya 2013). The catch is immediately frozen onboard. Some of the 15,500 Ecuadorian artisanal/small-scale fishery (FAO 2013) vessels target fish from the *Scombridae* family, mainly using long lining. The artisanal fleet's landings are negligible compared to industrial landings, ranging from 1609 to 6879 t per year from 2007 to 2013 (Cabanilla 2013). Total annual industrial landings have increased exponentially since 1950 (Fig. 1). Bycatch of tuna landed by the industrial fleet (≈4 %) mainly consists of commercially interesting species (i.e. from the *Xiphidae*, *Coryphaenidae* and *Istiophoridae* families). According to the Inter-American Tropical Tuna Commission (IATTC, which regulates tuna fisheries in the EPO), interactions with or bycatch of sea turtles, sharks —mainly *Carcharhinus falciformis* and *Carcharhinus longimanus* (Román-Verdesoto and Orozco-Zöller 2005)— dolphins and *Scombridae* juveniles by tuna purse seiners is dominated by sets with FADs (IATTC 2013). FAD sets are also known to be associated with higher fuel use per tonne of landings (Parker et al. 2014) and higher levels of bycatch (Bromhead et al. 2003). Shark bycatches in particular have been high in the EPO, but a generally decreasing trend has been identified (IATTC 2013). It should be noticed that landing of sharks and shark fins is forbidden in Ecuador since 2007 (Pacheco Bedoya 2013). It is also reported that considerable improvement has been reached in the EPO since the 1990s towards reducing dolphin mortalities to under 1000 mortalities per year (https://www.iattc.org/DolphinSafeENG.htm, IATTC 2013). Certain tuna stocks in the EPO, targeted by Ecuadorian fleets, are in a delicate state (Gilman 2011) and considered as fully exploited. Landings of Skipjack tuna (*Katsuwonus pelamis*) in particular are responsible for the exponential increase in Ecuadorian tuna landings until 2012. Such pattern is likely due to an increase in fleet size, because both effort and biomass have been relatively constant in the last 10 years (Maunder 2014). Moreover, despite uncertainty regarding the status of the skipjack tuna EPO stock, there is no evidence that the stock is overfished (Maunder 2014).

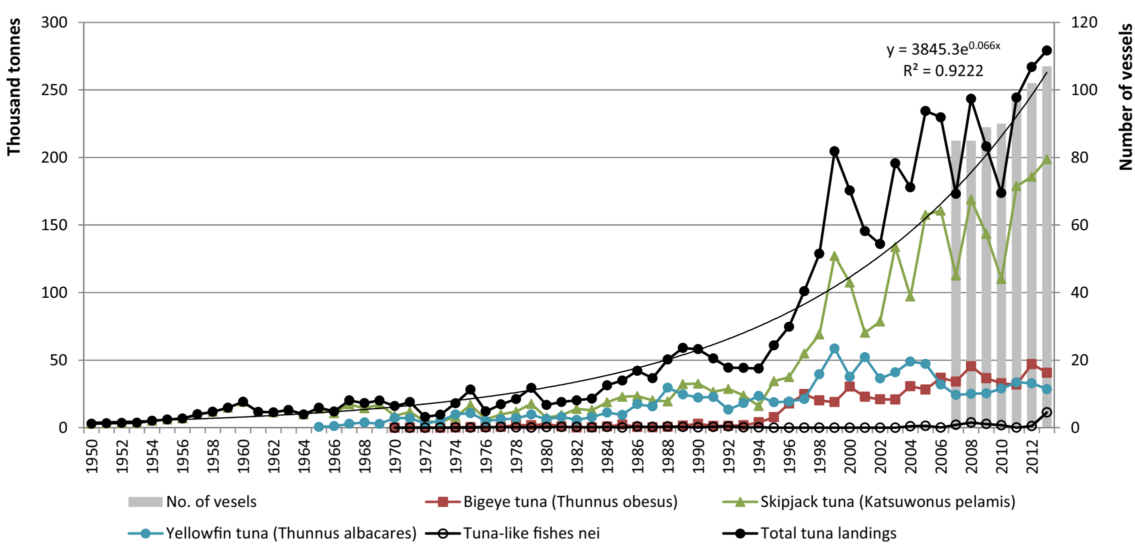

Fig. 1 Annual tuna landings (Ecuadorian and foreigner vessels landing in Ecuador) from 1950 to 2013, based on statistics from FishStatJ (http://www.fao.org/fishery/statistics/en), and number of vessels from 2007 to 2013. Total annual landings increased at an exponential rate (*regression curve*)

As of 2014, 27 tuna processing plants were active in the country, according to the Vice-Ministry of Aquaculture and Fisheries (Viceministerio de Acuacultura y Pesca, http://www.viceministerioap.gob.ec/). Plants are located in two coastal provinces: 81 % in Manabí, mainly in the city of Manta (70 % of annual landings), and 19 % in Guayas, in Guayaquil (5 % of landings) and Posorja (25 % of landings) (Pacheco Bedoya 2013) (Fig. 2). The number of plants has increased since 2008, when there were only 18 processing plants, with an cumulative installed capacity of 447,600 t/year (Hamilton et al. 2011). Most industrial tuna products are destined for export markets, mainly in the European Union (especially Spain, Germany and the Netherlands). Ecuadorian production and export of tuna products increased 16-fold and 95-fold, respectively, from 1976 to 2011 (Fig. 3). The value of tuna exported, 14 million USD in 1990, increased to 1034 million USD by 2013 (Fig. 4). Residues from tuna processing are usually sent to reduction plants to produce fishmeal.

Tuna fisheries are regulated in Ecuador by the 2005 Fisheries Law and overseen by the Vice-Ministry of Aquaculture and Fisheries, the IATTC and the Ecuadorian National Fisheries Institute (Instituto Nacional de Pesca, INP). The latter two institutions keep onboard observers and detailed capture and discard logs.

Given the global relevance of the Ecuadorian tuna processing industry, this study evaluates environmental impacts of the fishery and the processing industry, identifies hotspots by studying a major fish processing plant and its supplying fleet and contrasts results with those of other international fish processing industries and other animal protein sources. We assessed the dedicated sub-fleet and fish processing plant, owned and operated by Negocios Industriales Real S.A. “NIRSA” (http://www.nirsa.com/), for the years 2012 and 2013. NIRSA owned and operated 13 purse seiners, which supplied 46–50 % of their tuna intake. The remaining catch is purchased from third-party fishing vessels. NIRSA’s processing volumes (61,000 t of raw tuna processed per year) represent roughly 33 % of

