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# Environmental assessment of the Peruvian industrial hake fishery with LCA

Angel Avadí<sup>1,2</sup>  · René Adrien<sup>3</sup> · Víctor Aramayo<sup>4</sup> · Pierre Fréon<sup>5</sup>

## Abstract

**Purpose** The Peruvian hake (*Merluccius gayi peruanus*) stock has been in a delicate state in the last decades due to overexploitation combined with adverse climatic events. The stock is showing certain signs of recovery since 2012. This work analyses the environmental impacts of current fleet operations and its likely trend.

**Methods** The fleet was divided into coherent segments, per holding capacity and engine power. The validity of both segmentations, as well as the presence of an effect of economies of scale driving fuel use intensity (FUI), was tested. Life cycle assessment was used to calculate environmental impacts, per individual sampled vessel and per segment, complemented

with indicators of energy efficiency and biotic resource depletion.

**Results and discussion** The fleet is highly fuel-efficient (120 kg fuel per tonne fish) when compared with other reported values, despite a large overcapacity that increases the impact of the construction and maintenance phases. Significant inter-annual FUI variations were observed (80.0 kg t<sup>-1</sup> in 2008 to 210.3 kg t<sup>-1</sup> in 2006), but no clear trend. Neither significant differences in FUI among fleet segments nor a clear effect of economies of scale were found (but FUI analysis was based on a small sample of 32 values for nine vessels, two of which had data for a single year). Only the largest vessels, featuring 242 m<sup>3</sup> holding capacity and 850 hp engine power, were found to have lower FUI than any of the other vessels, but no statistical test could be applied to validate this difference. Differences in environmental impacts of individual vessels are mostly dominated by their relative FUI. Fuel use and, to a lower extent, maintenance are the main sources of environmental impacts. The most contributing impacts to ReCiPe single score are climate change, human toxicity and fossil depletion. The fishery's impacts on the biotic natural resource were orders of magnitude higher than many other global hake stocks, due to overexploitation.

**Conclusions** The environmental impacts of the national hake fleet are relatively low during the study period, despite an overcapacity of the fleet. With the perspective of expanding its operations and obtaining better yields on the eventuality that the stock fully recovers, these impacts should decrease. More research based on additional FUI data is necessary to effectively compare the performance of these vessels with larger ones (featuring >180 m<sup>3</sup> and >500 hp, of which nine existed in 2016) before possibly recommending their preferential use.

**Keywords** Biotic resource depletion · Fleet management · Fuel use intensity · Life cycle assessment · Trawling

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## 1 Introduction

There is increasing concern about the negative impacts of animal protein production, from agriculture and from aquaculture or fisheries exploiting the whole range of aquatic ecosystems (Pauly et al. 2002; Daw et al. 2009; Pelletier et al. 2011; Nijdam et al. 2012; Sabaté et al. 2015). Fisheries are important sources of protein for human consumption, via both direct and indirect (fishmeal, fish oil) supply chains. Regarding fisheries, there are fundamental differences in the type and extent of environmental impacts, according to the type of fish caught (e.g. small or large pelagics, demersal), the fish gear used, the size and technology level of fishing vessels, the productivity of the ecosystem, the fishing zone affected and the exploitation status of the targeted stock (Pelletier et al. 2011; Avadí and Fréon 2013; Fréon et al. 2014a; Jones et al. 2014). Thus, it is relevant to study the environmental impacts associated with specific fisheries taking into consideration these factors.

In this work, we study the environmental performance of the Peruvian industrial fleet targeting a demersal species, the Peruvian hake (*Merluccius gayi peruanus*), one of the two sub-species of the South Pacific hake. This species is located in a highly productive ecosystem, the Northern Humboldt Current ecosystem (Chavez et al. 2008), but its stock has been heavily affected by both natural phenomena (i.e. El Niño) and overexploitation by fisheries (Wosnitza-Mendo et al. 2005). Furthermore, the fishery uses bottom trawling at various depths, a fishing practice generally perceived as highly unfriendly with the marine ecosystem, especially because it disturbs the seafloor. Fuel use is nonetheless the main contributor to conventional environmental impacts such as climate change (Avadí and Fréon 2013), and especially in fuel-intensive demersal fisheries such as hakes (Tyedmers 2004; Vázquez-Rowe et al. 2011). By determining the fuel efficiency (in terms of fuel use intensity,  $FUI = \text{fuel used per tonne fish landed}$ ) and environmental impacts of the fleet (and of different fleet segments if relevant), our objective is to inform decision makers of the hake fleet regarding past and future use strategies, from an environmental standpoint. Nonetheless, the efficiency of energy use by industrial systems has also economic undertones, especially when the cost of energy is an economic limiting factor, as it is for many fisheries (Utne 2009). Moreover, we evaluated the environmental impacts of Peruvian hake, in absolute terms and relative to those of other hake fisheries worldwide, the latter in terms of climate change, impacts on the biotic natural resource related to biomass removal (biotic resource depletion) and energy cost of fish proteins. The objective of this comparison is to inform on the status of the stock and the environmental sustainability of its dedicated fishery. To summarise, this study aims at assessing (1) fuel efficiency of the fishery and (2) its absolute and comparative environmental impacts, including the use of fishery-specific indicators.

### 1.1 The Peruvian hake stock

The Peruvian hake is a demersal species in the Northern Humboldt Current System of Peru, with relatively high trophic level ( $TL = 4.4 \pm 0.6$ ; Froese and Pauly 2014). It is accepted that abundance of hake of Peru is related to several factors such as fishing mortality, El Niño-Southern Oscillation (ENSO) events, the abundance of some of its prey such as sardine and *anchoveta* (Tam et al. 2008) and to poorly known transboundary migration of the species. It is commonly accepted that Ecuador and Peru share a single hake stock (CeDePesca 2010).

The Peruvian Marine Institute (IMARPE) applies different biomass assessment methods based on (1) demersal trawl sampling, calibrated with acoustic surveys in some cases; (2) the swept area of a bottom trawl; (3) virtual population analysis for comparison with real-data scenarios; and (4) dynamic age-structured models based on capture data from commercial fisheries.

As of today, it is not completely clear (nor agreed upon by experts) whether the Peruvian hake stock is recovering—despite certain alleged recent positive signs during the last years (Icochea Salas 2013; CeDePesca 2015)—because population processes in long-lived species such as hake may take decades (Hutchings 2000), considering as well the fact that only a few strong cohorts appear from time to time and become the bulk of the biomass. Further information on the Peruvian hake stock is provided in the [Electronic Supplementary Material](#).

### 1.2 The Peruvian hake fishery

The Peruvian hake fishery is composed of an industrial fleet, nearly mono-specific, and a small-scale fleet also targeting other demersal species. Historically, the industrial trawling fleet consisted of three sub-fleets, namely coastal trawlers (32.6–142 m<sup>3</sup> holding capacity), medium-sized trawlers (142–425 m<sup>3</sup> holding capacity) and large trawlers (>425 m<sup>3</sup> holding capacity), all of which utilised off-board produced ice to preserve the fish. Today, mainly coastal trawlers and a handful of medium-sized trawlers remain in the fishery. Trawling sets take place at different bottom depths.<sup>1</sup> As of 2012 and according to Ministry of Production (PRODUCE) statistics, the fleet nominally consisted of ~70 vessels, yet the actual number of operating vessels has diminished from 46 in 2008 to 19 in 2012, 10 of which were responsible for the bulk of landings (IMARPE data). Since the implementation of an individual vessel quotas (IVQs) system in

<sup>1</sup> The Peruvian hake fishery takes place at four strata: I (36.6–91.5 m), II (91.5–183 m), III (183–366 m) and IV (>366 m). Only the first three are relevant for this fishery, while stratum IV is rarely exploited because of a combination of factors: irregular surfaces (non-draggable bottoms), technical limitations, increased fuel consumption and lower stock concentration.

