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A set of sustainability performance indicators for seafood: Direct human consumption products from Peruvian *anchoveta* fisheries and freshwater aquaculture

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ABSTRACT

Different seafood products based on Peruvian *anchoveta* (*Engraulis ringens*) fisheries and freshwater aquaculture of trout (*Oncorhynchus mykiss*), tilapia (*Oreochromis* spp.) and black pacu (*Colossoma macropomum*), contribute at different scales to the socio-economic development, environmental degradation and nutrition of the Peruvian population. Various indicators have been used in the literature to assess the performance of these industries regarding different aspects of sustainability, notably their socio-economic performance. In this study, a novel set of indicators is proposed to evaluate the sustainability performance of these industries in Peru, based on life cycle assessment (LCA) and nutritional profiling, as well as on energy and socio-economic assessment approaches. The emphasis is put on the potential of different products to contribute to improving the nutrition of the Peruvian population in an energy-efficient, environmentally friendly and socio-economically sound way. The set of indicators includes biotic resource use (BRU), cumulative energy demand (CED), energy return on investment (EROI), production costs, gross profit generation, added value, and nutritional profile in terms of vitamins, minerals and essential fatty acids; as well as a number of life cycle impact assessment indicators commonly used in seafood studies, and some recently proposed indicators of resource status (measuring the impacts of fish biomass removal at the species and ecosystem levels). Results suggest that more energy-intensive/highly processed products (cured and canned *anchoveta* products) represent a higher burden, in terms of environmental impact, than less energy-intensive products (salted and frozen *anchoveta* products, semi-intensive aquaculture products). This result is confirmed when comparing all products regarding their industrial-to-nutritional energy ratio. Regarding the other attributes analysed, the scoring shows that salted and frozen *anchoveta* products generate fewer jobs and lower gross profit than canned and cured, while aquaculture products maximise them. Overall, it was concluded that less energy-intensive industries (*anchoveta* freezing and salting) are the least environmentally impacting but also the least economically interesting products, yet delivering higher nutritional value. Aquaculture products maximise gross profit and job creation, with lower energy efficiency and nutritional values. The proposed set of sustainability indicators fulfilled its goal in providing a multi-criteria assessment of *anchoveta* direct human consumption and freshwater aquaculture products. As often the case, there is no ideal product and the best trade-off must be sought when making decision regarding fisheries and seafood policy. No threshold for performance of the different indicators is offered, because the goal of the comparison is to contrast the relative performance among products, not of products against reference values.

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1. Introduction

Seafood systems represent an important source of protein and other nutrients, especially to coastal human populations worldwide. A variety of processing methods and products has been

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developed, ranging from fresh fish to energy-intensive canned or cured seafood products. These products exert different pressures on the environment and society, while producing different socio-economic benefits. Sustainability assessment of seafood systems has been addressed by means of certification and eco-labelling mechanisms, life cycle approaches, economic and bio-economic analyses and modelling, indicator systems, etc (e.g. Ayer and Tyedmers, 2009; Kruse et al., 2008; Leadbitter and Ward, 2007; McCausland et al., 2006; Samuel-Fitwi et al., 2012). Given the complexity of the seafood systems, it is necessary to combine approaches and integrate in a consistent way the supply chain, management, environmental, energy, socio-economic and nutritional features of the studied systems in order for sustainability to be comprehensively assessed.

Sustainability indicators can be defined as variables or combinations of variables collected and analysed with a well-defined analytical or policy goal, and for which certain reference values are significant in the context of the analysed system (Rametsteiner et al., 2011; Singh et al., 2009). Indicators are expected to feature certain properties, such as (Pingault and Préault, 2007; Roth, 2002): pertinence, reliability (i.e. scientifically sound), operationality (easy to estimate and update), legitimacy (accepted use, appropriation by stakeholders), interpretability (easy to understand and communicate), genericity (allowing comparison at various spatio-temporal scales), and defined in a finite interval (e.g. 1–5, A–D, etc). Indicators can be organised within an indicator system or dashboard when several of them are required (Halog and Manik, 2011; Shin and Shannon, 2010). For Joerin et al. (2005) and Balestrat et al. (2010), modelling is often necessary to build a system of indicators, for a model allows the indicators to be organised into a coherent whole. A number of knowledge and politically-driven indicator development frameworks have been proposed and adopted by leading international organisations (reviews in Bowen and Riley, 2003; Rametsteiner et al., 2011; Singh et al., 2009).

A large percentage of the Peruvian population, notably in remote Andean areas, suffers malnourishment, including iron and vitamin deficiency (FAO, 2000, 2011; INEI, 2011). Annual per capita edible fish consumption in Peru was estimated to vary between 4.2 and 11.2 kg (up to 22.5 kg in whole fish equivalents, in the period 2005–2011), being much higher in the coastal and Amazonian regions than in the Andean region (INEI, 2012a). These mean values rank Peru, according to FAOSTAT, as the 61st country in fish and seafood consumption worldwide, whereas it is the second fishing country (first, when only catches in national waters are considered). The main types of fish products consumed in Peru are listed in Table 1.

Table 1
Consumption patterns of fish products in Peru (2005–2011).

Product	Consumption[a] (kg person^{-1} y^{-1})				Area of consumption	Main species
	2005	2007	2009	2011		
Fresh fish	11.6	13.8	13.2	11.7	Coastal areas	Jack mackerel, Mahi mahi, jumbo squid
Canned fish	3.1	4.2	4.3	6.1	National level	Jack mackerel, tuna, *anchoveta*
Frozen fish	2.8	2.4	3.5	3.8	Major cities	South Pacific hake, jumbo squid
Cured (salted) fish	1.1	1	1.1	0.9	Provinces	Chub mackerel, jack mackerel, *anchoveta*
Total	18.6	21.4	22.2	22.5		

[a] Figures expressed in whole fish-equivalent volumes (INEI, 2012a,b). National consumption of freshwater aquaculture products is marginal, and mostly limited to the producing communities and regions.

Most fish consumed in Peru is sourced by fisheries other than *anchoveta*, and scarcely by freshwater aquaculture. Seafood, especially that derived from the *anchoveta* supply chains, has been often suggested as a suitable means to improve nutritional intake of vulnerable human communities and consumers at large (De la Puente et al., 2011; Jiménez and Gómez, 2005; Landa, 2014; Paredes, 2012; Rokovich, 2009). Analysing the factors limiting such consumption – e.g. prices, availability, preferences, etc. (Olsen, 2004), – as well as the nutritional-toxicological conflict associated with seafood intake (Sioen et al., 2009, 2008; Ström et al., 2011) and the particular characteristics of the *anchoveta* exploitation (Fréon et al., 2013), exceeds the scope of this study. We rather focus on the sustainability assessment of those *anchoveta* and aquaculture products, to inform on their relative sustainability performance and assist in providing information for future popularisation or policy/management measures involving these products. Our emphasis was put on the different products' potential to contribute in an energy-efficient and socio-economically sound way to improve the nutrition of the population. We propose a novel set of sustainability performance indicators addressing the three conventional pillars of sustainability (environment, society and economics). It is mainly based on life cycle assessment (LCA) and additional nutritional, energy and socio-economic assessment approaches to evaluate *anchoveta* (*Engraulis ringens*) direct human consumption (DHC) and freshwater aquaculture products in Peru. Finally, we use the results of this assessment to suggest directions for further sustainable development of fishfood industries.

2. Methods

Sustainability assessment of the following products and their comparison was carried out: canned, frozen, salted and cured *anchoveta*, as well as cultured rainbow trout, black pacu and red hybrid tilapia. The selection of species is determined by the goals of the ANCHOVETA Supply Chain project (http://anchoveta-sc.wikispaces.com), which include the sustainability assessment of *anchoveta*-based products (including Peruvian fed aquaculture); and the promotion of increased consumption of these products in Peru.

The production system assessed includes infrastructure, heavy equipment, use of water and chemicals, energy use, agricultural inputs to *anchoveta* products (e.g. vegetable oils), fish and the whole aquafeed subsystem (including agricultural inputs), and transportation of key inputs. For both *anchoveta* DHC and aquaculture systems the analysis encompassed cradle to gate and distribution interventions.