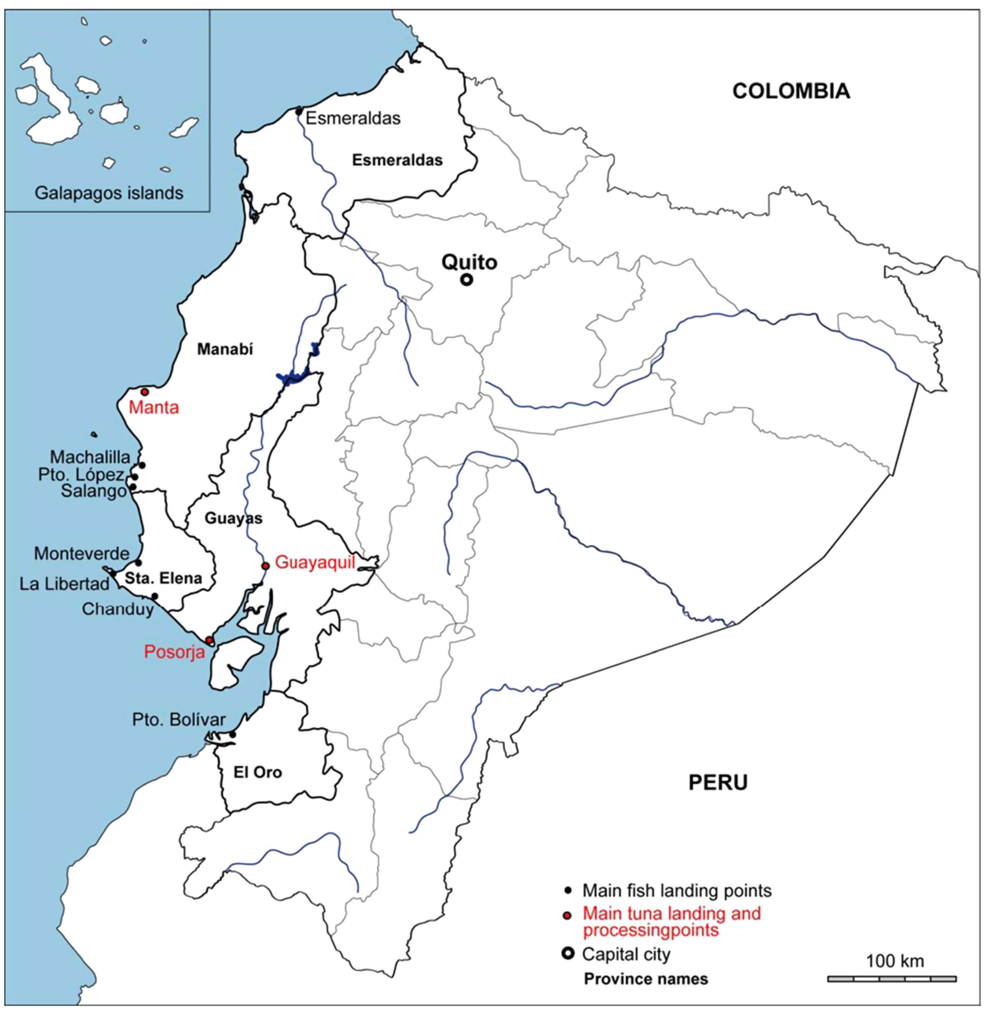

Fig. 2 Main fish landing points and tuna landing and processing points in Ecuador (map is a combination of maps from http://d-maps.com)

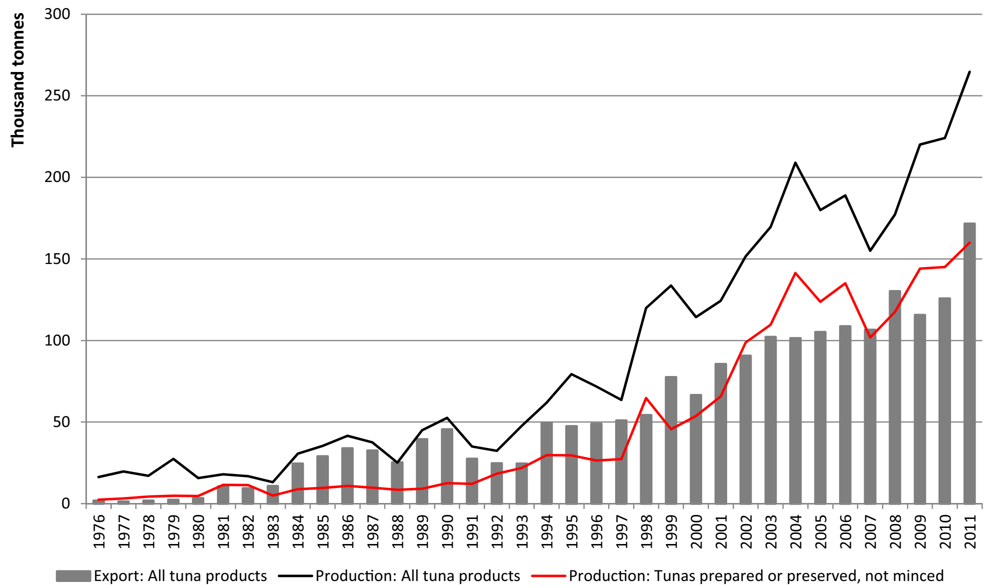

Fig. 3 Historic (1976–2011) Ecuadorian tuna processing and export volumes, based on statistics from FishStatJ (http://www.fao.org/fishery/statistics/en). "All tuna products" include whole or partially processed fish (*longfin*, *bluefin*, *bigeye*, *skipjack*, *yellowfin* and other tuna-like fish), as well as loins, fresh, chilled or frozen. "Tunas prepared or preserved, not minced" corresponds to canned tuna products (http://www.fao.org/figis/)

Ecuador's annual tuna processing. Canned tuna products by NIRSA represented 55 and 52 % of the Ecuadorian market in 2013 and 2014, respectively.

2 Methods

The life cycle assessment (LCA) framework (ISO 2006a; ISO 2006b) was applied to assess environmental impacts of Ecuadorian industrial tuna processing, from cradle to gate, using 1 t of tuna product (in either product type studied, as detailed below) as the functional unit (FU). We also used a secondary functional unit, namely 1 t of "fish in product", to include all process losses and normalise the final product/raw fish ratios among the different processing routes analysed. No specific standard other than the ISO 14040/14044 (ISO 2006a; ISO 2006b) was followed to carry out the study. The recent Product Category Rule "PCR 2014:11 Fish, otherwise prepared or preserved; caviar and caviar substitutes" (http://www.environdec.com) was consulted, as well as the *Goal and scope description* document of the PEFCR pilot "Seafood for human consumption" (http://ec.europa.eu/environment/eussd/smgp/pef_pilots.htm), but this work diverges from these guidelines in the following aspects: It excludes the recycling of packaging materials, it includes the valorisation of fish residues and models them as an avoided product (raw material for the fishmeal industry), and it excludes the distribution and consumption phases.

From the life cycle phases of both fisheries and fish processing plants, namely, construction, use, maintenance and end-of-life (EOL), primary data were collected for use and maintenance only. Construction, structural maintenance and especially EOL are systematically excluded in processed seafood LCA literature (Hospido et al. 2006; Iribarren et al. 2010; Vázquez-Rowe et al. 2014; Almeida et al. 2015) and fisheries LCA literature (Avadí and Fréon 2013) under the assumption that their contributions to overall impacts are negligible. In a very fuel-efficient fishery, however, construction and structural maintenance may have non-negligible contributions (Avadí et al. 2014b; Fréon et al. 2014a); thus, we prophylactically included these life cycle phases for the fishery, and the construction phase for the tuna processing plant (the latter to confirm or deny its perceived negligibility). The system boundary thus includes all inputs and emissions associated with the construction, use, maintenance and EOL of the tuna fishery until the landing port, as well as those associated with the construction, use and maintenance of the processing plant, from fish landing until the storage of final products.

Operational data (capture, effort and vessel maintenance) was collected for the sub-fleet of 13 NIRSA purse seiners for the period 2012–2013, and the mean fuel use intensity (FUI) of this sub-fleet was assumed to represent that of the national fleet. Since no detailed structural data for Ecuadorian vessels were collected,[1] the construction and EOL phases were built using data from Peruvian purse seiners (Avadí et al. 2014b; Fréon et al. 2014a) of similar holding capacities, and extrapolations were made when necessary. Construction of air scouting equipment (helicopters) was included as a background process, while its fuel (aviation gasoline, or avgas) consumption was modelled from primary data. A conservative lifetime of 20 years was assumed for all vessels.

[1] Data collection originally aimed to fulfil the needs of a scope 2 carbon footprint calculation, which excludes the first and last life cycle phases of production systems (BSI 2011; BSI 2012); thus, no construction data were collected for the NIRSA fleet.