2004, many vessels are still registered but do not perform fishing trips, or only a few ones a year, due to the possibility of transferring IVQs within a fishing company. The most often-used vessels were coastal and medium-sized trawlers, contributing roughly equally to total landings. As of 2008, there were no more large trawlers in operation in Peru, and even in previous years when still a few operated, their contribution to total landings was minimal. The small-scale hake fleet consists of vessels using a variety of fishing gears: drift nets, long lines and, occasionally (and illegally), artisanal trawls and purse seines. Landings by the small-scale fleet represent less than 7% of total landings, and the environmental impact of this segment of the fleet is not considered in this study. The industrial hake fleet concentrates in the area of Paita (5° S), in Northern Peru, which is historically the area of greater resource concentration. Fishing areas have been shrinking since 2004 ([Electronic Supplementary Material](#)). The hake fishery has been at a quite low level, both in terms of landings and fleet size since 2002, yet it is expected that both an improved stock assessment as a better fishery management can revitalise this fishery in the medium-long term.

Fishery management takes the form of regulation of fishing periods, areas and individual vessel quotas. IMARPE is the scientific advising body, while the PRODUCE establishes legal regulations. For instance, the main piece of legislation governing the hake fishery, other than the current Fisheries Law, is Supreme Decree 016-2003-PRODUCE, entitled “Fisheries Management Regulation for the Resource Hake”. Enlargement of the fleet is not authorised (i.e. new fishing permits are not allowed). Provisional legislation is often produced, including fishery temporary closures and regulation of mesh sizes for the fishing gear (90–110 mm).

The industrial hake fishery features discard rates of ~15% ([CeDePesca 2010](#)), mostly composed of hake juveniles locally called “pescadilla” and crabs, because by-catch is preferably retained on board given that it predominantly consists of economically interesting species. This by-catch is composed of up to 25 species, dominated by lumptail searobin (*Prionotus stephanophrys*). By-catch represented on average ~6% of total catches during the period 2006–2012 ([IMARPE 2008](#); [CeDePesca 2010](#)). Historical landings ([Fig. 1](#)) show that, since 2002, annual landings have been kept below 50,000 t. Most hake landings are destined to exports, such as frozen fillets ([Paredes 2012](#)). Around 40–60% of hake are subject to muscular parasite infestation ([Salas 1972](#); [Durán and Oliva 1980](#)); thus, losses due to muscle histolysis<sup>2</sup> occur

<sup>2</sup> Above a certain threshold of infestation, aggravated by poor refrigeration conditions and time elapsed before freezing, the protozoan *Kudoa peruvianus* generates muscle histolysis (liquefaction or “milky”) in hake captures.

during the filleting process in an estimated proportion of ~10%.

## 2 Material and methods

### 2.1 Fleet segmentation and effect of economies of scale

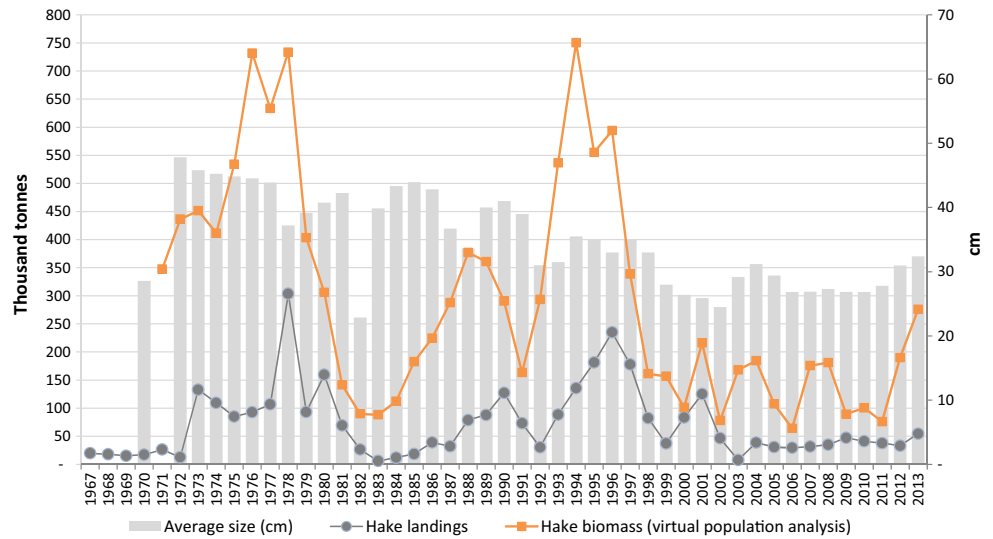
When analysing a fishing fleet, especially one featuring vessels of different sizes and behaviours (e.g. targeting different fishing areas), the practice of subdividing it into coherent segments to be analysed separately and in relation to each other contributes to shedding light into eco-efficiency questions, including fuel use intensity, effect of economies of scale, etc. Based on previous experiences ([CeDePesca 2010](#); [Avadí et al. 2014](#); [Fréon et al. 2014b](#)) that highlight the relevance of segmentation to compute and understand the drivers for environmental impacts and eco-efficiency per segment, we attempted a segmentation strategy for the hake fleet beyond the official sub-fleet segments (32.6–142 and 142–425 m<sup>3</sup>). Using this last subdivision would have resulted in having all the nine vessels for which we had data, but one, in the same segment.

Holding capacity has been proven a suitable segmentation criterion for purse seiners ([Fréon et al. 2014b](#); [Avadí et al. 2015](#)), because their performance (e.g. expressed as FUI or capture per unit of effort (CPUE)<sup>3</sup>) is limited mainly by their holding capacity and much less by their engine power beyond certain threshold. For trawlers, it would be expected that their performance depends mainly on the trawling activity instead (especially when fishing grounds are not too remote), which is driven by the engine power. In order to verify this assumption, we first segmented the fleet based on both holding capacity and engine power. The first strategy was based on histograms of holding capacities (four segments <60, 60–120, 120–180 and >180 m<sup>3</sup>) and the second on histograms of engine power (five segments <300, 300–400, 400–450, 450–550 and >550 hp). A second segmentation by engine power was investigated (four segments <300, 300–450, 450–550 and >550 hp), but the five-segment one was retained because of a better balance regarding the number of sampled vessels and of fishing sets per segment. Both histograms were constructed from the entire hake fleet ([Electronic Supplementary Material](#)).

Then, we investigated whether FUI of the hake fleet is mainly determined by differences in vessels’ holding capacities or engine power. We did that by studying the relationships between FUI and different factors that could impact it such as holding capacity (HC), engine power (HP), CPUE (for this

<sup>3</sup> CPUE is the ratio of catches ( $C$ ) to the corresponding standardised effort ( $E$ ; e.g. trawling hours of a standard vessel or numbers of fishing days) deployed to get  $C$ . It is a conventional index of abundance in fishery research, but it depends not only on biomass ( $B$ ) but also on “catchability”:  $CPUE = C/E = qB$ , where  $q$  is the catchability coefficient.

**Fig. 1** Historical annual Peruvian hake landings including mean individual fish sizes, and total biomass estimation, based on PRODUCE and IMARPE data, respectively (1972–2013). Average sizes are based on detailed daily individual sampling by IMARPE (unpublished data, pers. comm. R. Castillo 2013; CeDePesca 2010)



fishery, capture per effective trawling time), distance between the fishing area and the main harbour of Paita (DistPaita) and bottom depth of the fishing ground (Depth) via a multiple regression:

$$\text{FUI} \sim \text{HC} + \text{HP} + \text{CPUE} + \text{DistPaita} + \text{Depth} \quad (1)$$

These analyses were based on a reduced dataset of FUI—dataset A: annual FUI of nine vessels, 32 data points, between 2006 and 2010—(Table 1). Due to missing data in this matrix

of vessel years, a smaller but complete matrix of seven vessels (two vessels removed, including the largest one) and four years (2007 removed), labelled as dataset A', was retained for the tests (Electronic Supplementary Material).