2.1. Life cycle assessment

Life cycle assessment (LCA) is an ISO-standardised framework for conducting a detailed account of all resources consumed and emissions associated with a specific product along its whole life cycle (ISO, 2006a). LCA has been widely applied to study the environmental performance of fisheries (Avadí and Fréon, 2013), seafood including aquaculture products (Aubin, 2013; Henriksson et al., 2011; Parker, 2012) and industrialised seafood products (Hospido et al., 2006; Iribarren et al., 2010). LCA consists of a goal and scope definition phase, where the functional unit (FU) and system boundary are defined; a life cycle inventory (LCI) phase, where life cycle data related to the FU is collected; a life cycle impact assessment (LCIA) phase where a set of characterisation factors are used to calculate environmental impacts on a wide number of impact categories; and an interpretation phase, where conclusions are drawn from the LCI and LCIA results (ISO, 2006a,b). The midpoint-based CML methods, baseline 2000 and 2001 (Guinée et al., 2002), are the most commonly used in fisheries and seafood LCA studies (Avadí and Fréon, 2013; Parker, 2012). The newer ReCiPe method (Goedkoop et al., 2009) extends and complements two previous and widely used methods (Parker, 2012): CML and Ecoindicator 99 (Goedkoop and Spriensma, 2001), and combines midpoint and endpoint indicators. The CML method includes characterisation factors for more substances than ReCiPe, and therefore was used for toxicity impact categories, complemented by USEtox (Rosenbaum et al., 2008), a consensus toxicity model.

A combination of LCIA methods is thus proposed, from which some environmental performance indicators are extracted:

- ReCiPe is used for computing midpoints and an endpoint single score, the latter based on the midpoints and a weighting set (Goedkoop et al., 2013). See details on the calculation of the single score in the Supplementary material.
- CML baseline 2000 and USEtox are used to compute toxicity impact categories, and their respective results are compared. Such a comparison is suggested due to the high uncertainty associated with toxicity models in LCA.
- Cumulative energy demand (CED) (Hischier et al., 2010) is used to compute the total use of industrial energy (VDI, 1997).

To complete the inventories upstream, all background processes were taken from the ecoinvent database v2.3 (Ecoinvent, 2012) and the life cycle impact assessments were computed using SimaPro v7.3 (PRé, 2012). Detailed description of the production systems and environmental performance analyses of these products are presented in Avadí et al. (2014b,c).

The FU for which all indicators were computed was defined as one tonne (t) of (a) edible fish in a DHC product in the case of *anchoveta*, and (b) fresh fish edible portion for cultured species. Both types of products can be considered as final outputs of the *anchoveta*-based supply chains. Mass allocation was applied for computing the relative impacts of fish products and their associated processing residues (fish residues are valorised as inputs to the residual fishmeal industry).

Impacts of the seafood consumption phase have been excluded from the analysis. Distribution (transportation, retailing) of fresh and frozen products is limited in Peru, whereas canned products are distributed nationally. Potential impacts of distribution patterns for *anchoveta* DHC products were compared here with those of aquaculture products, if distributed nationally over an extended land-based refrigerated chain. Exports exceed the scope of this work and were not considered.

2.2. Sustainability indicators

A number of indicators were selected from the large indicators pool available in the literature, in such a way that all aspects of

Table 2
Overview of proposed sustainability indicators (including impact categories included in life cycle impact assessment methods) and their traits according to the PROLIGD set of criteria.

Sustainability dimension	Indicator (unit)	Reference publications	Calculation	Indicator traits						
				P	R	O	L	I	G	D
Ecological	$I_{BNR,sp}$ (years)	Langlois et al. (2014)	Manual	X	X	X		X	X	X
	$I_{BNR,eco}$ (years)	Langlois et al. (2014)	Manual	X	X	X	X	X	X	X
	BRU (g C/kg)	Pauly and Christensen (1995)	Manual	X	X	X	X	X	X	X
	BRU-based discard assessment	Hornborg (2012), Hornborg et al. (2012a, b)	Manual	X	X	X		X	X	X
Environmental	LCA/ReCiPe Climate change, Ozone depletion, Terrestrial acidification, Freshwater eutrophication, Marine eutrophication, Photochemical oxidant formation, Particulate matter formation, Ionising radiation, Agricultural land occupation, Urban land occupation, Natural land transformation, Water depletion, Metal depletion, Fossil depletion Single score (Pt)	Goedkoop et al. (2009)	LCIA methods	X	X	X	X	X	X	X
	LCA/CED (MJ)	Hischier et al. (2010)	LCIA methods	X	X	X	X	X	X	X
	LCA/CML[USES-LCA] Human toxicity, Fresh water aquatic ecotoxicity, Marine aquatic ecotoxicity, Terrestrial ecotoxicity	Guinée et al. (2002), Van Zelm et al. (2009)	LCIA methods	X	X	X	X	X	X	X
	LCA/USEtox (CTUe, CTUh[a])	Rosenbaum et al. (2008)	LCIA methods	X	X	X	X		X	X
Nutritional	GEC (MJ/kg)	Tyedmers (2000)	Manual	X	X	X	X	X	X	X
	Nutritional profile (Nutrient Rich Food index)	Drewnowski and Fulgoni III (2008)	Manual	X	X		X	X		X
Energy efficiency	gross edible EROI (%)	Tyedmers (2000), Tyedmers et al. (2005), Hall (2011)	Manual	X	X	X	X	X	X	X
	edible protein EROI (%)	Tyedmers (2000), Tyedmers et al. (2005), Hall (2011)	Manual	X	X	X	X	X	X	
Economic	Production costs (USD)	Kruse et al. (2008)	Manual	X	X	X	X	X	X	X
	Value added (USD)	Kruse et al. (2008)	Manual	X	X	X		X	X	X
	Gross profit generation (USD)	Accepted accounting indicator	Manual	X	X			X	X	X
Social	Employment (USD)	Kruse et al. (2008)	Manual	X	X		X	X	X	X

Abbreviations: BRU: biotic resource use; CED: cumulative energy demand; CTU: comparative toxic units; EROI: energy return on investment; GEC: gross energy content; IBNR, sp: impacts on Biotic Natural Resources at the species level; IBNR, eco: impacts on Biotic Natural Resources at the ecosystem level; LCA: life cycle assessment; LCIA: life cycle impact assessment; P: pertinence; R: reliability; O: operationality; L: legitimacy; I: interpretability; G: genericity; D: defined in a finite interval (all indicators expressed as a percent of the higher value).

[a] CTUe provides an estimate of the potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a chemical emitted (PAF m^3 day kg^{-1}) (Rosenbaum et al., 2008). CTUh provides an estimate of the increase in morbidity in the total human population per unit mass of a chemical emitted (cases per kilogram), assuming equal weighting between cancer and non-cancer due to a lack of more precise insights into this issue (Rosenbaum et al., 2008).

sustainability (especially the environmental dimension) are addressed (Table 2). Main criteria for such selection were: (1) the above mentioned expected properties (e.g. pertinence, reliability, operationality, etc), to the largest possible extent; (2) historical, previous use in the seafood research field; and (3) comparability with other food systems (Gerbens-Leenes et al., 2003; Jones, 2002; Kruse et al., 2008; Ness et al., 2007; Potts, 2006; Singh et al., 2009). Sustainability dimensions addressed by selected indicators were: environmental (including energy use, resource use, toxicity-related effects and sea use indicators)); social (including employment, energy efficiency and human nutrition) and economic aspects (gross profit and added value).

A growing panel of indicators of ecosystem impacts of fisheries can be found in the literature (e.g. Hornborg et al., 2012a; Langlois et al., 2014; Libralato et al., 2008; Shin et al., 2010). For the purpose of LCA, a small set of indicators was selected which mostly represents the impacts of *anchoveta* production relative to the potential given by the level of primary production and intrinsic productivity of the exploited species. The selected indicators are thus based on ecosystem level indicators such as net primary productivity (NPP), fisheries performance indicators such as maximum sustainable yield (MSY) of a given stock, and the commonly used (in aquaculture and fisheries) biotic resource use indicator (Langlois et al., 2014). Due to the lack of proper data, the specific ecological impacts of producing agricultural inputs to aquafeeds used in aquaculture could not be calculated (but conventional environmental impacts are included). Biotic resource use (BRU) is estimated for agricultural materials from the carbon content of the crop, for animal husbandry and aquaculture products from the carbon content of feed compositions; and for fish inputs to aquafeeds, using the primary production required (PPR) equation. The PPR indicator was first proposed by Pauly and Christensen (1995) and is now widely used by many fisheries and aquaculture researchers. PPR to sustain catches of a specific fishery is considered an equivalent of the BRU of a fish raw material derived from that fishery (Papatryphon et al., 2004; Tyedmers, 2000). BRU is also useful for rendering comparable the impacts of species removal (catches, by-catches, discards), crops and animal products.