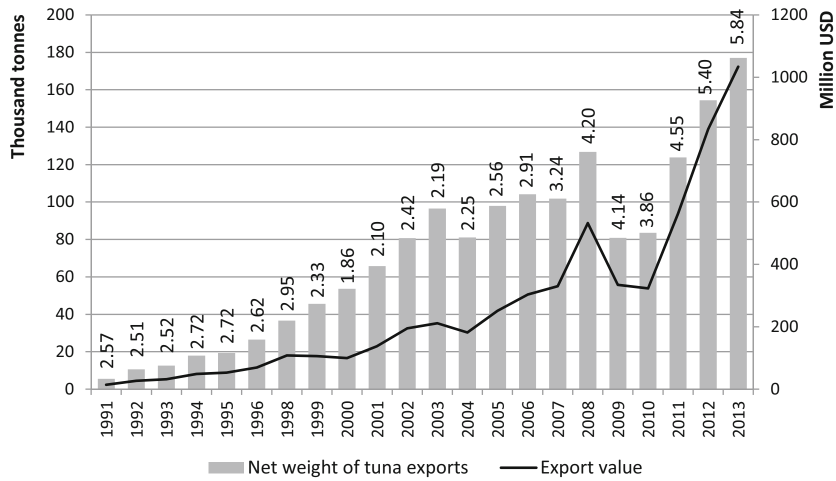

Fig. 4 Historic trade value of Ecuadorian tuna exports: total trade volume in 1991–2012, based on statistics from Comtrade (http://comtrade.un.org/data/) (labels correspond to average annual prices of tuna products, in thousand USD/t)

Individual life cycle inventories (LCIs) compiled for operation and maintenance (fuel use, landings, lubricants, refrigerants, etc.) of the NIRSA sub-fleet were aggregated into segments, in order to analyse fleet performance. These segments correspond to ranges of holding capacity: smaller (270–370 t), medium-small (520–540 t), medium (950 t) and larger, helicopter-supported vessels (1050–1750 t) (Fig. 5). This sub-division does not correspond to the official classification of tuna purse seiners established by the IATTC, which aggregates into a single class all vessels with holding capacity greater than 363 t, because we found it to be insufficient for detailed analysis, given that most NIRSA purse seiners would correspond to the largest official class (Table 1 and Fig. 5). ANOVA tests were performed to assess whether these segments really have different fuel performance.

Life cycle inventories (LCIs) were compiled for the operation (use and maintenance) of NIRSA's Posorja-based fish processing plant, also for 2012–2013. Data were collected as an aggregation of annual inputs and outputs; thus, for instance, no individual tuna can sizes were modelled, but total annual consumption of cans (in kg) and total annual production of canned products were. To model the construction phase, data from Peruvian fish processing plants were scaled up and used as a proxy (Avadí et al. 2014a), with a lifetime of 40 years. Peruvian and Ecuadorian fish processing plants were assumed to be similar regarding performance, technology and lifespan, because both countries feature emergent economies with a large and important exports-oriented fish processing industry.

The NIRSA plant produces three types of tuna products (production process map is depicted in Fig. 6): canned tuna loins and bellies (canned tuna) in vegetable oil, tuna loins packed in flexible pouches (pouched tuna), and pre-cooked tuna loins frozen in thermo-shrinkable plastic bags (bagged tuna, a semi-finished product for export only). These tuna products are representative of the national tuna processing industry. Various vegetable oils were used, with the inventory dominated by soybean oil (79 %) and sunflower oil (16 %). A custom process for soybean oil from Bolivia, previously used in Avadí et al. (2014a), was used as proxy of all vegetable oils (Bolivia was one of the main origins of soybean oil consumed in Ecuador, together with Paraguay and Argentina[2]).

Ecuadorian grid electricity was modelled based on official electricity generation emission factors (MAE 2012; MAE 2013). This customised electricity process was used in all electricity-consuming processes, including wastewater treatment and can manufacturing. Wastewater treatment, which follows a conventional physical-chemical process, was modelled as a background process (see below). Manufacturing of tinplate cans and other packaging was modelled according to a recent Peruvian fish processing study (Avadí et al. 2014a). Fish residues sent for reduction into fishmeal were modelled using previous models for the dedicated Peruvian *anchoveta* (*Engraulis ringens*) fishery developed by the ANCHOVETA-SC project.[3] The difference in fishmeal yields for fresh anchoveta (4.21) and fish residues (5.5) was considered when modelling tuna residues as avoided landings of fresh anchoveta by the least efficient segment of the Peruvian anchoveta fleet, which is overall the most fuel-efficient fleet in the world, with a FUI of ≈16 kg/t (19 L/t) (Fréon et al. 2014a; Avadí et al. 2014b). The rationale was that Ecuadorian fisheries providing raw material for the fishmeal industry are likely less fuel-efficient. Composition of antifouling paint was assumed equivalent to that used by the Peruvian industrial fishery (Fréon et al. 2014a).

[2] According to trade statistics from TradeMap, http://www.trademap.org/Country_SelProductCountry_TS.aspx?nvpm=1|218||||1507|||4|1|1|1|2|1|2|1|

[3] ANCHOVETA-SC was a 2010–2014 French-Peruvian project devoted to analysing environmental and sustainability performances of Peruvian supply chains based on the anchoveta fishery (http://anchoveta-sc.wikispaces.com).

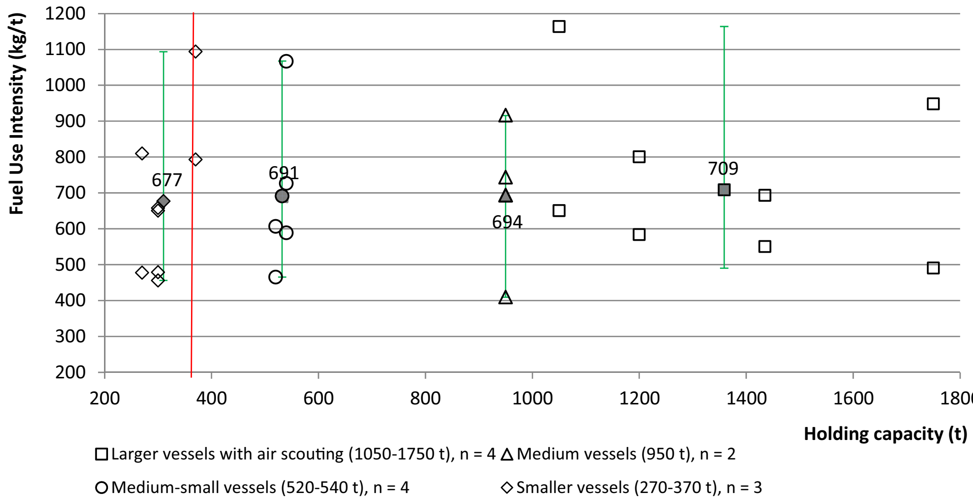

Fig. 5 Fuel use intensity of four segments of the Negocios Industriales Real S.A. "NIRSA" tuna fleet (sample $n=13$ purse seiners with 25 FUI/year/vessel data points) for the period 2012–2013. *Grey-fill* symbols represent landings-weighted fuel use intensity per segment; the *vertical line* represents the lower limit of the upper class of the official Inter-American Tropical Tuna Commission industrial tuna purse-seiners classification, and *error bars* represent the range of FUIs within each segment. Density of marine diesel: 0.832 kg/L

Inventory flows and calculated impacts were allocated among co-products based on the relative mass of fish transformed by each of the three production processes. Mass allocation was used because all co-products had similar energy contents, the production system is driven by canned tuna but the other co-products are increasing in economic importance for the industry, and because it was applied in the fish canning studies cited.

Some of the most common impact categories in fisheries and fish processing LCAs were used (Hospido et al. 2006; Parker 2012; Vázquez-Rowe et al. 2014): climate change, cumulative energy demand, marine ecotoxicity, marine eutrophication, metal depletion, particulate matter formation and photochemical oxidant formation. These impact categories were calculated as implemented in the life cycle impact assessment method ReCiPe v1.07 (Goedkoop et al. 2009), except for cumulative energy demand (VDI 1997; Hischier et al. 2009). The aggregated ReCiPe single score was also used for comparison purposes; its egalitarian—precautionary— perspective with its average weighting set (human health, 40 %; ecosystems, 40 %; resources, 20 %) was retained, for it assumes high- and medium-risk scenarios for damage assessment (Goedkoop et al. 2009). The software *SimaPro v7.3* (PRé 2012) was used for computations. Background processes were taken directly or adapted from *ecoinvent v2.2* (see Electronic Supplementary Material for a list of processes adapted from *ecoinvent* and the ANCHOVETA-SC project).