Surprisingly, the results of the above step did not show any effect of the vessel's holding capacity or engine power on the FUI. In consequence, we investigated the reasons of the absence of effect of economies of scale. This was performed by analysing effective trawling time, CPUE, fishing depth, fishing area and distance to landing port according to

**Table 1** All sampled vessels ordered by increasing holding capacity

	Trawler 1	Trawler 2	Trawler 3	Trawler 4	Trawler 5	Trawler 6	Trawler 7	Trawler 8	Trawler 9
Holding capacity (m <sup>3</sup> )	52	75	99	102	114	135	139	141	242
Engine power (hp)	365	365	425	200	380	380	500	480	850
Mean annual landings (t year <sup>-1</sup> )	710	326.5	1315	(117.0)	628.6	651.7	1714	476.3	(4533)
2006: FUI (kg t <sup>-1</sup> )	200.2	290.5	194.6	–	217.4	194.0	197.9	288.0	104.6
2006: Fishing days	149	80	123	–	97	93	136	43	245
2007: FUI (kg t <sup>-1</sup> )	–	–	202.1	–	–	–	132.6	–	–
2007: Fishing days	–	–	14	–	–	–	35	–	–
2008: FUI (kg t <sup>-1</sup> )	113.8	75.6	75.5	–	82.9	86.9	76.3	137.2	–
2008: Fishing days	23	54	117	–	35	54	124	5	–
2009: FUI (kg t <sup>-1</sup> )	143.1	74.4	108.3	–	80.2	85.6	82.6	101.5	–
2009: Fishing days	54	10	75	–	111	19	99	70	–
2010: FUI (kg t <sup>-1</sup> )	138.9	172.8	104.1	176.01	216.9	100.6	106.1	140.7	–
2010: Fishing days	83	34	116	9	7	91	107	61	–
Landings-weighted mean FUI, without 2007 (kg t <sup>-1</sup> )	154.8	154.5	108.3	–	106.0	112.0	103.7	133.4	–
Total fishing days 2006–2010	309	178	445	9	250	257	501	179	245
Mean annual fishing days	77 ± 47	45 ± 26	89 ± 41	–	63 ± 43	64 ± 30	100 ± 35	45 ± 25	–

Fuel use intensity (FUI) means were computed without considering year 2007 (only two data points), and means in bracket correspond to a single year and therefore cannot be compared with others. The number of fishing days corresponds roughly to the number of daily trips

segmentation using ANOVAs and ad hoc pairwise tests. These latter analyses were performed both on datasets A and B (Electronic Supplementary Material).

Furthermore, we investigated the effect of economies of scale and inter-annual variability on environmental impacts by means of pairwise comparisons of the life cycle impact assessment (LCIA) results (including uncertainty propagation, see Sect. 3.3) for all individual vessels in dataset A'.

## 2.2 Life cycle assessment

In the seafood sector, the life cycle assessment (LCA) framework (ISO 2006a,b) is often used to estimate environmental impacts of activities and products. Seafood LCA studies often extend conventional LCA results with additional indicators based on fishery and ecosystem management (Vázquez-Rowe et al. 2012; Avadí and Fréon 2013; Cashion et al. 2016).

LCA was applied to assess the environmental impacts of the Peruvian industrial hake fishery, using 1 t of whole hake landed on ice as functional unit, modelled as a “co-production” of hake and by-catch (60 kg by-catch per tonne hake), that is to say, as a single process with two products. Allocation between the “co-products” was performed by mass. Historical capture and effort data for the period 2006–2012, for the whole industrial fleet, were used to estimate its FUI based on a small sample of vessel-specific annual landings and fuel expenditures (dataset A'). Detailed structural and operational data for these vessels was obtained from IMARPE and from two anonymous private fishing companies.

We used some of the impact categories most commonly used in fishery LCAs (Avadí and Fréon 2013), namely climate change, cumulative energy demand, marine ecotoxicity, marine eutrophication, metal depletion, particulate matter formation and photochemical oxidant formation. These impact categories were computed as implemented in the life cycle impact assessment method ReCiPe v1.07 (Goedkoop et al. 2009), using *SimaPro v7.3* (PRé 2012). Background processes were taken from *ecoinvent 2.2*. The aggregated ReCiPe single score was also used for comparison purposes; the egalitarian perspective was retained, because its weighting set used to compute the single score assumes high and mid-risk scenarios (the most precautionary perspective) for damage assessment (Goedkoop et al. 2009). The single issue method cumulative energy demand (CED) (VDI 1997; Hischer et al. 2009) was also used, to inform calculations on energy cost of protein.

We constructed life cycle inventories of each vessel using mean values for each parameter relevant to the construction, use and maintenance of active trawlers, across years and per above-mentioned ad hoc segments by holding capacity. Inventories are presented aggregated per these categories of holding capacity (Table 2). This approach was necessary because, while data on fuel use, landings and engines was

available per vessel and year (dataset A), inventory data regarding the vessel herself and her fishing gear characteristics was scarce. Moreover, the environmental impacts of fisheries are highly associated with their FUI, but other inventory items also contribute substantially to certain impact categories (Avadí and Fréon 2013). Some of these inventory items, such as materials and substances consumed during the use and maintenance phases, are clearly proportional to the vessel size (Fréon et al. 2014b), of which holding capacity is a common proxy. Light ship weight, a key inventory item, was only approximated from purse seiners using its well-demonstrated relation with vessel's beam, length, height and holding capacity—available for dataset B—(Fréon et al. 2014b). The fishing gear characteristics were extrapolated from the few data pertaining to a few individual trawlers. The end-of-life phase was excluded from the system boundary due to lack of data, but it was assumed a very low contribution to impacts per FU due to the longevity of fishing vessels in Peru (30–40 years), following findings on another Peruvian fishery (Fréon et al. 2014b). For the use phase, PRODUCE and IMARPE landing data was complemented with company-provided data on landings and fuel use per vessel for the study period. Environmental impacts were then computed for each individual vessel and per fleet segments according to both segmentation criteria (holding capacity and engine power). The impacts of an average tonne of hake landed by the fleet, consisting of a weighted mean of all contributions to total landings per vessel and per segment, were also computed on the same basis. Uncertainty data was added to the main life cycle inventory items (fuel use and landings) and propagated with Monte Carlo, via pairwise segment comparisons with 500 runs each, to complement the ANOVA tests on the fleet segments. Ecoinvent default uncertainty data was retained for all background processes.

## 2.3 Energy cost of protein and biotic resource depletion indicators: comparison with other hake fisheries

Selected results from the Peruvian fishery were compared with published results from other hake fisheries and with another *Merlucciidae* fish, the Patagonian grenadier (*Macruronus magellanicus*). This comparison was performed using climate change as a fairly representative category of environmental impacts and energy return on investment (EROI) as a measure of energy efficiency. Climate change was retained because fuel use, its main contributor, is also the main contributor to most other impact categories in fishery LCAs. EROI (Tyedmers 2000) is defined as the quotient between the energy obtained from the assessed product and the industrial energy inputs necessary for its production. In this case, we calculated the edible protein EROI (ep-EROI), which divides the total energy obtainable from the protein content of the fish's edible yield by the CED of landing the whole fish

**Table 2** Abridged life cycle inventories for mean representative vessels for each segment (per holding capacity) in the Peruvian trawling fleet targeting hake

	Unit	Coastal trawlers (32.6–142 m <sup>3</sup> ) <sup>a</sup>		Medium-sized trawlers (142–425 m <sup>3</sup> )	
		<60 m <sup>3</sup>	60–120 m <sup>3</sup>	120–180 m <sup>3</sup>	>180 m <sup>3</sup>
Basic data					
Population (2008–2012) <sup>b</sup>	No.	6	33	9	4
Sample (2006–2010) <sup>b</sup>	No.	1	4	3	1
Average length	m	17.2	20.2	24.0	33.4
Average beam	m	5.0	5.8	6.5	7.9
Average depth	m	2.3	3.0	3.6	4.7
Average holding capacity	m <sup>3</sup>	52	98	138	242
Construction (per vessel)					
Marine steel (hull, structure)	t	33.7	65.3	100	167
Engine	t	1.4	1.9	2.9	6.7
Steel (transmission)	t	0.337	0.653	1	1.5
Zinc	t	0.047	0.091	0.14	0.23
Bronze (propeller)	t	0.095	0.183	0.281	0.3
Copper (electric network)	t	0.379	0.735	1.125	1.609
Electric motors	t	0.269	0.522	0.800	0.900
Fishing gear	t	2.924	3.086	3.249	4.304
Paint	t	142	275	421	501
Antifouling	t	80	155	238	299
Batteries	kg	67	131	200	334
Use (per functional unit)					
FUI (2006, 2008–2010) <sup>c</sup>	kg t <sup>-1</sup>	149.0	147.9	133.1	104.6
Lubricant and hydraulic oil	kg t <sup>-1</sup>	71.4	84.2	212.1	354.2
Ice	t year <sup>-1</sup>	310.8	443.4	570.0	2720
Antifouling emissions	kg year <sup>-1</sup>	32.1	62.2	95.2	119.6
Average landings (2006, 2008–2010)	t year <sup>-1</sup>	710.0	756.5	947.3	4533