Pauly and Christensen (1995) estimated the primary production required for a fishery based upon a 9:1 conversion ratio of wet weight to carbon and a transfer efficiency between trophic levels of 10% (both figures are conservative); by means of the widely used Eq. (1):

$$\mathrm{BRU} = \mathrm{PPR} = \left(\mathrm{catch} \times 9^{-1}\right) \times 10^{\mathrm{TL}-1} \quad (1)$$

where PPR stands for primary production required (in $\mathrm{g\,C} \times \mathrm{kg}^{-1}$) and TL for trophic level of landed species. Actual catch data (kg) was used for calculations, as recommended by (Hornborg et al., 2013). BRU-based discard assessment approaches, as described in Hornborg (2012) and Hornborg et al. (2012a,b), consist of calculating PPR of species in the discarded fraction of a fishery, and establishing the proportion of threatened species in the discard.

Sea use endpoint impact categories, namely the impacts of biomass removal on biotic natural resources (BNR) at the species level ($I_{\mathrm{BNR,sp}}$) and at the ecosystem level ($I_{\mathrm{BNR,eco}}$) were proposed by Langlois et al. (2014). They express the time (in years) necessary for restoring the biomass uptake of the harvested species, and for regenerating the amount of biomass removed (as an expression of the biotic natural resource depletion in the ecosystem). The indicators are calculated by Eqs. (2) and (3):

$$I_{\mathrm{BNR,sp}} = \frac{\mathrm{referenceflow} \times 1}{\mathrm{MSY}} \quad (2)$$

where the reference flow is the inventory flow for which impacts are assessed, and the 5-year average of the total annual catch can be used in substitution of the maximum sustainable yield (MSY) of the stock, when the stock is over-exploited; and

$$I_{\mathrm{BNR,eco}} = \frac{\mathrm{BRU}}{[A \times E_{\mathrm{NNP}}]} \quad (3)$$

where BRU is expressed in $\mathrm{t}\,C \times \mathrm{t}^{-1}$, A is the ecosystem area in km^2 and E_{NPP} is the net primary productivity of the ecosystem in $\mathrm{t\,km}^{-2}$ in one year. These sea use indicators were calculated for different segments of the *anchoveta* fishery: the small- and medium-segments landing for DHC and the industrial segment landing for reduction into fishmeal and fish oil that are used in aquafeeds. The MSY for *anchoveta* has been estimated to be over 5 million tonnes by Csirke et al. (1996), but the authors did not provide a fixed number but rather a range. Therefore a 5-year average of total landings were used as proxy (5.5 million t, for 2006–2010), given that *anchoveta* stock is presently considered as fully exploited and previously as over-exploited, as it recovered from over-exploitation after the 1997–1998 El Niño event (IMARPE, 2010). The MSY of hake has been estimated in ~27,000 t until the stock, considered as over-exploited, fully recovers (Lassen et al., 2009).

LCA-based indicators were calculated, including specific impact categories and the weighted single score computed by ReCiPe, as detailed above (Table 2).

Cumulative energy demand (CED) is a good estimation of the energy embedded in a product. It is also useful for the computation of more sophisticated energy efficiency indicators. Gross energy content (GEC), expressed in $\mathrm{MJ} \times \mathrm{kg}^{-1}$, is a good indicator of the nutritional characteristics of an agricultural or seafood material, because it is based on the lipid, protein and carbohydrate contents of the material (by means of an unweighted sum):

$$\mathrm{GEC} = \mathrm{Proteincontent} \times P_{\mathrm{energy}} + \mathrm{Lipidcontent} \times L_{\mathrm{energy}} \quad (4)$$

where P_{energy} is the average energy content of protein (23.6 MJ $\times\, \mathrm{kg}^{-1}$) and L_{energy} is the average energy content of lipids (39 $\mathrm{MJ} \times \mathrm{kg}^{-1}$). No relevant carbohydrate content is present in seafood, thus, it is excluded from the formula. Used P_{energy} and L_{energy} are associated with GEC, which includes energy losses in excretions. An alternative would be to use metabolizable energy rather than gross energy content of protein and lipid (for instance, $P_{\mathrm{energy}} = 16.7\ \mathrm{MJ} \times \mathrm{kg}^{-1}$).

CED and GEC are also used for computing two different variations of energy return on investment (EROI), by means of Eqs. (5) and (6) (Hall, 2011; Mitchell and Cleveland, 1993; Tyedmers, 2000):

$$\mathrm{GrossedibleEROI} = \frac{[\mathrm{GEC} \times \mathrm{EY}]}{\mathrm{CED}} \quad (5)$$

where EY represents the fish edible yield; and:

$$\mathrm{EdibleProteinEROI} = \frac{[P \times P_{\mathrm{energy}} \times \mathrm{EY}]}{\mathrm{CED}} \quad (6)$$

where P is the protein content of fish, P_{energy} is the energy content of protein (23.6 $\mathrm{MJ\,kg}^{-1}$), EY represents the edible yield of the fish (often fillets) and CED represents the total industrial energy input (in $\mathrm{MJ\,kg}^{-1}$).

BRU and CED complement resource and energy use impact categories included in ReCiPe.

Nutrition information labels for seafood products use standard profiles (Drewnowski and Fulgoni III, 2008). Comparisons of nutritional characteristics of different seafood products have focused on vitamins, minerals, protein, energy content and especially Omega-3 fatty acids. We customised the Nutrient Rich Food index ($\mathrm{NRF}_{n \times 3}$) described in Drewnowski and Fulgoni III (2008) which aggregates values for various beneficial nutrients and nutrients to limit. Positive nutrients are those more relevant to tackle the nutritional deficiencies observed in Peru (see below),

Table 3
Sea use indicators of *anchoveta* DHC and freshwater aquaculture products, per tonne of fish in product.

Product	Usable fraction (%)[a]	Fresh fish (*t*)[b]	Aquafeed (t)	FMFO (t)	$I_{BNR,sp}$ (years)	Ranking (1 = best)
Fresh *anchoveta* (HGT, for DHC)	75	1.33			0.24	5
Fresh *anchoveta* (whole, for reduction)	100	1			0.18	4
Frozen *anchoveta* (gutted)	75	1.33			0.24	5
Salted *anchoveta* (HGT)	27	3.7			0.67	8
Canned *anchoveta* (production average)	50	2			0.36	7
Cured *anchoveta* (production average)	19	5.26			0.95	9
Trout, semi-intensive, commercial	60	1.67	2.33	0.61	0.11	3
Black pacu, semi-intensive, commercial	42	2.38	3.33	0.2	0.04	2
Tilapia, intensive, commercial	36	2.78	3.89	0.19	0.04	1

[a] Usable fraction of whole fresh fish.
[b] Tonnes of fresh fish equivalent to 1 tonne of fish in product. For aquaculture products a feed conversion ratio of 1.4 was used, and inclusion ratios of fishmeal and oil (FMFO) into feeds were 26% for trout, 6% for black pacu and 5% for tilapia (Avadí et al., 2014b).

and only two nutrient to limit present in detrimental quantities in some of the studied seafood products were retained (saturated fatty acids and sodium). The $NRF_{n\times 3}$ index is based on nutrient density (Darmon et al., 2005) and the LIM model of nutrients to limit (Maillot et al., 2007). It is calculated for a Q = 100 g portion of seafood and formalised in Eqs. (7)–(9):

$$NRF_{n\times3} = NRF_n - LIM \tag{7}$$

where *NRF* stands for nutrient rich food, *n* is the number of positive nutrients assessed and LIM is a measure of the nutrients to limit delivered by the seafood product compared to maximum recommended values (MRV).

$$NRF_n = \frac{\left(\sum_{1-n}\left((\text{Nutrient}/\text{DV}) \times 100/n\right)\right.}{\text{ED}} \tag{8}$$

where *DV* represents the recommended daily values[1] for each nutrient assessed (n = 10), and ED is the energy density of the food item, in kcal. Included nutrients, expressed together with their DV per 100 g of the food item, are protein, Omega-3 fatty acids (EPA + DHA), other non-saturated lipids (including Omega-6 fatty acids), vitamins A, B-12 and D; calcium, potassium, phosphorus and iron.

$$LIM = \frac{\left(\sum_{1-2}(\text{DA}/\text{MRV})/2\right) \times 100}{Q} \tag{9}$$

where DA is the daily amount, in g, provided by the seafood item in a portion of Q = 100 g; DI represents the daily intake of food (in g) and MRV values are taken from Maillot et al. (2007). The LIM model includes originally three nutrients to limit, namely saturated fat, added sugars and sodium. We simplified the original equation (Maillot et al., 2007) to exclude added sugars, since they are not present in the studied products; and refer to the 100 g seafood portion rather than to the whole daily food intake.