Data and model uncertainty are inherent elements of LCA. It has been suggested that absolute uncertainty is less relevant than relative uncertainty in comparative studies (Henriksson et al. 2015). In this work, we focused on exploring the sensitivity of the model to extreme values and process changes. The sensitivity of results was thus evaluated regarding variations in key (i.e. most contributing) inventory items.

Finally, results at the inventory and impact assessment levels were compared with published results of environmental impacts of seafood processing, as well as of other sources of animal protein.

3 Results and discussion

3.1 Life cycle inventories

The NIRSA sub-fleet had a landings-weighted mean FUI of 663 kg/t (797 L/t) in 2012 and 722 kg/t (868 L/t) in 2013. Mean FUI per segment apparently increased with holding capacity, a rather counterintuitive result. Nonetheless, when the range of FUI per segment is considered (Fig. 5), all segments show a very similar performance, raising questions regarding the sources of variability within segments rather than across them. These homogenous FUIs across segments (ANOVA, p value=0.95) render the segmentation useless. Such homogeneity within the observed range of variability regarding FUI and individual vessel sizes could be associated with tuna catchability being similar in the respective segments' preferred fishing areas, with the "skipper effect" (Vázquez-Rowe and Tyedmers 2013), or simply due to uncertainty given the few data points available (25 landing-fuel use data pairs). Other fisheries' FUI studies have also shown relative performances per segment which are not dominated by the efficiency gains expected from economies of scale, but by other factors such as legal constraints, catchability associated

Table 1 Main characteristics of the Ecuadorian tuna purse seining fleet, per classification by the Inter-American Tropical Tuna Commission

Holding capacity range (t)	Holding capacity range (m^3)	Mean holding capacity (t)	Mean length (m)	Mean beam (m)	Mean height (m)	Number of vessels						
						2007	2008	2009	2010	2011	2012	2013
46–91	54–107	76	16.15	6.78	3.38	5	4	4	3	2	1	1
92–181	108–212	155	33.13	7.36	3.96	13	12	12	11	13	11	10
182–272	213–318	227	35.63	8.42	4.36	12	14	16	16	16	18	20
273–363	319–425	319	41.39	9.13	4.75	11	11	12	13	12	**12**	**11**
>363	>425	875	60.50	11.43	6.00	44	44	45	47	55	**60**	**65**
Sum:						85	85	89	90	98	102	107
Percentage of the national fleet represented by NIRSA vessels											12.7 %	12.1 %
Percentage of the national tuna landings contributed by NIRSA vessels											11.4 %	10.9 %

Numbers in bold represent the fleet segments containing the Negocios Industriales Real S.A. "NIRSA" sub-fleet in the reference years. Source: Pacheco Bedoya (2013)

with stock condition, and distances travelled (Almeida et al. 2013; Avadí et al. 2014b; Fréon et al. 2014b; Ziegler and Hornborg 2014).

Calculated FUI figures were also considerably higher than 2009 mean values reported for tuna fisheries in the Pacific Ocean (354 L/t), tuna-targeting purse seiners in all oceans (368 L/t), as well as all tuna catches by all types of fishing gear (375 L/t) (Parker et al. 2014) and all large pelagics landings caught with surrounding nets (434 L/t) (Parker and Tyedmers 2014). They were also higher than the mean FUI of 436 L/t reported for Spanish tuna fisheries (on three oceans, including the Pacific) in 2003 (Hospido and Tyedmers 2005). Reasons for such underperformance may include inter-annual variations in tuna catchability and the fact that fuels are generally subsidised in Ecuador (Prieto Bowen 2009), and thus skippers perhaps do not apply sufficient fuel-saving strategies. Fuel used for air scouting played a minor role in FUI.

In order to improve the FUI of the Ecuadorian tuna fishery, the sources of underperformance should be investigated in detail and then addressed by means of management approaches, including for instance technical fuel-saving strategies, a prioritisation of the best performing vessels, and retrofitting of the worst performing ones. For instance, replacing main engines of 20 years ago with current models can achieve fuel efficiency improvements in the order of 10 % (Notti and Sala 2012). Moreover, technical improvements regarding the propulsion system, coupled with innovation and research into better fishing practices, can contribute to significant fuel use reductions (Notti et al. 2011).

LCIs for the NIRSA tuna fleet were extrapolated to represent the complete amount of tuna processed by NIRSA (Table 2). Commercial tuna bycatch (2 and 3 % of landings in 2012 and 2013, respectively) was excluded from the assessment, and their impacts assigned to the dominant tuna component of landings.

Abridged LCIs for the three tuna products studied, and for the overall tuna processing operation of NIRSA, are presented in Table 3 (see Electronic Supplementary Material for detailed LCIs). It is noticeable that canning consumed less electricity and more fuel per tonne of processed fish than bagging, while bagging consumed more electricity and less fuel than canning. The energy performance (i.e. energy input per product output) of pouching was similar to that of canning, and all processes yielded a similar amount of residues (≈40 % of whole fish weight), given their common fish pre-processing stage. The percentages of fish in the final product were ≈50, ≈70 and ≈99 % for canned, pouched and bagged tuna, respectively.

3.2 Life cycle impact assessment

Contributions of the construction and EOL phases to impacts of purse seiners were negligible for most impact categories, except for metal depletion. Based on ReCiPe single score, the use phase