<sup>a</sup> All vessels in the sample for the 120–180-m<sup>3</sup> segment are below 142 m<sup>3</sup>, thus correspond to the coastal trawlers sub-fleet

<sup>b</sup> IMARPE statistics on the fleet (active vessels, landings) were available for 2008–2012, but individual fuel use and landing data were available for 2006–2010. The study period was fixed to the latter period, while fleet data from 2011 to 2012 was used to identify trends

<sup>c</sup> Fuel use intensity (FUI), in kilogrammes of marine diesel per tonne of hake, including landings and discards at sea. FUI figures are based on 28 data points (landings and fuel use) of the sub-sample of seven vessels over 4 years. FUI of the >180 m<sup>3</sup> is based on a single data point (2006, year of the highest FUI for the rest of the fleet). Lifespan of vessels is estimated in 30–40 years

equivalent of that edible portion (Eq. 2). We used ep-EROI because fish is perceived as a source of protein in the context of direct human consumption and to allow comparison with previous studies (e.g. recent ep-EROI estimations of fish from several Atlantic fisheries (Vázquez-Rowe et al. 2013, 2014a)). To compute ep-EROI, we used a generic energy content— heating value as by the Atwater general factor system (FAO 2003)—of 16.7 MJ per kilogramme of protein, species-specific edible yield of 47% and protein content of 16.6% (Avadí and Fréon 2014).

$$\text{ep-EROI} = (\text{edible yield}_{\text{fish}} \times \text{protein content}_{\text{fish}} \times 16.7) \text{ CED}^{-1} \quad (2)$$

LCAs of wild-caught fish can also be complemented with fishery-specific impact categories and indicators, such as the biotic resource use (net primary productivity appropriation) (Pauly and Christensen 1995); mean trophic level of landings, proportion of predatory fish and inverse fishing pressure (Shin et al. 2010); lost potential yield (Emanuelsson et al. 2014); energy-based approaches applied to the occupation of marine

space and removal of biomass (Taelman et al. 2014); and biotic resource depletion indicators expressed as the time required for a fish stock or an ecosystem to recover itself from a given rate of biomass extraction (Hélias et al. 2014; Langlois et al. 2014) (review of approaches in Avadí (2014)). We retained the indicator “impact on the biotic natural resource at the species level” ( $I_{\text{BNR,sp}}$ ) which is based on historical catches and maximum sustainable yield (MSY), to compare the extraction of 1 t of hake, from several global hake stocks, in terms of the relative biotic resource depletion exerted by fisheries on each stock. This indicator benefits from the following properties: (1) it fits within a sea use impact pathway comparable to the land use pathway (Fig. 1 in Langlois et al. (2014)) and allows to calculate an endpoint indicator; (2) it takes into account depletion and regional scarcity, key aspects in LCA for both abiotic and biotic resources, yet notably missing from most LCIA methods for biotic resources (Hauschild et al. 2013) (in LCA studies, depletion is most commonly expressed simply in terms of net primary productivity appropriation, while scarcity is usually neglected); and

(3) it is comparative in nature, as it indicates the relative time of recovery resulting from a given extraction.  $I_{\text{BNR,sp}}$  does not depend only on the stock size, as it was the case in the former version of the indicator (Langlois et al. 2014), but also on its level of exploitation. Indeed, Hélias et al. (2014) incorporated a weighting factor in the equation of  $I_{\text{BNR,sp}}$  [ $1 \pm \sqrt{(1 - \text{catches} \times \text{MSY}^{-1})}$ ] which is an estimate of the ratio of the actual fishing effort to the fishing effort at MSY ( $E \times E_{\text{MSY}}^{-1}$ ). This way, harvesting fish from bigger stocks is not always more sustainable than harvesting from smaller ones, as demonstrated in the [Electronic Supplementary Material](#). To highlight relative levels of overexploitation, we compared an “overfishing through fishing mortality” indicator ( $F/F_{\text{MSY}}$ ) (Emanuelsson et al. 2014) for the Peruvian hake and two distinctive European hake stock, although this later indicator does not take into account differences in scarcity between stocks.

We thus computed  $I_{\text{BNR,sp}}$  following Eqs. 3 and 4:

$$I_{\text{BNR,sp}}(\text{overexploited stock}) = m \left( \text{MSY} \left[ 1 + \sqrt{(1 - \text{catches} \times \text{MSY}^{-1})} \right] \right)^{-1} \quad (3)$$

$$I_{\text{BNR,sp}}(\text{non-overexploited stock}) = m \left( \text{MSY} \left[ 1 - \sqrt{(1 - \text{catches} \times \text{MSY}^{-1})} \right] \right)^{-1} \quad (4)$$

where  $m$  is the mass of the functional unit (1 t). If average catches are higher than the MSY due to non-equilibrium situation, catches are set as equal to MSY. We used the revised midpoint characterisation factors for  $I_{\text{BNR,sp}}$  proposed by Hélias et al. (2014). Stock and fishery data from the RAM Legacy Stock Assessment Database (Ricard et al. 2012) were used to compute the characterisation factors in Hélias et al. (2014), except for two European hake stocks not included in the RAM database. For the latter, we used data on catches and fishing mortality consistent with achieving MSY from the International Council for the Exploration of the Sea (ICES 2015). The MSY for Peruvian hake (39,250 t year<sup>-1</sup>) was determined from data on the report of the “Third International Panel of Experts on the Evaluation of the Peruvian Hake (*Merluccius gayi peruanus* Ginsburg). Precautionary management of hake” (IMARPE 2009) and an independent report (CeDePesca 2010). See [Electronic Supplementary Material](#) for details on  $I_{\text{BNR,sp}}$  calculations.

### 3 Results and discussion

#### 3.1 Fuel use intensity and fleet segmentation

The FUI of the Peruvian trawling fleet for hake was estimated at  $120 \pm 48$  kg fuel per tonne fish (landing-weighted mean and standard deviation of all data points). In comparison, the

trawling fleet targeting the other South Pacific hake sub-species (*Merluccius gayi gayi*) of the Chilean coast features a FUI of 440 kg fuel per tonne fish. Other trawling fleets targeting different species of hake in European and African waters have a FUI ranging between 370—trawling fleet of the Namibian coast—and 2100 kg fuel per tonne fish—Galician Northern Stock trawling fleet—(Vázquez-Rowe et al. 2014b). Therefore, the Peruvian fleet is highly fuel-efficient when compared with other reported values, which is probably due to higher density of the hake in this extremely productive ecosystem of the Northern Humboldt Current System, when compared to other ecosystems (Montecino and Lange 2009).