In order to better take into account the specific nutritional deficiencies occurring in Peru, we also produced a weighted version of the index, applying a weighting set based on the relevance of the studied food products for tapping. Details on those deficiencies, the weighting factors and the weighted ranking of seafood and other protein foods consumed in Peru are presented in the Supplementary material, where results are contrasted with the canonical $NRF_{n\times 3}$ ranking.

Socio-economic indicators are calculated based on statistical data, company data and publications by experts. Notably, the majority of revenue, cost and employment figures for industries other than aquaculture were obtained from literature: we used *anchoveta* processing-specific data when possible, and otherwise performed a mass allocation of Peruvian seafood industries data from Christensen et al. (2013). The indicators are defined as follows:

- Employment, the labour associated with producing one functional unit (Kruse et al., 2008), adjusted as full time jobs (including direct and indirect). PRODUCE statistics on fish landings, processing and production corresponding to the year 2009 were used for computations.
- Value added, the monetary added value per functional unit (Kruse et al., 2008). This indicator represents the difference between the selling price of a good and the cost of all inputs purchased (Heijungs et al., 2012), especially raw materials (e.g. fresh fish and agricultural inputs, aquafeed, fry, packaging, fuels and energy, etc).
- Gross profit, the monetary value retained by commercial entities per functional unit, defined in the context of this study as the difference between the selling price and its production cost. Production costs represent the cost of producing one functional unit (Kruse et al., 2008). The cost structure excludes (due to data gaps and for simplicity) certain taxes, subsidies, rights, depreciation costs and capital costs.

All indicators proposed feature different units, and thus were presented separately by means of a representation device based on a percentage scale relative to the highest observed value of each indicator for all products, as a means of standardisation. Doing this also addresses the need of a finite interval for all indicators, although at the expense of sensitivity to the range of analysed products. For that reason indicators were presented both for all products and clustered by industry (DHC vs. aquaculture). Table 2 also depicts the compliance of each indicator with the desired criteria. Certain indicators are novel and thus lack legitimacy (e.g. some ecological and socio-economic ones), while others (i.e. nutritional profile), are complex to compute.

The effects of long and medium term environmental changes, such as climate change and El Niño events, were not considered despite their importance in the Humboldt Current ecosystem (Bertrand et al., 2008) because no consistent data is available. There are two opposing Peruvian scenarios of climate change – intensification vs. decrease of the upwelling strength (Bertrand et al., 2010; Brochier et al., 2013; Gutiérrez et al., 2011), – showing opposed results on the abundance of *anchoveta*. Regarding El Niño, the last three strong events (1972/73, 1982/83, 1997/98) show a different picture regarding the variability of the *anchoveta* biomass (Ñiquen and Bouchon, 2004), which depends on the actual regime of the ecosystem during the event (Bertrand et al., 2004). These changes are expected to dramatically change the relative performances of fisheries. The major effects of those changes on fishery products will be a modification of the catch rate and roughly

[1] US Food and Drug Administration Daily Values – DV (FDA, 2013) and FoodDrinkEurope Guideline Daily Amounts – GDAs (http://gda.fooddrinkeurope.eu) were used.

Table 4
Selected Life Cycle Impact Assessment results of *anchoveta* DHC and freshwater aquaculture products, per tonne of fish in product at plant gate (*anchoveta*) or at farm gate (aquaculture).

Impact categories	Unit	Fresh *anchoveta*	Canned *anchoveta*[a]	Frozen *anchoveta*	Salted *anchoveta*	Cured *anchoveta*[a]	Rainbow trout[d]	Black pacu[e]	Red tilapia[f]
ReCiPe									
Climate change	kg CO_2eq	115.38	2583	193.57	126.11	2906	4672	4653	9897
Terrestrial acidification	kg SO_2eq	1.23	14.19	1.47	1.08	17	63.74	65.58	136.09
Freshwater eutrophication	kg P eq	0.01	1.03	0.05	0.06	1.83	16.68	24.45	11.41
Agricultural land occupation	m^2a	2.6	1997	4.51	5.34	3462	8,084	9,376	7799
Water depletion	m^3	0.29	32.64	3.07	2.33	31.61	25,402	13,242	4010
Single score	Pt	22.95	798.17	37.68	45.52	1033	849.52	1045	1573
CML-toxicity									
Human toxicity	kg 1,4-DB-e	42.98	14,356	70.04	114.34	18,443	2208	1480	2258
Ecotoxicity[b]	kg 1,4-DB-e	38,896	2,873,606	60,202	103,519	3,741,057	1,153,270	1,119,651	1,651,079
Others									
Cumulative energy demand	MJ	6809	68,990	8278	6681	79,377	71,912	79,176	146,776
Biotic resource use[c]	kg C	5786	9489	7715	20,625	28,661	50,038	14,555	17,556

Notes: efficiencies used for *anchoveta* products, respect to fresh whole fish: canned = 50%, frozen = 75%, salted = 27%, cured = 19%. Edible yields of aquaculture products: trout = 60%, black pacu = 42%, tilapia = 36%.
[a] Production average.
[b] Summarises CML impact categories freshwater aquatic ecotoxicity, marine toxicity and terrestrial ecotoxicity.
[c] BRU is calculated for the whole fish equivalent, including discards.
[d] Trout systems: semi-intensive, lake-based, commercial feed.
[e] Black pacu systems: semi-intensive, pond-based, commercial feed.
[f] Tilapia systems: intensive, pond-based, commercial feed.

proportional changes in fuel use, and hence in environmental, economic and social (employment) performances (Bertrand et al., 2010; Gutiérrez et al., 2011). Regarding aquaculture, atmospheric changes such as increase in air and freshwater temperature, changes in seasonality (phenology) of rain, intensification and higher frequency of extreme events (storms, drought and flood), may affect yields via feeding rates, water temperature, etc. (Cochrane et al., 2009; OLDEPESCA, 2010; Soto and Quiñones, 2013). Intensive and semi-intensive Peruvian aquaculture (tilapia, trouts in river and lakes) considered here are expected to suffer less from climate change than extensive aquaculture of black pacu in the Amazonian region, due to better control of the environmental conditions in the former. However, infrastructure of aquaculture (ponds, cages) may suffer directly from storm events. Limiting our analysis to trends, the most likely result of climate change and El Niño events is a decrease of fishing yield and therefore an increase of the contribution of fishing to the environmental and socio-economic impact of the different products. This would result in a slight decrease of the present contrast between less refined products (fresh, frozen and salted *anchoveta*) and the most refined ones (canned and cured *anchoveta*) or the one belonging to long supply chain (aquaculture products).

Table 5
Energy return on investment (EROI) of *anchoveta* for direct human consumption (DHC) and freshwater aquaculture products, per tonne of fresh fish input equivalent at plant gate (*anchoveta*) or output at farm gate (aquaculture).

Fish product	GEC[i] (MJ kg^{-1})	CED[ii] (MJ kg^{-1})	Edible yield[iii] (%)	Protein content (%)	Lipid content (%)	gross edible EROI	edible protein EROI
Anchoveta (fresh fillets)[a,iv]	19.5 ± 2.2	5.1	57.7 ± 9.6	19.1 ± 0.1	8.8 ± 0.8	165.1	37.1
Anchoveta (HGT)[b]	7.9 ± 0.2	1.7	75	19.1 ± 0.1	8.8 ± 0.8	417.2	232.3
Anchoveta (canned, HGT, with vegetable oils)[c]	6.9 ± 2.4	41.4	50	21.3 ± 1.8	9.0 ± 5.7	15.6	11
Anchoveta (gutted, fresh/frozen)[a]	19.5 ± 2.2	8.5	75	19.1 ± 0.1	8.8 ± 0.8	96.1	53.5
Anchoveta (salted)[c]	5.3	6	27	18.4	5.9	82.8	66.3
Anchoveta (cured, fillets, with vegetable oils)[c]	6.5 ± 0.1	78.7	19	30	4	8.2	8.7
Cultured rainbow trout[d]	7.2 ± 1.6	71.9	59.4 ± 5.2	18.4 ± 1.7	7.6 ± 3.4	5.9	3.5
Cultured black pacu[e]	8.2 ± 2.0	75.1	41.8 ± 3.4	15.0 ± 1.9	12.4 ± 5.4	4.6	1.9
Cultured red tilapia[f]	4.5 ± 0.5	79.2	36.0 ± 1.4	18.3 ± 1.5	1.9 ± 0.2	4.3	1.8

Notes: [i]Excluding vegetable oil added to canned and cured *anchoveta* products. [ii]CED of canned, salted and cured *anchoveta* calculated for 1 kg of raw fish processed. [iii]Values represent a percentage of the whole fish weight. When averages are calculated from different reported values, they are accompanied by the calculated standard deviation. [iv]*Anchoveta* fresh fillets is not a product commercialised in Peru, yet it is shown for comparison.
[a] GEC calculated from a study of *anchoveta* muscle (calorimetry measurements, IRD, 2011, unpublished), lipid content is an average of values (IMARPE-ITP, 1996; Torry Research Station, 1989; calorimetry measurements, IRD, 2011, unpublished).
[b] IMARPE-ITP (1996), Torry Research Station (1989).
[c] ITP (2007).
[d] Austreng and Refstie (1979), Celik et al. (2008), Dumas et al. (2007), Fallah et al. (2011), USDA (2012).
[e] Almeida et al. (2008), Bezerra (2002), Torry Research Station (1989), Machado and Sgarbieri (1991).
[f] Mendieta and Medina (1993), Torry Research Station (1989), USDA (2012).