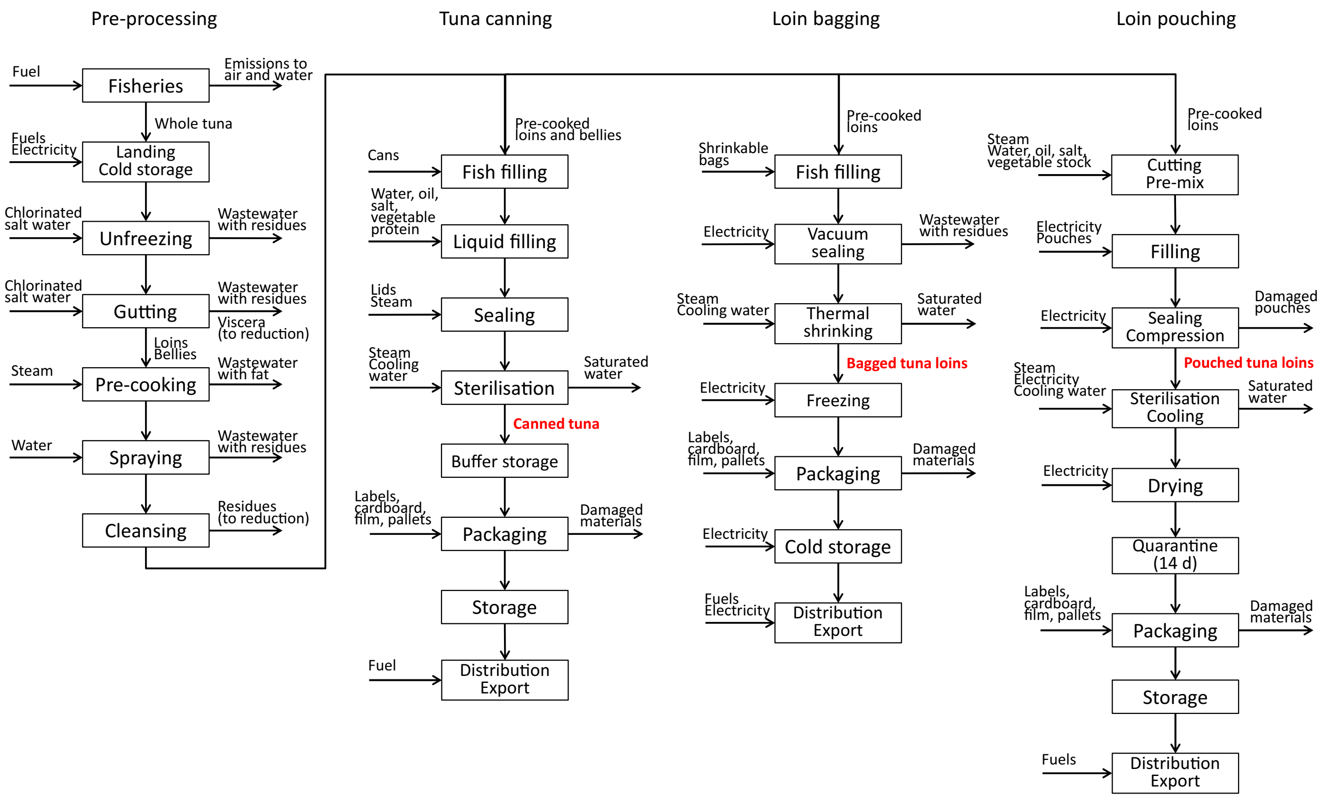

Fig. 6 Process map of tuna processing. Primary data was available for all processes, but distribution was excluded from the assessment. Background data includes the provision of fuels, electricity, packaging materials (based on previous models), chemicals and other ingredients (vegetable oils, etc.; based on previous models)

Table 2 Aggregated life cycle inventories for tuna fishing operations by Negocios Industriales Real S.A. "NIRSA" (annual inputs and outputs) in 2012 and 2013, and extrapolation to total amount of tuna processed by NIRSA in the same period (numbers in brackets represent the contribution of each column to annual tuna processed)

Inventory items	Unit	From the NIRSA fleet		Extrapolation	
		2012 (46 %)	2013 (50 %)	2012 (100 %)	2013 (100 %)
Landings	t	29,451	28,740	64,583	57,073
Diesel	t	19,376	20,647	40,689	37,464
Gasoline	kg	45,359	35,438	95,251	64,303
Lubricating oil	kg	319,001	318,913	669,886	578,681
Freon	kg	10.9	21.8	22.9	39.5
CO_2	kg	1353	2115	2841	3838
Aviation fuel (avgas)	kg	86,303	60,044	181,231	108,953
Bilge water	m^3	45.2	29.6	94.9	53.7
Welding (arc)	m	331,604	346,057	696,351	627,936
Chlorine	kg	48.0	32.5	100.8	59.0
De-greaser	kg	480.7	208.7	1009	378.6
Detergent	kg	6814	5438	14,308	9868
Thinner	kg	7398	8650	15,536	15697
Rust converter	kg	6938	1189	14,568	2158
Paint	kg	38,079	51,546	79,963	93,532
Net maintenance, steel	kg	9020	4510	18,942	8184
Net maintenance, PP	kg	21,656	23,306	45,476	42,290
Net maintenance, nylon	kg	262,074	317,663	550,343	576,414

PP polypropylene

Table 3 Abridged life cycle inventories for tuna processing by Negocios Industriales Real S.A. "NIRSA" (use phase only), annual inputs and outputs for 2012 and 2013

		All tuna products		Canned tuna		Pouched tuna		Bagged tuna loin	
	Year	2012	2013	2012	2013	2012	2013	2012	2013
Fishery									
Diesel	t	40,689	37,464	31,758	29,915	3394	3538	5538	4011
Gasoline	t	95.3	64.3	74.3	51.3	7.9	6.1	13.0	6.9
Avgas	t	181.2	108.9	141.5	87.0	15.1	10.3	24.7	11.7
Landed fish	t	64,583	57,073	50,407	45,573	5387	5390	8790	6110
Processing									
Electricity	MWh	17,911	16,314	12,537	11,905	1454	1537	3920	2872
Fuel use	GJ	156,480	143,141	134,500	123,519	12,789	13,006	9192	6616
Drinking water	m^3	9,242,125	8,002,653	9,232,866	7,993,163	3518	4449	5741	5042
Containers and lids (cans)	t	8732	9119	8732	9119	0	0	0	0
Vegetable oils	t	6330	5849	6330	5849	0	0	0	0
Empty pouches	t	244.7	366.7	0	0	244.7	366.7	0	0
Plastic bags	kg	13,558	9270	0	0	0	0	13,558	9270
Plastic pieces	kg	6386	10,598	4984	8463	617	1121	869	1135
Cardboard	t	2053	1832	1603	1463	198.2	193. 8	279.4	196.1
Labels	kg	223,251	179,310	174,247	143,179	21,554	18,966	30,384	19,195
Plastic film	kg	455,152	261,264	355,245	208,620	43,943	27,634	61,945	27,968
Waste									
Process water (including process liquid losses)	m^3	176,581	199,717	137,821	159,474	14,728	18,863	24,032	21,380
Process liquid losses	t	7751	8511	N/A	N/A	N/A	N/A	N/A	N/A
Raw solid fish residues	t	4686	3301	3657	2636	390.8	311.8	637.7	353.4
Cooked solid fish residues	t	21,326	18,471	16,645	14,749	1779	1745	2902	1977
Production									
Tuna product	t	30,820	26 790	24,055	21,392	2571	2530	4194	2868

was responsible for 83–88 % of weighted impacts in all studied fleet segments, while the combination of use and maintenance phases accounted for 92–95 % of weighted impacts. Fuel combustion was by large the main contributor to overall (normalised and weighted) impacts of the fishery, as previously found for many other fisheries worldwide (Avadí and Fréon 2013). The midpoint impact categories contributing most to the single score were, in descending order, climate change, fossil depletion, human toxicity and acidification. Environmental impacts per segment followed the same pattern as FUI (Table 4) and thus were

Table 4 Impact assessment of the Negocios Industriales Real S.A. "NIRSA" tuna purse seiner fleet, per segment and per landed tonne (average of 2012–2013)

Impact category	Unit	270–300 t	370–520 t	950 t	1050–1750 t	Weighted average
Climate change	kg CO2 eq.	2170	2667	2716	2763	2623
Cumulative energy demand	MJ	32,490	39,883	40,682	41,387	39,269
Human toxicity	kg 1,4-DCB eq.	7273	9096	10,012	10,239	9423
Marine ecotoxicity	kg 1,4-DCB eq.	31,199	47,039	41,245	26,191	33,834
Marine eutrophication	kg N eq.	1.4	1.7	1.8	1.8	1.7
Metal depletion	kg Fe eq.	147.0	184.8	276.2	314.5	251.9
Particulate matter formation	kg PM10 eq.	8.1	9.9	10.1	10.2	9.7
Photochemical oxidant formation	kg NMVOC	31.4	38.6	38.9	39.4	37.6
ReCiPe single score	Pt	361.3	446.2	467.7	477.8	447.8