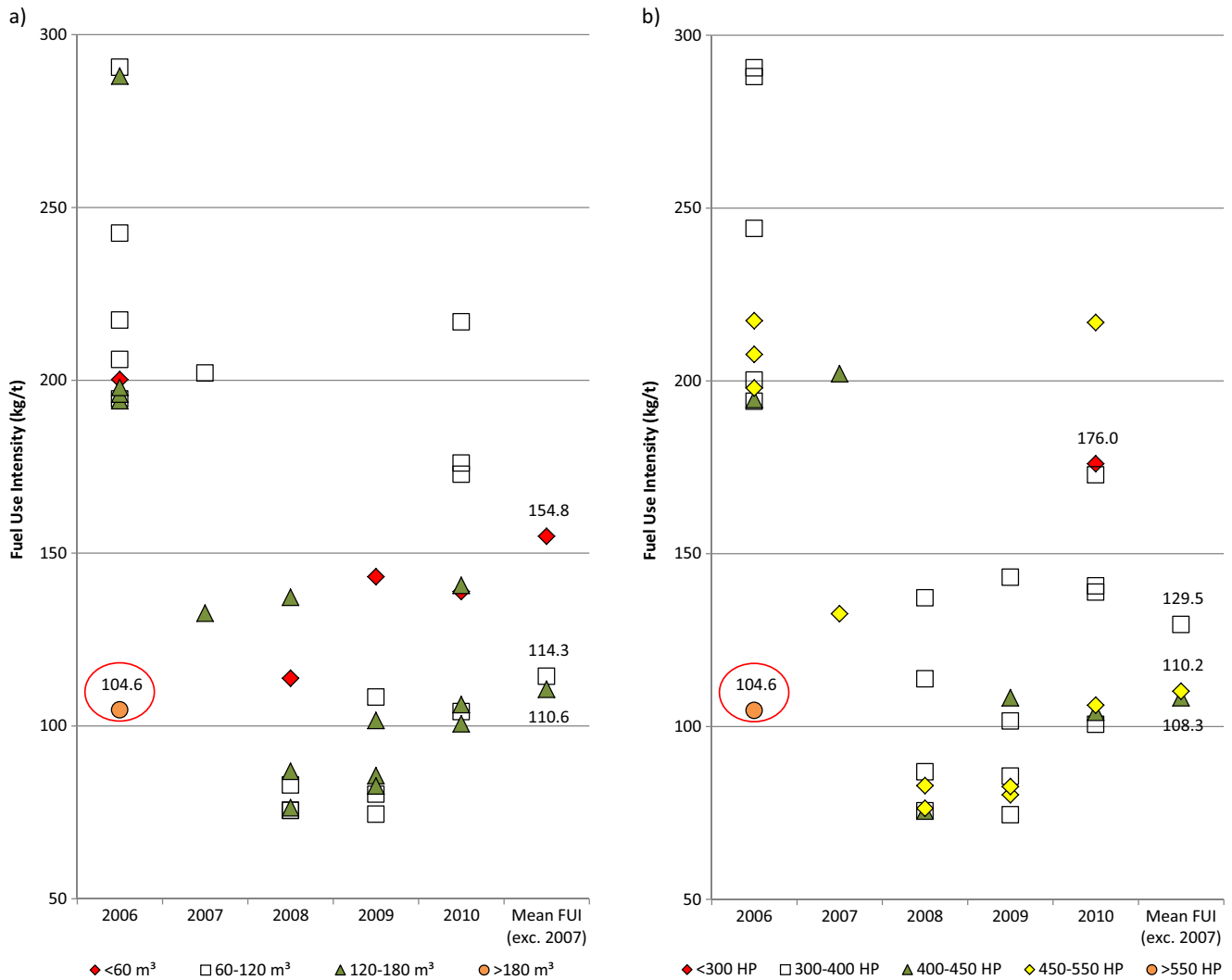
The multiple regression performed on the sub-sample data of seven vessels for which FUI data was systematically available for four years out of five (dataset A') shows that none of the presumed five predictors (Eq. 1), including holding capacity and engine power, had a significant effect (all  $p$  values  $> 0.05$ ;  $R^2 = 0.5$ ). Furthermore, a pairwise test indicates no significant difference in FUI among any pair of vessels. These results confirm some of the conclusions on another study on trawlers (Ziegler and Hornborg 2014), that the differences in FUI among vessels of different size are generally small. This conclusion was further tested by means of a two-way ANOVA without replication on the same dataset A', which confirmed that the year has a highly significant effect on FUI ( $p < 0.001$ ), while the vessel size does not ( $p > 0.05$ ).

FUI estimations per fleet segment (Fig. 2) show a seemingly decreasing (but not significant) trend with increasing holding capacity but rather similar mean values regardless of the engine power. Nonetheless, it is worth noting that the upper segments of holding capacity and horsepower are not considered here due to missing data. But when looking at the FUI for year 2006 only, which is consistent, this upper segments show the lowest values of the series. Indeed, the FUI value of the largest vessel is lower by 53% than the average of all other vessels, which is substantial. Possibly, the effect of economies of scale appears only for the largest vessels, above thresholds of  $\sim 180$  m<sup>3</sup> of holding capacity and 550 hp. But this result could be confounded by a “skipper effect” (Thorlindsson 1988; Vázquez-Rowe and Tyedmers 2013). Further considerations on economies of scales are presented in the [Electronic Supplementary Material](#).

Mean annual FUI values range from 80.0 kg t<sup>-1</sup> in 2008 to 210.3 kg t<sup>-1</sup> in 2006. There was no absolute ascending or descending trend, but the years 2008 and 2009 (not significantly different,  $p > 0.05$ ) featured the lowest FUI values and 2006 (highly significantly different from all other years, all pairwise test  $p < 0.001$ ) the highest, 2010 displaying intermediate values ([Electronic Supplementary Material](#)).

Surprisingly, there was no significant (all  $p$  values  $> 0.05$ ) correlation between the mean annual FUI and two common abundance indices, namely the biomass and the mean CPUE,





**Fig. 2** Fuel use intensity (FUI) of the studied sample from the industrial Peruvian hake fleet, for the years 2006–2010 (each of the data points represents the annual performance of an individual vessel, except for the landing-weighted means), per **a** holding capacity and **b** engine

power. The means of the largest segment of each sub-figure was not computed because there was only one vessel (circled in red) in this segment that worked only in 2006

nor between FUI and catchability, naturally estimated by the ratio CPUE/biomass. A cross-correlation table among key fleet performance variables (Table 3) shows that only the correlation between annual values of CPUE and abundance is highly significant ( $p < 0.01$ ), suggesting that CPUE does not suffer from its usual biases (e.g. Harley et al. (2001)). This result could be explained by the paucity of data (only five

years of FUI, one of them with only two vessels) that limits to three, the number of degrees of freedom of simple regressions. It could also reflect differences in fishing strategies of the different segments according to changes in catchability, although this is not reflected in the available data. It should be noted that, during the period 2006–2007, a larger proportion of juveniles was detected than for 2008–2009, a situation

**Table 3** Cross-correlations between capture per unit of effort (CPUE), biomass, landings, catchability and fuel use intensity (FUI) in the period 2004–2013

	Mean CPUE	Biomass	Catchability	FUI
Mean CPUE ( $\text{t h}^{-1}$ )	1	(8)	(8)	(3)
Biomass (t)	0.758*	1	(8)	(3)
Catchability ( $\text{CPUE biomass}^{-1}$ )	0.031	-0.594	1	(3)
FUI ( $\text{kg fuel t fish}^{-1}$ )	0.565	-0.419	0.094	1

Number in brackets indicate the number of degrees of freedom, which varies according to FUI data availability