Table 6
Nutritional profile of various *anchoveta* DCH and other Peruvian fish products (see text for ranking method).

Edible portion		Energy kcal 100^{-1} g	Basic profile (%)				Vitamins (μg 100^{-1} g)			Minerals (mg 100^{-1} g)					Ranking (1 = best)
			Protein	Lipids (total, Omega-3, SFA)	Water	Ash	A	B-12	D	Ca	Na	K	P	Fe	
Anchoveta products	Fresh/frozen (gutted)	465.8[a] 188.2[b]	19.1	8.8, 2.5, 1.3	70.8	1.2	15	0.6	<0.1	77.1	78	241.4	174	3	2
	Canned (HGT)[c]	166	21.3	9.0, 2.6, 2.7	59.8	3.5	18.5	11.2	6.4	365	408	380.5	400.5	2.5	1
	Salted (HGT)[c]	126.1	18.4	5.9, 1.7, 2.2	43	6.2	12	0.9	1.7	232	1 223	544	252	4.6	3
	Cured (fillets)[c]	155.8	30	4.0, 1.2, 2.2	48.1	17.6	12	0.9	1.7	232	3 668	544	252	4.6	7
Fresh fish	Cultured rainbow trout[d]	171.1	18.4	7.6, 0.7, 1.4	73.8	1.2	84	4.3	15.9	25	51	377	226	0.3	4
	Cultured black pacu[e]	196.8	15	12.0, 0.4, 4.8	71.6	2.1	6	2.2	2.9	35	35.3	164.9	631.8	0.5	6
	Cultured red tilapia[f]	108.6	18.3	1.9, 0.1, 0.6	80.5	1.4	0	1.6	3.1	10	52	302	170	0.6	5

Notes: When alternative values for the same parameter were available, averages were used. For energy calculations, the following conversion factor was used for MJ kg^{-1} to kcal 100^{-1} g: 0.1×0.004184^{-1}. For the Omega-3 figures, only eicosapentaenoic acid (EPA, 20:5) and docosahexaenoic acid (DHA, 22:6) were considered, and are expressed as percentages of the total product weight, in parenthesis. Due to the variety of data sources, a ±2% error may occur in the total percentage of the basic profiles. Data for cultured species is relative to edible portions.

[a] Calorimetry measurements for *anchoveta* muscle/fillets (IMARPE, 2011, unpublished data),

[b] Torry Research Station (1989), IMARPE-ITP (1996), Peter Tyedmers (pers. comm., 2012), industry data (http://www.tasa.com.pe/), USDA (2012) values for European anchovy.

[c] ITP (2007), González et al. (2007), (Reyes et al., 2009), USDA (2012) and http://www.nutraqua.com/ values for canned sardine and cured European anchovy.

[d] Austreng and Refstie (1979), Celik et al. (2007), Dumas et al. (2007), Fallah et al. (2011), Sousa et al. (2002) and USDA (2012).

[e] Almeida et al. (2008), Almeida and Bueno Franco (2006), Barua and Chakraborty (2011), Bezerra (2002), González et al. (2007), Melho Filho et al. (2013), Torry Research Station (1989), Machado and Sgarbieri (1991), Oishi et al. (2010), (Van der Meer, 1997) and http://www.nutraqua.com/ values for vitamins are averages of *Pangasius hypophtalmus*, *Lates niloticus* and *Oreochromis niloticus niloticus*.

[f] Torry Research Station (1989), Mendieta and Medina (1993) and USDA (2012) values for mixed tilapia species.

3. Results and discussion

The indicator set was applied to all products described (Table 2–8). Results of the most relevant and not overlapping indicators are graphically presented both aggregated (Fig. 1), and by industrial cluster (*anchoveta* DHC industry-based in Fig. 2a and aquaculture-based in Fig. 2b), initially without considering distribution, which is discussed later. Results are detailed and discussed in the next sections, by sustainability dimension: ecological/environmental, energy and nutrition, and socio-economic performance.

Companion papers of the Anchoveta-SC project provide specific guidelines and recommendations for a sustainable management of the fishery (Avadí et al., 2014c; Fréon et al., 2014a,b), aquaculture (Avadí et al., 2014b) and transformation sector (Avadí et al., 2014a; Fréon et al., in prep.).

3.1. Ecological and environmental performance

$I_{BNR,sp}$ and $I_{BNR,eco}$, the two indices related to biotic natural resources (BNR) at species and ecosystem level respectively, were estimated at 0.2 and 21 years per million t of fresh headed-gutted-tailed (HGT) fish, respectively. The effect of the removal of *anchoveta* biomass associated with the studied products ranges between 0.04 and 0.95 years per million t of landed *anchoveta*. These values represent the time in years necessary to rebuild, at the species level, the production of one tonne of fish in product (*anchoveta* DCH or aquaculture product whose diet included FMFO). The product ranking according to $I_{BNR,sp}$ is presented in Table 3. The ecological impact on the BNR ranking was not included in the multi-criteria device depicted in Fig. 1 and Fig. 2. The rationale for this is that we preferred to emphasise direct rather than indirect sustainability

Table 7
Nutritional profile of other animal protein sources consumed in Peru.

Edible portion	Energy kcal 100^{-1} g	Basic profile (%)				Vitamins (μg 100^{-1} g)			Minerals (mg·100^{-1}g)					Ranking (1 = best)	Consumption[e] (kg person^{-} y^{-1})
		Protein	Lipids (total, Omega-3, SFA)	Water	Ash	A	B-12	D	Ca	Na	K	P	Fe		
Beef (lean)[a,b]	105	21.3	10.0, 0.04,4.1	75.9	1.1	0	2.7	0	16	59	271	208	3.4	3	5.1
Chicken (lean)[a,b]	119	21.4	9.3, 0, 2.7	75.5	1	16	0.3	3.3	12	64	144	173	1.5	5	17.4
Eggs[a,b]	141	13.5	8.4, 0.6, 3.1	75.4	0.9	140	0.9	2.1	34	142	138	194	1.1	2	6.6
Fresh cheese[a,b]	264	17.5	20.1, 0.05, 13.7	55	4.1	420	1.8	0.7	783	704	126	375	1.3	8	2.4
Hake (edible portion)[c,d]	102.3	16.6	1.2, 0.5, 0.3	82.1	1.2	7.3	0.5	1	14.7	64	403.7	180	0	1	N/A
Milk[a,b]	63	3.1	7.6, 0, 4.6	87.8	0.7	28	0.2	0.2	106	106	303	94	1.3	6	48.1
Pork (carcass)[a,b]	198	14.4	15.1, 0.01, 7.9	69.2	1.2	2	0.6	0	12	42	253	238	1.3	7	1
Shrimp[a,f]	71	13.6	1.0, 0.1, 0.1	83	1.9	54	1.1	0.1	54	566	113	244	0.2	4	N/A

Notes: See notes for Table 6.

[a] USDA (2012).

[b] Reyes et al. (2009).

[c] IMARPE-ITP (1996).

[d] Dias et al. (2003).

[e] INEI (2012b).

[f] PRODUCE (2012).

Table 8
Socio-economic indicators for the *anchoveta* DHC processing industries and comparison with the reduction industry (per tonne of processed whole fish) and aquaculture (per tonne of production), for the reference year 2009 (two other seafood products added for comparison).