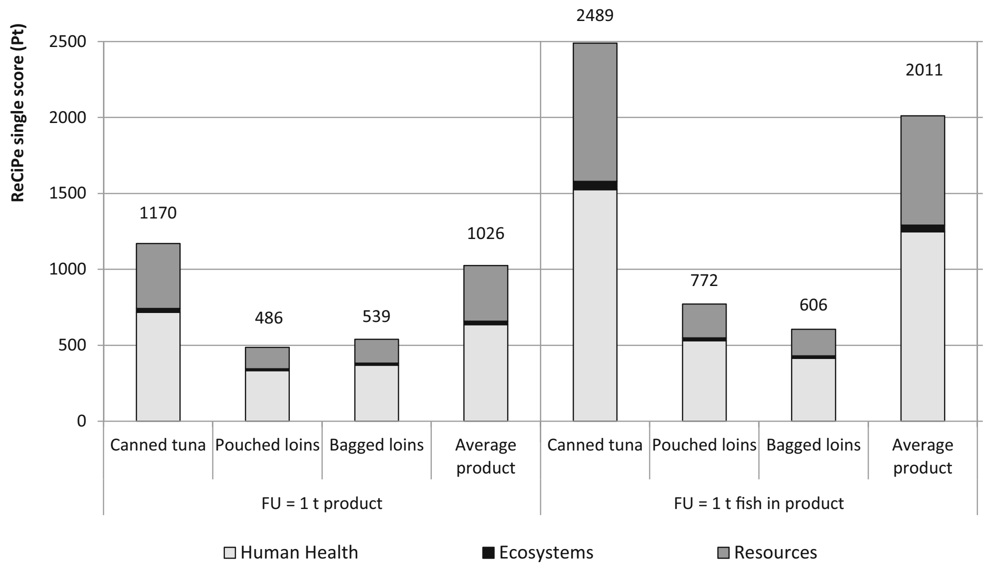

Fig. 7 Impact assessment of tuna products (including a volume-weighted average product) produced by Negocios Industriales Real S.A. "NIRSA" in 2012–2013, per two functional units (FU) and according to ReCiPe single score (per Areas of Protection)

higher overall than those reported in previous studies on tuna fisheries (Hospido and Tyedmers 2005; Tyedmers and Parker 2012).

The construction phase of the processing plant was negligible. The main contributors to impacts associated with plant operation, expressed as 1 t of mass-weighted average final product, were the provision of tinplate cans (58.0 % of the ReCiPe single score) and fuel use by the fishery (22.6 %), followed by the provision of thermo-shrinkable bags (6.3 %), vegetable oil (4.3 %), food-grade composite pouches (4.2 %) and purified water (3.3 %), and the combustion of heavy fuel for the plant's boilers (3.5 %). For the dominant product, canned tuna, contributions of sub-processes to total impacts (per tonne of product) were as follows: can filling and sealing = 74.6 %, fishery = 21.2 %, sterilisation = 1.9 %, landing and cold storage = 0.9 %, pre-cooking = 0.7 %, packaging and storage = 0.6 %, fish cleansing and portioning = 0.1 %, spraying-cooling <0.1 %, gutting <0.1 %, and reception and unfreezing <0.1 %. The decrease in impacts due to recycling fish residues (≈40 % of tuna processed) was negligible. For all impact categories, canned tuna had higher impacts than the other products. Depending on the FU used, either pouched or bagged loins had the second highest impacts, both for endpoints (Fig. 7) and midpoints (Fig. 8).

It was not possible to thoroughly compare these results with those of the Spanish tuna processing industry in the LCA study of Hospido et al. (2006) because of different system boundaries: They reported impacts of the fishery

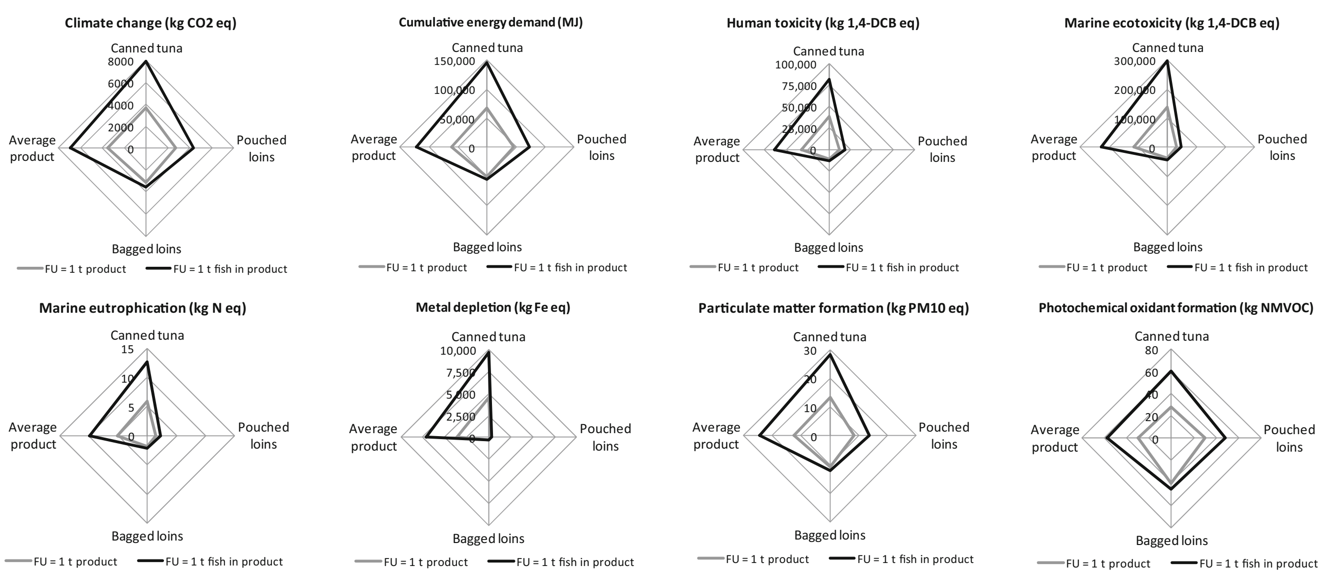

Fig. 8 Impact assessment of tuna products (including a volume-weighted average product) produced by Negocios Industriales Real S.A. "NIRSA" in 2012–2013, per two functional units (FU) and according to selected impact categories midpoint indicators

Table 5 Comparison of key environmental impacts of tuna packaging alternatives (production)

Packaging product	Climate change (kg CO_2 eq.)	Metal depletion (kg Fe eq.)	Cumulative energy demand (MJ)
Per kg of packaging material			
Tinplate can	8.4	23.8	151.9
Retort pouch	3.8	0.2	95.1
Thermo-shrinkable plastic bags	2.9	≈0	100.9
Per t of tuna product			
Tinplate can	1641	4653	29,658
Retort pouch	316.4	15.0	7 921
Thermo-shrinkable plastic bags	9.3	≈0	325.1

Average composition of retort pouches (http://www.flexpack.org): oriented polyethylene terephthalate (18 %), aluminium foil (40 %) and polypropylene (42 %)

separately (Hospido and Tyedmers 2005). Nonetheless, both that study and ours show that, after fisheries, container filling and sterilisation are the main contributors to impacts, due to consumption of materials (e.g. tinplate cans) and energy, respectively. A carbon footprint analysis of Thai tuna canning, based on a fuel-intensive tuna fishery, also identified the provision of raw materials, tinplate cans and process energy as the main drivers of global warming potential (climate change) (Mungkung et al. 2012). A recent study of canned sardine from Portugal (Almeida et al. 2015), supplied by a fishery with a FUI of 111–113 L/t (Almeida et al. 2013), also identified the provision of (aluminium) cans as the main contributor to most impact categories. Another recent study on Peruvian anchoveta processing (Avadí et al. 2014a) confirms this trend and, moreover, identifies potentials for reducing impacts of fish packaging by favouring pouches or at least larger cans. Package comparison and other eco-design approaches for tuna products have been also previously discussed (Franklin Associates 2008; Zufia and Arana 2008; Poovarodom et al. 2012). The latter study suggests that between equivalent 85 g canned and pouched tuna products, the pouched one had a slightly higher global warming potential, but only because a carbon credit is introduced, associated with a higher recycling rate of waste tinplate cans than of waste pouches (final disposal is excluded from our study). Thus, it seems that less energy- and material-intensive packaging materials indeed reduce environmental impacts of processed fish products (Table 5). Retort pouches are being increasingly used in Ecuador for export consumer tuna products.

Climate change impacts (per kilogram of product and of protein) of Ecuadorian tuna products were compared to those of alternative fish and animal protein sources from global food supply chains (Table 6). Ecuadorian tuna products had higher climate change impacts than many other tuna and seafood products (based on more energy-efficient fisheries or less resource-intensive processes and packaging) and lower than most non-aquatic protein sources such as beef, pork, milk and cheese.