\* $p < 0.01$

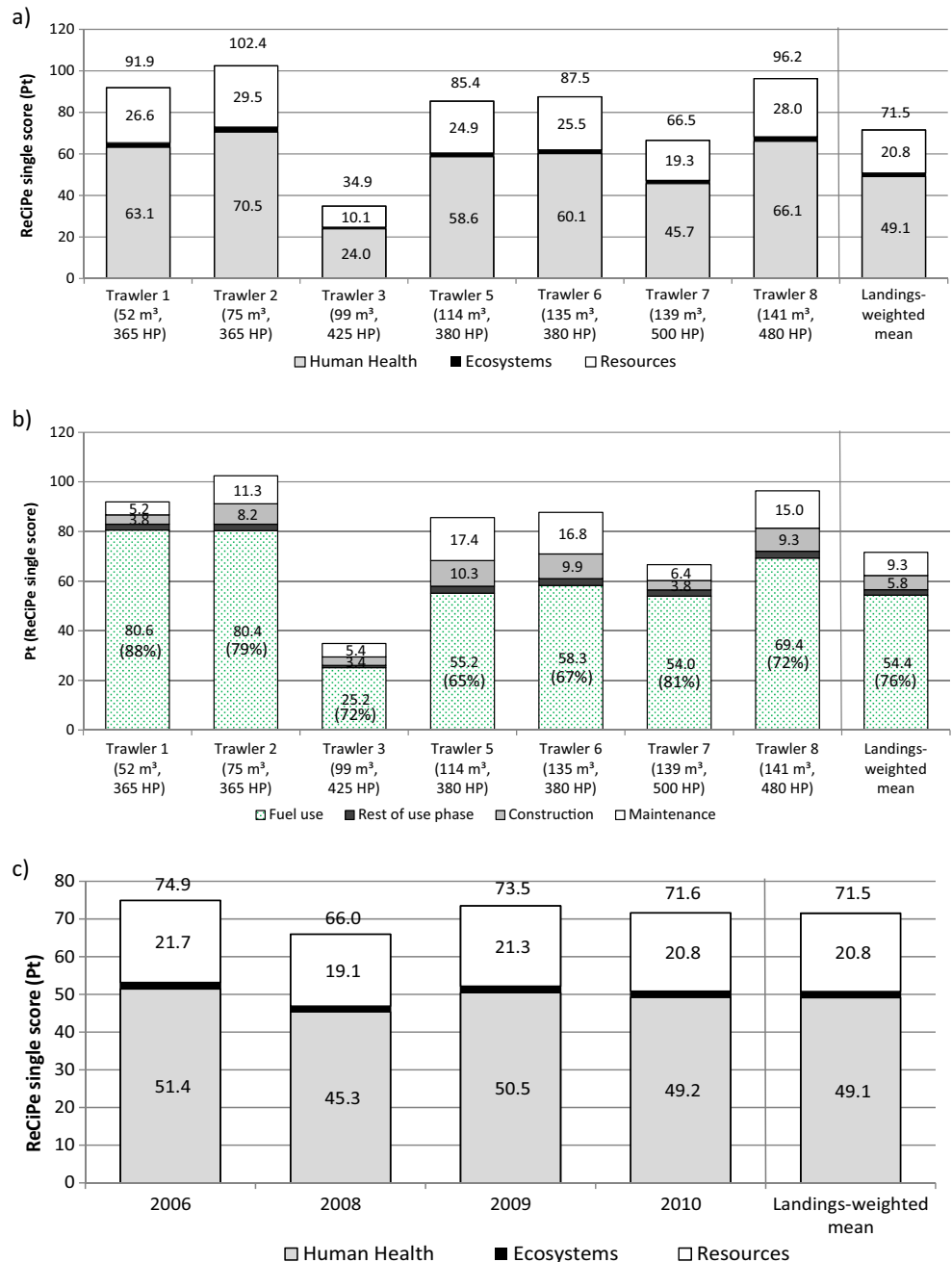
that affected the fishery and that is likely to explain most of the contrasts in FUI during these two periods.

Given that neither holding capacity nor engine power explains the variance in FUI across segments per either of the two criteria, but that engine power explains more of the variance of CPUE as detailed below, we present the LCIA results per the second criterion or per individual vessels (see [Electronic Supplementary Material](#) for some results per holding capacity). The battery of statistical tests performed found no significant effect of economies of scale on FUI; thus, no significant differences are expected among environmental impacts driven by FUI of the sampled vessels (dataset A').

### 3.2 Environmental impacts

Based on dataset A', we first calculated at the endpoint level the environmental impacts per individual vessels using each vessel's mean annual landings and FUI (Fig. 3a, b). Then, the same approach was used per year, using landing-weighted averages of all vessels which operated in a given year (Fig. 3c) (see [Electronic Supplementary Material](#) for a version of Fig. 3 including all nine vessels in dataset A). It is noticeable from the comparison of all vessels that there is no linear trend in impacts according to holding capacity. The two vessels that display the lowest impacts (trawlers 3 and 7) are those who

**Fig. 3** ReCiPe single scores for the sub-sample of seven vessels of the Peruvian hake industrial fleet, per tonne of whole hake landed on ice. **a** Per area of protection per individual vessel. **b** Contribution analysis per life cycle phase (absolute values, relative ones in parenthesis) per individual vessel. **c** Per area of protection per year, excluding 2007 and two data points corresponding to vessels with data for a single year