Indicator	Unit	Landings			Reduction (FMFO)	Direct Human Consumption				Aquaculture			Other products	
		Steel fleet	Vikinga fleet	SMS fleet		Canning	Curing	Salting (artisanal)	Freezing	Trout	Black pacu	Tilapia	Trawled hake	Cultured shrimp
Production	$t\,y^{-1}$	5,043,916	939,588	341,476	1,617,497	95,589	9772	3450	43,985	12,817	564	1261	47,162	13,425
Revenues	10^3USD y^{-1}	683,444	115,356	44,392	1,675,995	101,224	24,909	13370	81,006	49,146	2153	3331	12,734	45,810
Employment (direct)	jobs y^{-1}	10,744	6361	7144	12,550	8032	2515	338	1827	13,024	492	672	389	2180
	jobs t^{-3}	2	7	21	8	84	257	98	42	1016	872	533	8	162
Production costs	10^3USD y^{-1}	514,984	86,226	19,089	1,136,332	78,955	17492	8815	66,318	32,594	1132	2232	5985	33,563
	USD t^{-1}	102.1	91.8	55.9	702.5	826	1790	2555	1508	2543	2007	1770	126.9	2500
Value added	10^3USD y^{-1}	120,901	20,906	39,065	491,029	60,734	14945	4145	13 365	25695	1192	1758	5094	22,450
	USD t^{-1}	24	22.3	114.4	303.6	635.4	1529	1201	303.9	2005	2113	1394	108	1672
Gross profit	10^3USD y^{-1}	164,460	29,130	25,303	539,663	22,269	7417	4327	14,689	16,553	1021	1099	6749	12,247
	USD t^{-1}	33.4	31	74.1	333.6	233	759	1245	334	1291	1811	871.7	143.1	912.3

Notes: Value added = revenues − purchased inputs, gross profit = revenues − costs. Industry data was available regarding production costs and revenues for curing and salting (P. Echevarría, pers. comm., 03.2013), canning and SMS *anchoveta* landings for direct human consumption (DHC) (Fréon et al., 2013), and hake landings (Paredes, 2013). For other landings, reduction and DHC, calculations are based on data for the whole Peruvian fisheries and processing industries, including all species (Christensen et al., 2013), adjusted for *anchoveta* based on contribution rates (by mass): 70% of SMS landings (Avadí et al., 2014a), 50% of canning and 10% of freezing (Peruvian industry experts, personal communications, 2012–2013). Similar adjustments made for hake trawling: 95% (IMARPE, unpublished data). For aquaculture, prices and employment figures are from Mendoza (2011, 2013) and production costs:revenues and purchases:other costs ratios used are from Berger et al. (2005), Maradiague et al. (2005), MAXIMIXE (2010) and Rebaza et al. (2008). All production figures are from PRODUCE statistics, the SMS fleet production figure adjusted for illegal, unreported and unregulated fishing landings.

impacts of the studied products. Moreover, the BNR ecological impact assessment lacks completion as long as land use impacts – biodiversity, biotic production potential and ecological soil quality (Milà i Canals et al., 2007) – associated with aquafeeds and aquaculture are not included.

By applying a trophic level (TL) of 2.7 for *Engraulis ringens* (Froese and Pauly, 2011; Pauly et al., 1989) to Eq. (1), a BRU of 5569 g C kg^{-1} was obtained for fresh landed *anchoveta*, discards included. In the *anchoveta* fishery, by-catch is low, consisting mostly of jellyfish and other pelagic species, the latter not being discarded (Avadí et al., 2014a). Discards are mostly composed of *anchoveta* juveniles, representing in average 3.9% of catches although higher values can be observed some years (Torrejón et al., 2012). *Anchoveta*, being a relatively low-TL species (although certain authors suggest a higher average TL, e.g. Espinoza and Bertrand (2008) and Hückstädt et al. (2007)), appropriates less primary productivity than other commercial wild-caught and cultured fish. Much higher values were obtained for *anchoveta* products, ranging from 7715 C kg^{-1} for frozen fish to 50,038 C kg^{-1} for farmed trout (Table 4 Regarding *anchoveta* products, the difference among BRU values is due to the fact that residues of *anchoveta* transformation (losses) are considered. Regarding cultured fish, these species are fed with commercial aquafeeds containing *anchoveta* fishmeal and fish oil, as well as agricultural inputs. All of these ingredients appropriate primary productivity and are subject to a conversion ratios (FCR). The FCRs used for all Peruvian aquaculture species was 1.4 (Avadí et al., 2014b), while fishmeal and fish oil yields were ~23 and ~4%, respectively. Cultivated trout shows the largest BRU due to the higher content of animal and fish inputs in feeds (Fig. 2b). Moreover, BRUs of all products are even higher when comparing them on the base of their edible yields. Both CML baseline 2000 (USES-LCA) and USEtox models yielded very similar results, when expressed as relative percentage contribution to environmental impact. Moreover, in the single score environmental indicators, all products show similar performance (although visually minimised by the log scale of Fig. 1), except for fresh, frozen and salted *anchoveta* products, which feature lower associated impacts and thus show a higher performance (Fig. 2a).

LCIA results, upon which environmental indicators are based, are summarised in Table 4 (detailed results are available in the reference publications) and show even more contrasted results than the single score. It is noticeable that in the selected impact categories, results are much higher for the more energy-intensive *anchoveta* products (canned and cured) than for the less energy-intensive (frozen, salted). Moreover, aquaculture products feature in general higher impacts than industrialised *anchoveta* products. The overall environmental performance of all products is determined mainly by the industrial energy demand (electricity and heat demand by fish processing industries, including the production of containers and energy embodied in commercial aquafeeds), as reflected for instance by the impact categories climate change and CED. Another important driver is the land use effect of using agricultural products (e.g. vegetable oils in canned and cured products, inputs to aquafeeds), as measured by the agricultural land occupation category.

When the distribution (regular or refrigerated transport and storage) of products is considered, important changes in environmental performance take place in the cases of fresh/chilled and frozen *anchoveta* products (Fig. 3). It remains that the environmental performance is better for *anchoveta* DHC products than for aquaculture ones, and for less energy-intensive DHC products than for more energy-intensive ones. For aquaculture products, the additional environmental burdens due to refrigerated distribution are in the range of 6 to 11%.

3.2. Energy and nutrition

Gross energy content of *anchoveta* is higher than other fish consumed in Peru, due to its relatively larger content of proteins and lipids. Moreover, fuel consumption of the *anchoveta* industrial fisheries impacting aquafeed averages 16 kg per tonne landed (Fréon et al., 2013), whereas it is 35 kg t^{-1} landed for the small- and medium-scale (SMS) fleet landing for DHC (Avadí et al., 2014a). On the other hand, industrial processing of *anchoveta* for certain DHC products, namely cured and canned, is energy-intensive in terms of fuels (heavy fuel, diesel and gas) and, to a lower extent, of electricity.

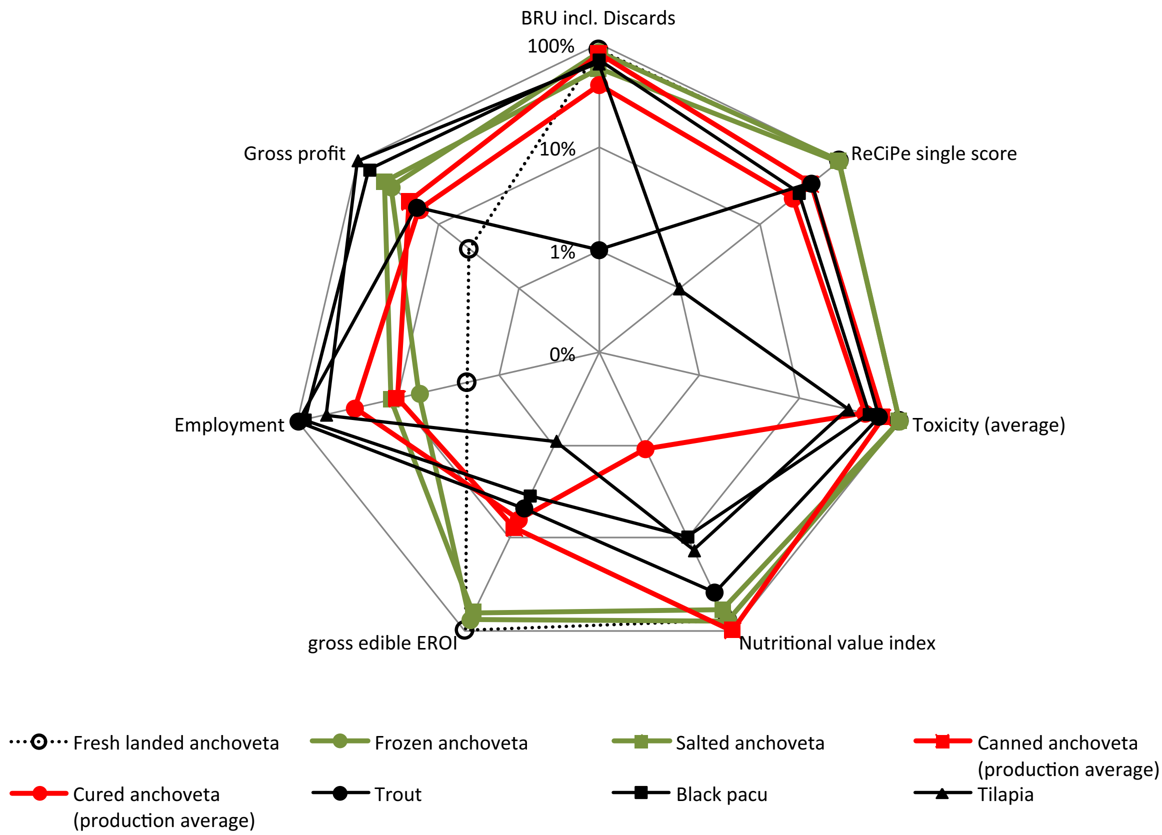

Fig. 1. Relative sustainability performance of Peruvian *anchoveta* direct human consumption (DHC) products and aquaculture products (at plant and farm gate, respectively), based on the proposed indicator set, per tonne of fish in product. All axes are in $\log_{10}$ scale; axes BRU (biotic resource use), single score and toxicity have been inverted so that higher values are better.