3.3 Sensitivity analysis

Since the provision of tinplate cans (containers) and the fuel use by the fishery contributed to 80.6 % of all impacts, we analysed the sensitivity of the model to variations and changes in inventory data. For the fuel use, we created extreme scenarios using the lower and higher individual FUIs reported. In practice, the lower FUI could never be generalised for the whole fleet, but actual overall fuel efficiencies likely range between the mean and the higher values. It is shown that if all fleet segments would operate at the higher reported FUI, environmental impacts per landed tonne of tuna (expressed at the endpoint level) would increase by 47 %, while if only the lower two fleet segments would be used, impacts would be reduced by 8 % (Fig. 9). For the provision of containers, various scenarios were created by simulating the use of large tinplate cans exclusively (i.e. “#300” cans[4]) instead of a portfolio of various can sizes, as well as by modelling the use of aluminium cans as alternatives for replacing current tinplate cans. At the endpoint level, it was estimated that replacing the tinplate can mix with an aluminium can mix would reduce environmental impacts by 63 %, while replacing the original tinplate can mix with a single can size (#300) would decrease them by 85 % (Fig. 10).

4 Conclusions

The energy performance and environmental impacts of processed tuna from Ecuador are determined mainly by the FUI of the supplying fishery and consumption of packaging materials

[4] Common tinplate cans used for fish products in South America include the “½lb Tuna” (size, 87×46 mm; can weight, 35.7 g; net weight, 170 g), the “¼ Club” or “RR-125” (size, 105×60×29 mm; can weight, 34.7 g; net weight, 125 g), and the “#300” or “Tall” (size, 76.2×112.7 mm; can weight, 54.2 g; net weight, 425 g). The two smaller cans are available also in aluminium.

Table 6 Comparison of climate change impacts (kg CO_2 eq.) per kilogram of product and kilogram of protein of Ecuadorian tuna products and other animal products from global supply chains

Product	Protein content (%)	Impact per kg product	Impact per kg protein
Ecuadorian tuna products (this study)			
Canned tuna in vegetable oil[a]	26.5	3.7	14.0
Pouched loins[a]	28.2–29.2	2.7	9.3–9.7
Bagged (frozen) loins[a]	22.0–24.4	3.1	12.9–14.3
Portuguese tuna products (Almeida et al. 2015)			
Canned tuna in olive oil[a]	26.5	7.7	29.1
Frozen tuna[a]	22.0–24.4	1.0	4.1–4.5
Peruvian fish products (Avadí et al. 2014a; Avadí et al. 2015)			
Canned anchoveta in vegetable oil	21.3	1.7	8.1
Fresh tilapia	18.3	1.9–4.1	10.4–22.4
Fresh trout	18.4	2.8–3.4	15.2–18.5
Spanish tuna products (Zufia and Arana 2008)			
Canned tuna in tomato sauce, no air transportation[a]	20.8	2.5	12.1
Various animal protein sources (Nijdam et al. 2012), without packaging			
Beef (*s*=15, *n*=26)	20	9–129	45–640
Pork (*s*=8, *n*=11)	20	4–11	20–55
Poultry (*s*=4, *n*=5)	20	2–6	10–30
Eggs (*s*=4, *n*=5)	13	2–6	15–42
Milk (*s*=12, *n*=14)	3.5	1–2	28–43
Cheese	25	6–22	28–68
Seafood from fisheries (*s*=9, *n*=18)	16–20	1–86	4–540
Seafood from aquaculture (*s*=7, *n*=11)	17–20	3–15	4–75

[a] Protein content values from the USDA National Nutrient Database for Standard Reference Release 27 http://ndb.nal.usda.gov/ndb/foods; *s* = number of studies in Nijdam et al. (2012) (not redundant with other studies cited in the table), *n* = number of analysed products in Nijdam et al. (2012)

(especially tinplate cans). Efforts to further reduce environmental impacts should focus on these two factors, for instance by optimising the product mix (e.g. increasing the proportion of pouched and other non-metal packaged products in the portfolio, using larger tinplate cans, shifting the tinplate can mix to an aluminium can mix) and improving the fuel use efficiency of the tuna purse seiner fleet. When modifying the product portfolio to include more environmentally friendly packaging, consumer preferences ought to be taken into consideration. Pouch presentations are becoming more common in Ecuador, in products both for national consumption and for export. The sources of relative inefficiency estimated for the Ecuadorian tuna fleet should be thoroughly investigated.

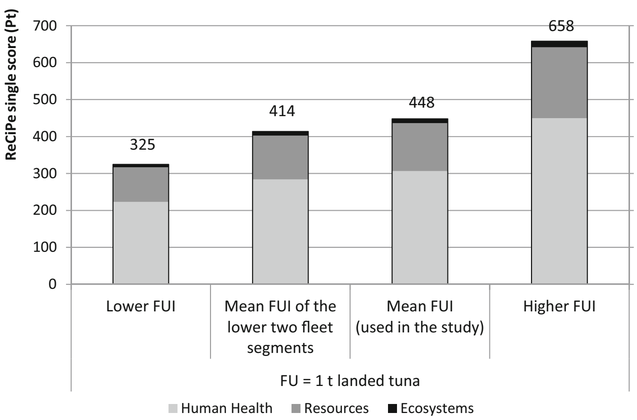

Fig. 9 Comparative impact assessment of landed tuna by the Negocios Industriales Real S.A. "NIRSA" fleet in 2012–2013, according to endpoint indicators, of alternative fuel use scenarios (*FU* functional unit, *FUI* fuel use intensity)

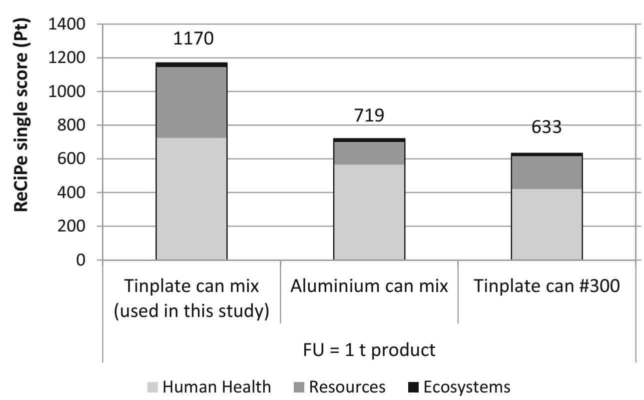

Fig. 10 Comparative impact assessment of canned tuna products by the Negocios Industriales Real S.A. "NIRSA" fleet in 2012–2013, according to endpoint indicators, of alternative container strategies (*FU* functional unit)

Possible solutions could involve increasing use of the most fuel-efficient fleet segments (if any, once identified after a FUI analysis based on an extensive dataset of the fleet) and reducing that of the less efficient, reducing the number of tuna sets with FADs and applying fuel-saving strategies associated for instance with engine use. Ecuadorian tuna products nonetheless feature environmental impacts that, despite being generally higher than those of other fish processing industries worldwide, are lower than those of many alternative sources of fish (e.g. many aquaculture products) and land animal protein.

Acknowledgments Data collection and life cycle impact assessment of this work were financed by Negocios Industriales Real S.A. (NIRSA) and managed by the Ecuadorian consultant firm Soluciones Ambientales Totales S.A. (SAMBITO). No conflicts of interest arose between the interests of NIRSA/SAMBITO and the independent scientific results and conclusions presented in this article.