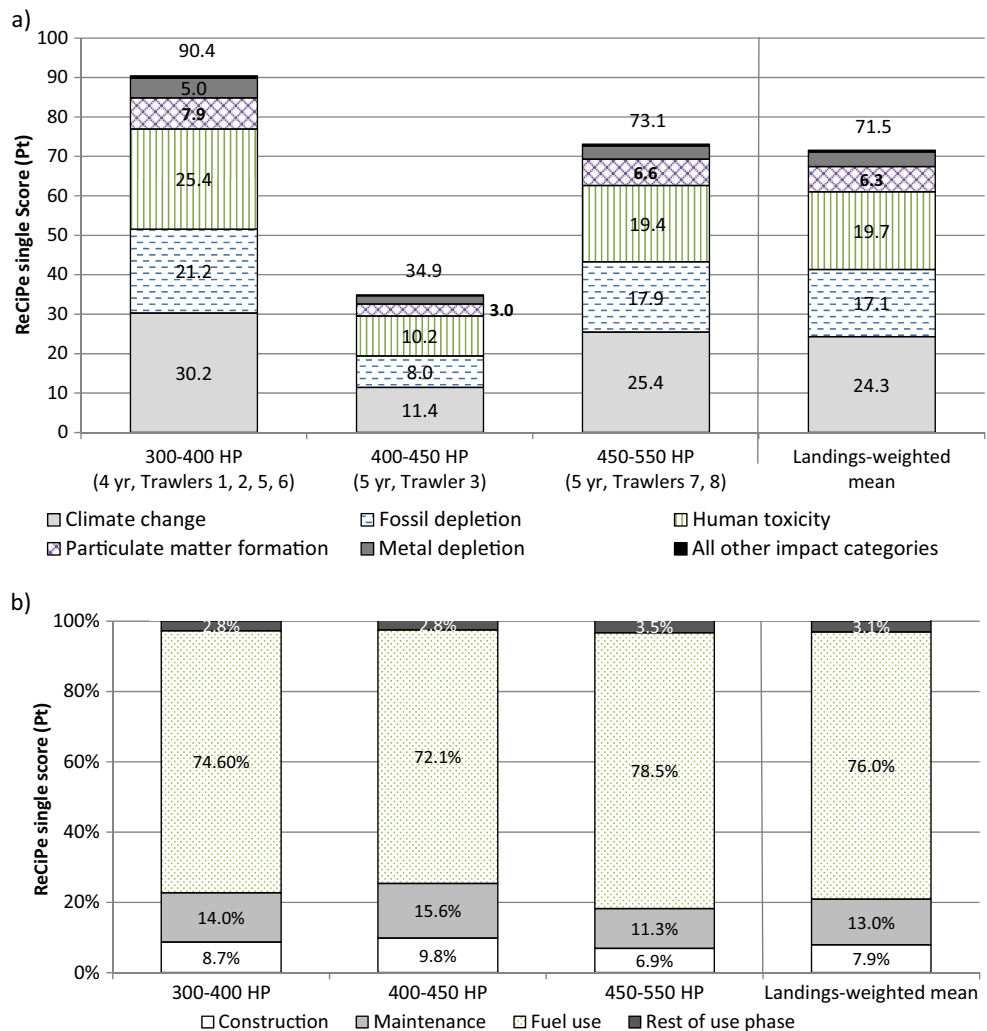


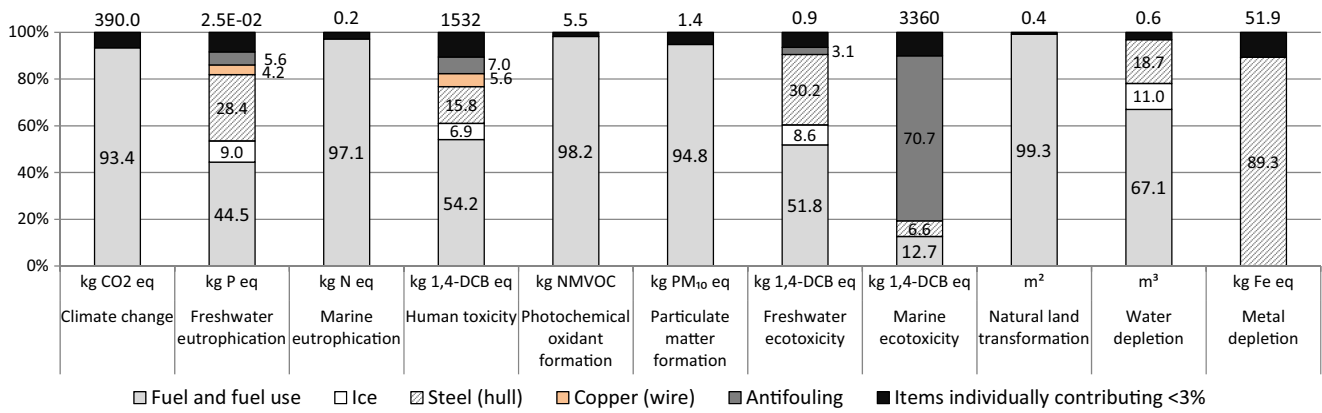
benefited first from the lowest FUI values (Table 1) and, to a lower extent, from the largest number of fishing days (Table 1), and therefore from the highest mean annual landings in their category. Trawlers 5 and 6, while featuring some of the lowest FUI (Table 1), feature higher impacts than trawlers 3 and 7 due to relatively lower mean annual landings on half the fishing days (Table 1). Regarding inter-annual variation, the year 2008 featured the lowest impacts, which is due to generally lower FUI across vessels for that year (Fig. 2).

Despite the absence of significant differences in FUIs across segments, we constructed as well life cycle inventories and carried out the life cycle impact assessment based on the five engine power segments in order to see if additional LCI items would result in significant differences in environmental impacts. Additionally, we assessed first the impact of the whole sub-fleet represented by dataset A' based on landing-weighted averages of all vessels but trawlers 4 and 9 (who worked during only one year). Figure 4a shows that the impact categories contributing mostly to this single score are, in decreasing order, climate change (19–24% in average), human toxicity (18–25%

in average), fossil depletion (17–18% in average), followed to a lesser extent by particulate matter formation and metal depletion. The lowest midpoint impacts are associated to segment 400–450 hp, which is represented by a single, high-performing vessel: the above-mentioned 99-m<sup>3</sup> trawler 3, favoured by a low FUI value and by relatively high mean annual landings (see [Electronic Supplementary Material](#)). The contribution of fuel use to impacts (~80% in average) is highlighted on Fig. 4b where the relative contributions of each life cycle phase to the ReCiPe single score are shown. Single scores do not suggest that impacts decrease with increasing engine power (Fig. 4a). Normalised midpoint results (ReCiPe normalisation set: world in year 2000, not shown) indicated that the most relevant impact categories were human toxicity and marine ecotoxicity (the latter paradoxically not counted among the main contributors to single scores), mainly driven by fuel use and antifouling emissions, respectively. Such large contribution of toxicity to the single score should be taken with caution given high associated uncertainties, as commonly stressed in the literature (Reap et al. 2008). Moreover, normalised results are normalised

**Fig. 4** ReCiPe single scores for the sub-sample of seven vessels of the Peruvian hake industrial fleet, per tonne of whole hake landed on ice, per fleet segment (excluding 2007 and segments represented by a single year of data for a single vessel). **a** Contribution analysis per impact category (“All other impact categories” groups all other 11 impact categories with pathways to the single score). **b** Contribution analysis per life cycle phase (as percentages of the single scores)





**Fig. 5** ReCiPe midpoints (selected categories) and contribution analysis for the landing-weighted means of the sub-sample of seven vessels of the Peruvian hake industrial fleet, per tonne of whole hake landed on ice

against a reference with few global data on ecotoxicity. Nonetheless, when comparing segments of the same fleet, the use of relative differences partially overcomes the overall uncertainty if all segments are modelled following the same assumptions, as we did.

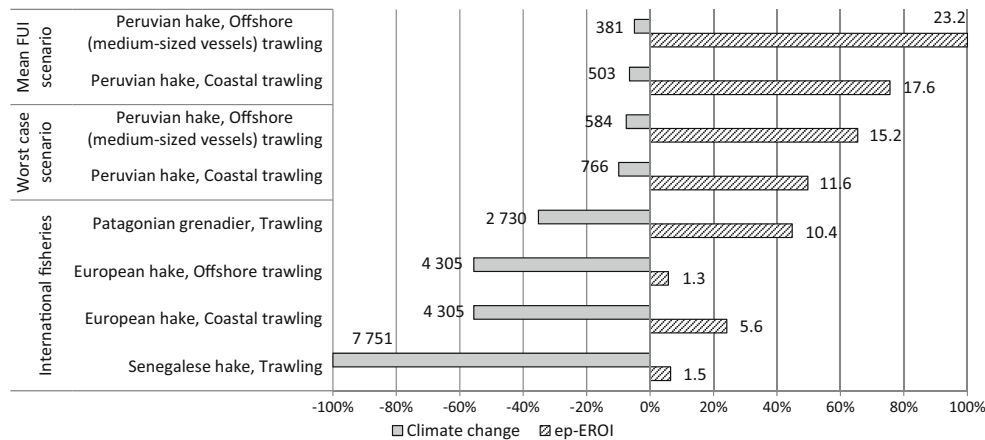
Differences in environmental impacts among segments are due to two main factors: FUI and mean annual landings per vessel, two non-correlated variables driving impacts per FU (one or the other, depending on the impact category). For instance, metal depletion and marine ecotoxicity depend on the vessel size (and associated metal consumption and antifouling release), which is divided by landed tone, while climate change and particulate formation depend nearly exclusively on FUI.

For the landing-weighted mean tonne of hake, a more detailed midpoint contribution analysis confirms and extends these findings: fuel use is the main contributor to most impacts, while antifouling is the main contributor to marine ecotoxicity, and other items (steel and copper provision, and

ice used for fish preservation on-board) represent a minor, yet important contribution to freshwater eutrophication and ecotoxicity, human toxicity and water depletion (Fig. 5).

### 3.3 Uncertainty analysis and explanation of variability

Uncertainty propagation (see [Electronic Supplementary Material](#) for details on tests) showed absolute uncertainty of the results for the average landed tonne (landing-weighted mean of all vessels in dataset A), expressed as a coefficient of variation, to be 21% for the single score and, in average, 30% for individual impact categories (with metal depletion, freshwater eutrophication and human and terrestrial toxicity having between 40 and 60% and ionising radiation 96%). When the average landed tonne is calculated as a landing-weighted mean of all engine power segments, all coefficients of variation are larger by up to 5%, with that of ionising radiation jumping to 139%.



**Fig. 6** Comparison of relative climate change impacts and edible protein energy return on investment (ep-EROI) of the Peruvian hake fishery under mean and highest fuel use conditions and other international hake trawl fisheries. The worst case scenario for the Peruvian medium-sized vessels (one trawler, 1 year) was determined by applying the same relative

difference between the mean and the highest value of the coastal vessels. Absolute values of climate change were expressed in kg CO<sub>2</sub> eq t<sup>-1</sup> and those of ep-EROI in %. Non-Peruvian fishery data from multiple sources (Vázquez-Rowe et al. 2013, 2014a,b). Climate change, as an undesired impact, is arbitrarily represented as negative

**Table 4** Number of daily trips, number of operating vessels and mean distance of the fishing areas to Paita for the Peruvian hake fleet from 2008 to 2012

	2008	2009	2010	2011	2012
Annual trips per vessel	43	47	64	64	189
Number of operated vessels	46	47	32	28	25
Mean distance of fishing areas <sup>a</sup> to Paita (km)	96.2	80.3	100.5	93.9	71.4

<sup>a</sup> IMARPE fishing areas are defined as A (03° 23' S–04° 00' S), B (04° 00' S–05° 00' S), C (05° 00' S–06° 00' S) and D (06° 00' S–07° 00' S)

Pairwise comparisons among all individual vessels show that when uncertainty data is considered (especially that of FUI, the main driving factor for most impacts), there is no clear discernible pattern among vessels regarding their environmental impacts regardless of their holding capacity or engine power. For instance,

- For half of the impact categories, trawler 1 > trawler5, and for the rest, the opposite is true.
- Impacts of trawler 8 > trawler 5 except for metal depletion and marine ecotoxicity and freshwater eutrophication, for which the opposite is true.
- Impacts of trawler 5 and trawler 6 are very similar, except for metal depletion and marine ecotoxicity, for which trawler 5 > trawler 6.