Gross edible and edible protein EROI analyses show that *anchoveta* products, especially those demanding less industrial energy over their production process, feature better EROI ratios than aquaculture products (Table 5). Among cultured fish, trout performs best because of its high energy content, high edible yield (i.e. the ratio edible part/total weight), and lower energy requirements for its semi-intensive farming phase. Peruvian tilapia, in the other hand, features lower energy efficiency, because of low GEC, low edible yields and high CED (due to a more energy-intensive farming phase).

A nutritional analysis of *anchoveta* DHC products and aquaculture products is presented in Table 6 Canned *anchoveta* products feature higher contents of protein, Omega-3 and vitamins B-12 than the other fish products listed. Detailed nutritional data (i.e. vitamin and mineral profile) was not directly available for industrialised Peruvian *anchoveta* products, but values were approximated from other anchovy and sardine products. Such figures support the conclusion that *anchoveta* is a very nutritious fish, except when in the form of cured fillets, because the LIM score exceeds the NRF_n one in Eq. (7) (mainly due to the extreme concentration of sodium). Regarding aquaculture products, trout flesh is the most nutritious among the listed species, featuring the highest levels of proteins, vitamins and minerals. Black pacu provides more energy per serving, due to larger lipid content. Black pacu is otherwise nutritionally poorer than the other species, due to a high content of saturated fat. Moreover, farmed tilapia has been found to feature a combination of fatty acids less beneficial than that of farmed salmonids (Weaver et al., 2008), yet tilapia is more expensive in Peruvian supermarkets than the other two cultured species.

The ranking of products according to the described nutritional index is as follows (from best to worst): canned, fresh/frozen, salted *anchoveta*, fresh trout, fresh tilapia, fresh black pacu and cured *anchoveta*. The counter-intuitive higher score of canned products compared to fresh/frozen one is explained by the nutritional value of ingredients, vegetable oil in particular: canned *anchoveta* was modelled as featuring soyabean oil (the most commonly used in Peru), thus the product features high energy, high concentration of non-saturated lipids, as well as high vitamin and Omega-3 contents. The 166 kcal 100^{-1} g energy content of canned *anchoveta* retained in Table 6 represents the average of a range of 125–207 kcal 100^{-1} g (ITP, 2007). Some of these products compete favourably, when compared with other sources of protein consumed in Peru (Table 7). Indeed, the overall nutritional ranking is as follows, from best to worst: canned, fresh/frozen and salted *anchoveta*, fresh trout, hake, eggs, fresh tilapia, fresh black pacu, beef (lean), shrimp, chicken (lean), milk, pork (lean), cured *anchoveta* and fresh cheese. Nonetheless, the main source of animal protein for the Peruvian population is the relatively less nutritional chicken, with 17.4 kg $person^{-1}$ y^{-1} (INEI, 2012b), due to competitive prices, easier conservation and more efficient distribution than fresh fish (Fréon et al., 2013).

We have not considered the potential content of heavy metals and other harmful substances (PBC, pesticides) in the flesh of fish, especially in cultured ones, due to lack of data. Ideally, those toxicity aspects should be included in nutritional assessments and comparisons of seafood products.

3.3. Socio-economic aspects

Anchoveta direct supply chains (fisheries, reduction and processing for DHC) provide the equivalent of about 77,000 jobs (Christensen et al., 2013) for a total production of about

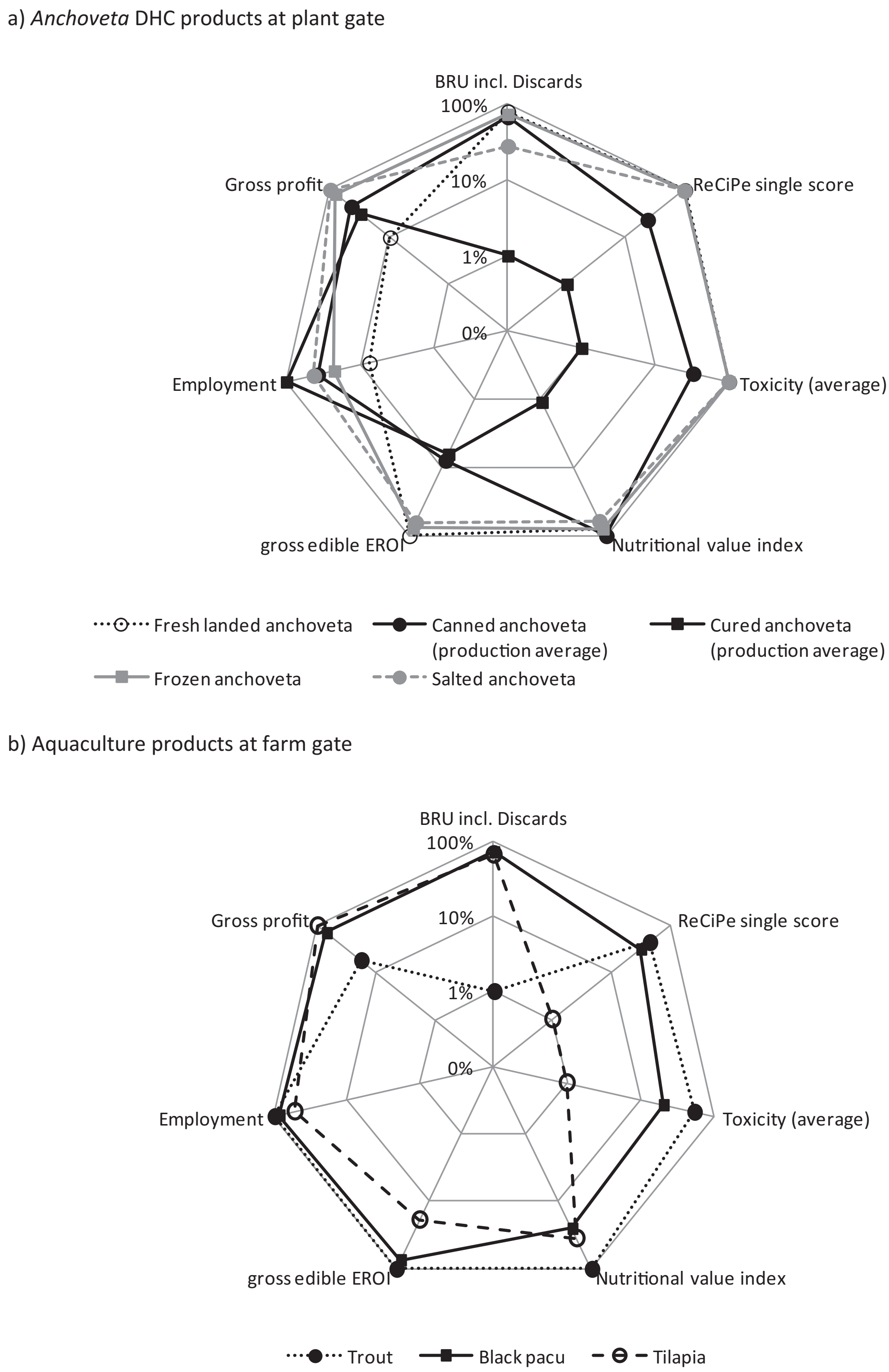

Fig. 2. Relative sustainability performance of Peruvian seafood products, by industrial cluster (same considerations as in Fig. 1).

2.3 million t, resulting from the processing of 6.5 million t of fresh fish in 2009. In contrast, aquaculture of the studied species provides ∼16,400 direct jobs (Mendoza, 2011) for a total production of 28,000 t during the same year. Fig. 1 shows that aquaculture products, together with the curing industry, provide more jobs per functional unit than *anchoveta* fisheries and other processes.