References

Almeida C, Vaz S, Cabral H, Ziegler F (2013) Environmental assessment of sardine (*Sardina pilchardus*) purse seine fishery in Portugal with LCA methodology including biological impact categories. Int J Life Cycles Assess 19:297–306

Almeida C, Vaz S, Ziegler F (2015) Environmental life cycle assessment of a canned sardine product from portugal. J Ind Ecol. doi:10.1111/jiec.12219

Avadí A, Fréon P (2013) Life cycle assessment of fisheries: a review for fisheries scientists and managers. Fish Res 143:21–38

Avadí A, Fréon P, Quispe I (2014a) Environmental assessment of Peruvian anchoveta food products: is less refined better? Int J Life Cycles Assess 19:1276–1293

Avadí A, Pelletier N, Aubin J et al (2015) Comparative environmental performance of artisanal and commercial feed use in Peruvian freshwater aquaculture. Aquaculture 435:52–66

Avadí A, Vázquez-Rowe I, Fréon P (2014b) Eco-efficiency assessment of the Peruvian anchoveta steel and wooden fleets using the LCA+DEA framework. J Clean Prod 70:118–131

Bromhead D, Foster J, Attard R et al. (2003) A review of the impact of fish aggregating devices (FADs) on tuna fisheries. Commonwealth of Australia

BSI (2011) PAS 2050:2011. Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. The British Standards Institution

BSI (2012) PAS 2050–2:2012. Assessment of life cycle greenhouse gas emissions. Supplementary requirements for the application of PAS 2050:2011 to seafood and other aquatic food products. The British Standards Institution

Cabanilla CL (2013) Desembarques artesanales de atunes en la costa Ecuatoriana Periodo 2007–2013 (Artisanal/small scale tuna landings in Ecuadorian shores, 2007–2013). Instituto Nacional de Pesca, Guayaquil

FAO (2013) Perfiles sobre la pesca y la acuicultura por países: La República Del Ecuador (Profiles on fisheris and aquaculture per countries: Ecuador). Food and Agriculture Organization of the United Nations, Rome

Franklin Associates (2008) Peer reviewed final report: LCI summary for six tuna packaging systems. Eastern Research Group, Prairie Village

Fréon P, Avadí A, Amelia R, Chavez V (2014a) Life cycle assessment of the Peruvian industrial anchoveta fleet : boundary setting in life cycle inventory analyses of complex and plural means of production. Int J Life Cycles Assess 19(5):1068–1086

Fréon P, Avadí A, Marín W, Negrón R (2014b) Environmentally extended comparison table of large-versus small-and medium-scale fisheries: the case of the Peruvian anchoveta fleet. Can J Fish Aquat Sci 71: 1459–1474

Gilman EL (2011) Bycatch governance and best practice mitigation technology in global tuna fisheries. Mar Policy 35:590–609

Goedkoop M, Heijungs R, Huijbregts M et al. (2009) ReCiPe 2008: a life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. First edition

Hamilton A, Lewis A, McCoy MA et al (2011) Market and Industry Dynamics in the Global Tuna Supply Chain. Pacific Islands Forum Fisheries Agency (FFA), Honiara

Henriksson PJG, Heijungs R, Dao HM et al. (2015) Product carbon footprints and their uncertainties in comparative decision contexts. PLoS One 1–11. doi:10.1371/journal.pone.0121221

Hischier R, Weidema BP, Althaus H-J et al. (2009) Implementation of life cycle impact assessment methods - ecoinvent report No. 3 (v2.1). Dübendorf: Swiss Centre for Life Cycle Inventories

Hospido A, Vazquez ME, Cuevas A et al (2006) Environmental assessment of canned tuna manufacture with a life-cycle perspective. Resour Conserv Recycl 47:56–72

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

IATTC (2014) Fishery report 2014: EPO Tunas and billfishes fishery. Inter-American Tropical Tuna Commission (IATTC), Fisheries and Resources Monitoring System - FIRMS

IATTC (2013) Annual Report of the Inter-American Tropical Tuna Commission 2009. IATTC, La Jolla

Iribarren D, Moreira MT, Feijoo G (2010) Life cycle assessment of fresh and canned mussel processing and consumption in Galicia (NW Spain). Resour Conserv Recycl 55:106–117

ISO (2006a) Environmental management – Life cycle assessment – Principles and framework (ISO 14040:2006). International Organization for Standardization (ISO)

ISO (2006b) Environmental management — Life cycle assessment — Requirements and guidelines (ISO 14044:2006). International Organization for Standardization (ISO)

MAE (2012) Factor de Emisión de CO2 del Sistema Nacional Interconectado del Ecuador. Informe 2012. Quito: Ministerio del Ambiente

MAE (2013) Factor de Emisión de CO2 del Sistema Nacional Interconectado del Ecuador. Informe 2013. Quito: Ministerio del Ambiente

Maunder M (2014) Status of skipjack tuna in the Eastern Pacific Ocean in 2014. Inter-American Tropical Tuna Commission (IATTC), La Jolla

Miyake MP, Guillotreau P, Sun C-H, Ishimura G (2010) Recent developments in the tuna industry. Food and Agriculture Organization of the United Nations, Rome

Mungkung R, Gheewala SH, Kanyarushoki C et al (2012) Product carbon footprinting in Thailand: a step towards sustainable consumption and production? Environ Dev 3:100–108

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

Notti E, Sala A (2012) Effects of engine replacement on the fuel consumption reduction in fisheries. Ancona: National Research Council - Institute of Marine Research (CNR-ISMAR)

Notti E, Sala A, Buglioni G (2011) Energy profiling can lead to reduced fuel consumption. Eur Fish Mag 27–29

Pacheco Bedoya JL (2013) Aspectos Biológicos y Pesqueros de las Capturas de Atún Registrada por la Flota Atunera Cerquera Ecuatoriana Período 2000–2013 (Biological and fishery aspects of tuna landings by the Ecuadorian purse seine tuna fleet in the period 2000–2013). Instituto Nacional de Pesca, Guayaquil

Parker R (2012) Review of life cycle assessment research on products derived from fisheries and aquaculture : a report for Seafish as part of the collective action to address greenhouse gas emissions in seafood. Final Report Prepared for : Sea Fish Industry Authority Pr

Parker RWR, Tyedmers PH (2014) Fuel consumption of global fishing fleets: current understanding and knowledge gaps. Fish Fish. doi:10.1111/faf.12087

Parker RWR, Vázquez-Rowe I, Tyedmers PH (2014) Fuel performance and carbon footprint of the global purse seine tuna fleet. J Clean Prod 103:517–524

Poovarodom N, Ponnak C, Manatphrom N (2012) Comparative carbon footprint of packaging systems for tuna products. Packag Technol Sci 25:249–257

PRé (2012) SimaPro by Pré consultants, http://www.pre-sustainability.com/simapro

Prieto Bowen IP (2009) The impact of fisheries subsidies on tuna sustainability and trade in Ecuador. Guayaquil: UNEP and Comisión Permanente del Pacífico Sur (CPPS)

Román-Verdesoto M, Orozco-Zöller M (2005) Bycatches of sharks in the tuna purse-seine fishery of the Eastern Pacific Ocean reported by observers of the Inter-American Tropical Tuna Commission, 1993–2004. La Jolla, IATTC

Tyedmers P, Parker R (2012) Fuel consumption and greenhouse gas emissions from global tuna fisheries: a preliminary assessment

Vázquez-Rowe I, Tyedmers P (2013) Identifying the importance of the “skipper effect” within sources of measured inefficiency in fisheries through data envelopment analysis (DEA). Mar Pol 38:387–396

Vázquez-Rowe I, Villanueva-Rey P, Hospido A et al (2014) Life cycle assessment of European pilchard (Sardina pilchardus) consumption. A case study for Galicia (NW Spain). Sci Total Environ 475:48–60

VDI (1997) Cumulative Energy Demand - Terms, Definitions, Methods of Calculation. Verein Deutscher Ingenieure, Düsseldorf

Ziegler F, Hornborg S (2014) Stock size matters more than vessel size: the fuel efficiency of Swedish demersal trawl fisheries 2002–2010. Mar Policy 44:72–81

Zufia J, Arana L (2008) Life cycle assessment to eco-design food products: industrial cooked dish case study. J Clean Prod 16:1915–1921