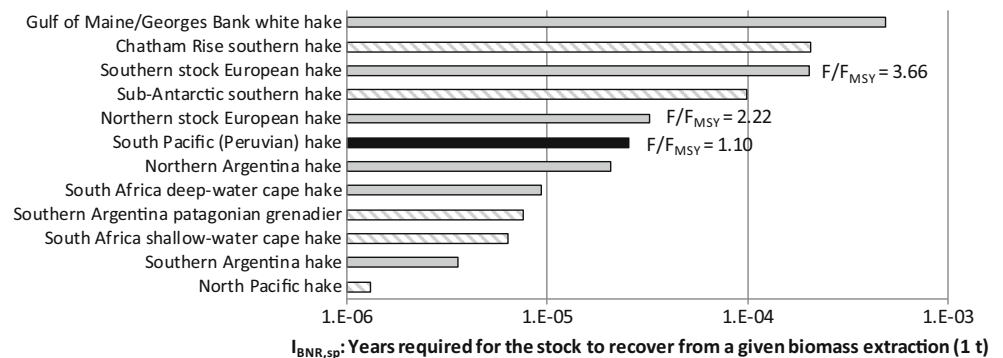
### 3.4 Energy cost of protein, overexploitation of the stock and overcapacity of the fleet

The Peruvian hake trawl fishery was compared with other international hake trawl fisheries and with the Patagonian grenadier fishery. Climate change was used as the LCA indicator because endpoint results (Fig. 3) identified this impact category as the main contributor to the single score and because other studies used this indicator. Climate change was complemented with the ep-EROI indicator. Results highlight the influence of FUI on the relative performance of the Peruvian fishery in comparison with others, and indirectly confirm its superior fuel efficiency (Fig. 6). The ep-EROI of Peruvian hake (17.6 to 23.2%) is higher than that of the other hake fisheries (1.3 to 10.4%) and could be even higher if

losses due to parasites were reduced, which could be achieved by improving on-board preservation. This ep-EROI is also higher than the mean ep-EROI for world fisheries of any kind, estimated at 8% (Tyedmers et al. 2005; Vázquez-Rowe et al. 2014a). These best performances are maintained even when using the highest FUI per segment of the Peruvian hake fishery for estimating both climate change impacts and ep-EROI (worst-case scenario in Fig. 6). It is worth noting that both climate change and EROI indicators would be improved even further if the Peruvian hake fishery had not worked in conditions of high overcapacity during the study period (2006–2010), due to the extremely low level of abundance. As indicated in Table 4, the annual number of daily trips from 2008 to 2010 (no data available for 2006 and 2007) varied from 43 to 64, whereas it reached 189 in 2012, a value close to expected values for such a fleet. This increase was due both to the recovery of the stock and to the decrease of the number of operative vessels from 46 to 19.

Finally, it was found that the Peruvian fishery exploiting the South Pacific hake stock features impacts on the biotic natural resource orders of magnitude higher than many other global hake stocks as shown in Fig. 7. The comparison of various hake stocks in terms of the overfishing through fishing mortality indicator confirms the overexploitation of the Peruvian hake stock ( $F/F_{MSY} > 1$ ), and the intensity of its overexploitation as relative to the northern stock European hake—higher—and southern stock European hake—much higher (Fig. 7). For these three stocks, there is a consistency in the results (at least regarding their ranking) of the  $I_{BNR,sp}$  and  $F/F_{MSY}$  indicators. The combination of these two biotic resource use types of indicators provides both a relative and absolute comparative indications of stock status, but the

**Fig. 7** Comparison of the impacts on the biotic natural resource at the species level ( $I_{BNR,sp}$ ) of fishing 1 t hake from various stocks and overfishing through fishing mortality ( $F/F_{MSY}$ ) from selected stocks. Stock assessment data from multiple sources (Ricard et al. 2012; Hélias et al. 2014; ICES 2015)



overfishing through fishing mortality indicator is more difficult to calculate, as few fisheries around the world benefit from  $F$  and  $F_{MSY}$  estimations.

#### 4 Conclusions and recommendations

The environmental assessment and statistical analyses performed on FUI show that the 400–450 hp engine power segment has lower impacts than both lower and higher segments. Nonetheless, this result is constrained by reservations due to the limited amount of data because this segment is represented by a single high-performing vessel (trawler 3) benefiting from relatively high mean annual landings. It remains that the performance of this segment was mainly associated to its low fuel use intensity, given that no clear compensatory fishing strategies seem to be deployed according to vessel's size. Given that in 2016 the largest segment of the whole fleet (180–384 m<sup>3</sup>, represented by the 242 m<sup>3</sup>, 850 hp trawler 9, and which would deserve a subdivision in at least two segments) counts 9 vessels out of 46, it would deserve a proper LCI and LCIA that hopefully would support the above results.

LCIA provides an overview of environmental impacts of the fleet operations, but EROI and  $I_{BNR,sp}$  provide additional information on the relation between stock and fishery and the energy efficiency of the latter. From an environmental standpoint, as suggested by the LCIA (but also from an economic perspective, e.g. fuel costs), it is not possible to identify a specific segment to which preference for fishing operations over the next years should be given. Future studies should concentrate on the analysis of additional data, especially regarding fuel use and midpoint/endpoint impacts to determine which vessel segment, if any, is more performant and eventually recommend its preference for future fishing operations. Indeed, more research based on additional FUI data is necessary to effectively compare the performance of these vessels with larger ones (such as trawler 9). Furthermore, an increased activity of these segments would largely reduce their environmental impacts in some impact categories related to the construction and maintenance phases, in particular metal depletion and marine ecotoxicity. Under the present regulation, IVQs are only transferrable among vessels belonging to the same operator; thus, this recommendation is unlikely to be followed by operators owning only small vessels (75% to date, according to the PRODUCE fleet database), except if encouraged by governmental incentives. For large companies, reforming the small vessels would not result in a loss of quotas, but would reduce their overall fishing capacity, something unpopular among many Peruvian vessel owners who still expect a recovery of the stock and fear shortage of capacity.

The Peruvian hake stock has been clearly overexploited in several periods, but despite the huge efforts to control the

industrial fishery and maintaining its current fully exploited status, the stock still exhibits typical symptoms of overexploitation such as shorter mean lengths, early age at maturity, restricted distributions patterns, etc., all of which are coherent with our results on the impacts on the biotic natural resource at the species level. Current harvesting volumes are still high regarding past recommendations. Furthermore, catchability is relatively high due to a combination of spatially near fishing areas (Table 4) and an apparent higher density of the stock on these areas (suggested by the fishing behaviour of vessels, which consistently and successfully target these specific fishing areas), which may favour a comparatively lower FUI. An intense effort must be put on the stock recovery, taking into account several environment-induced negative changes and the high variability of the Northern Humboldt Current ecosystem. A strengthening of the national stock recovery strategy would thus be advisable, with emphasis on enforcing the annual quotas and controlling illegal/unreported landings. Eventually, engaging in joint research on stock identity as well as joint stock assessment and management with Ecuador might be beneficial for both national hake fisheries. Moreover, fish preservation techniques should be improved (beyond using 0.6 t ice per tonne fish) to reduce parasite-induced losses and contribute with fishing efficiency. Finally, socioeconomic indicators would be required for sustainability-oriented decision making on future operations of the fleet exploiting a recovering or recovered stock.

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