The studied industries feature variable economic performances, canning and curing being more profitable, both in terms of gross profit and added value, than direct landing for fresh DHC, freezing and reduction into fishmeal, on a per tonne basis (Table 8).

According to calculations based on data in Christensen et al. (2013), gross profit per landed tonne is higher for the SMS fleet than for the industrial fleets. Fréon et al. (2013) confirm it and add that for SMS vessels, fishing (illegally) for IHC is more profitable than for DHC because the higher production costs of the latter are compensated by larger landings per fishing trip. Among the *anchoveta* processing industries (IHC, DHC), differences in gross

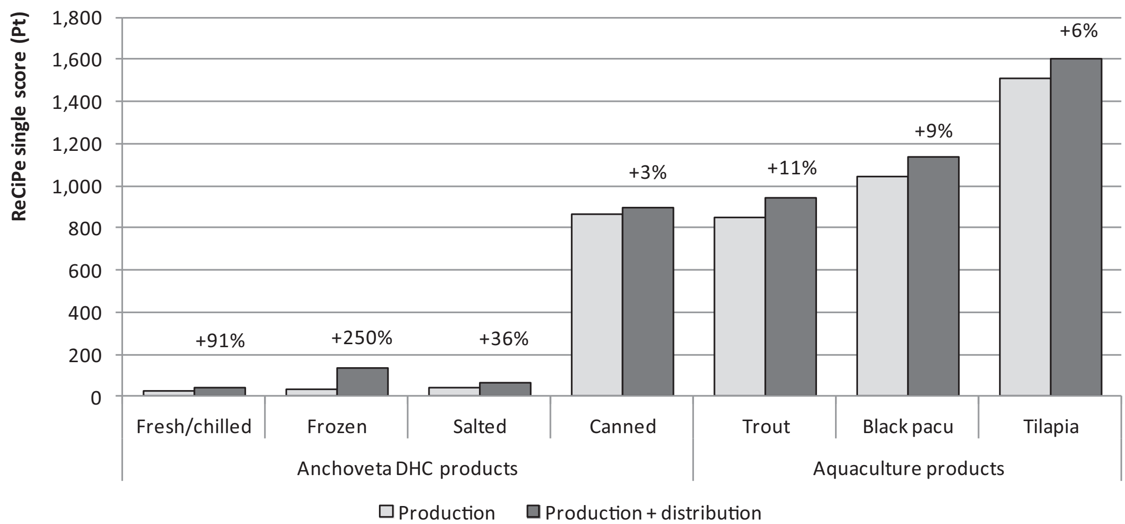

Fig. 3. Additional environmental impacts of distribution activities of *anchoveta* DHC and freshwater aquaculture products, per tonne of final product. Absolute values of ReCiPe single score are shown on the vertical axis and percentages express the relative increase in single score when distribution is added. Distribution is national and the same transport distance is used for all products. Storage along a cold chain is also taken into account, except for salted and canned *anchoveta* products.

profit per tonne produced are associated with variations in their production costs and cost structure[2]. The DHC industry currently pays a bit more to the SMS fleet per landed tonne than the fishmeal industry to the industrial fleets (third party owned vessels). In past years, nonetheless, it has been reported that fishmeal plants have paid to independent vessels higher prices than the DHC industry, in a successful strategy to ensure raw material, as a consequence to their overcapacity (Fréon et al., 2013).

The reduction industry is by far more profitable than *anchoveta* canning by volume and also on a per tonne basis. Primary data on the *anchoveta* curing and salting industry (P. Echevarría, pers. comm., 03.2013), suggest that those industries are more profitable on a per tonne basis.

Regarding the profit generated by reduction products, it is worth repeating that taxes, subsidies,[3] rights, depreciation costs and capital costs were excluded from calculations, in order to simplify and homogenise the basis for comparison among industries, and because their relative importance to the cost structure is rather low (Paredes and Gutiérrez, 2008; Paredes and Letona, 2013).

Due to its size, the fishmeal industry is ranked as the third source of foreign exchange for the Peruvian economy – 8% on average during 2000–2011, according to official statistics (SUNAT, 2012). Nonetheless, the *anchoveta* DHC industry shows a promising growth trend (Avadí et al., 2014c) and therefore represents a great socio-economic potential.

Aquaculture products feature higher production costs per produced tonne of fish than *anchoveta* DHC products per processed tonne of fish, but generate greater added value and gross profit (except when compared to *anchoveta* curing and salting).

3.4. Limitations and additional tools for decision-making

A missing aspect of the proposed panel of indicator is the policy and fisheries management dimensions. These dimensions are central within internationally accepted assessment mechanisms such as the Marine Stewardship Council's (MSC, 2010) certification, which in contrast does not make use of the environmental indicators proposed here. A combination of the criteria applied by an eco-label/ certification scheme and a sustainability indicators' set should cover all sustainability aspects inherent to seafood systems. MSC-related initiatives have been and are being carried out in Peru in relation to *anchoveta* fisheries and products (De la Puente et al., 2011; P. Echevarría, pers. comm., 03.2013).

Further limitations in the scope of the proposed indicators' set, especially in the environmental dimension, are due to inherent limitations of LCA in relation to fisheries and aquaculture, such as: destruction of habitats, spread of disease and escapees from aquaculture, impacts of certain substances released in the environment (oils, medicine, some antifouling substances), etc (Avadí and Fréon, 2013; Samuel-Fitwi et al., 2012; Vázquez-Rowe et al., 2012).

An additional aid to the decision-making can be offered by ratios, although such indicators must be used with caution. For instance, one can compute the gross profit generation per single score environmental impact for each tonne of product, or the employment per single score (or a combination of various indicators by single score). Other score ratios could be related to the nutritional value (score) or the embodied energy efficiency (EROI) of each product. Nonetheless, a score ratio can be excellent (or poor) for two different reasons: its numerator is high or its denominator is low. Two of these suggested ratios are presented in the Supplementary material.

3.5. Recommendations

In order to contribute to the nutrition of vulnerable (and often remote) communities in Peru, canned and salted *anchoveta* products are presently preferred for their longer shelf life and

[2] Detailed analyses of the cost structure of *anchoveta* canning are available in Fréon et al. (2013).

[3] Analysts in Peru have suggested that the balance between fishing rights paid by fishing/reduction companies (0.25% of the average monthly FOB value of fishmeal, per landed t of *anchoveta*) and subsidies by the State to fishmeal companies (known as "drawback", a subsidy of 5% of the FOB price of fishmeal) is counterproductive for the Peruvian society (Paredes, 2012). The drawback mechanism applies also for DHC products, when exported, yet theDHC industry does not pay any fishing rights (Paredes and Letona, 2013). Both industries pay very low taxes to social and compensation funds (Paredes and Letona, 2013). There are no fuel subsidies in Peru for the fisheries and processing sectors.

Table 9
Dashboard of fish products rankings by various criteria (dimensions of sustainability).

Ranking→ Product↓	Ecological	Environmental	Nutrition	Energy efficiency	Economic	Social	Sustainability (all combined)
Fresh *anchoveta*	1	1	1	2	6	9	3
Frozen *anchoveta*	1	1	2	5	7	8	4
Canned *anchoveta*	2	1	4	5	5	9	4
Salted *anchoveta*	5	2	8	4	6	7	5
Cured *anchoveta*	6	2	5	6	5	8	5
Cultured trout	7	4	6	9	6	1	5
Cultured black pacu	2	5	7	9	3	1	4
Cultured tilapia	2	8	8	9	3	4	6

Notes: 1 = best. The final ranking (last column) is computed by (i) averaging the rankings within the six dimensions of sustainability studied (Ecological = Marine ecological indicators (IBNR,sp, IBNR,eco) and biotic resource use; Environmental = ReCiPe single score and cumulative energy demand and toxicity (CML and USETox); Nutrition = Gross Energy Content and Nutrient Rich Food; Energy efficiency = gross edible EROI and edible protein EROI; Economic = production costs and value added and gross profit; and Social = employment)); and (ii) averaging those six partial rankings. For all columns, rankings were obtained by scaling all values within each column in relation to the best value among all products (thus the rankings correspond to values between 0 and ~100%). Individual product ranks were obtained by clustering calculated positions into homogenous classes of 10%. A detailed table which includes all individual rankings per indicator (as in Table 2), is presented in the Supplementary material C.

simpler transportation and storage requirements. Nonetheless, this advantage is questioned by the consumer preference and retail price of such products (Fréon et al., 2013). Should a cold chain be in place, fresh/frozen *anchoveta* products would be suitable alternatives. Despite an important increase in overall impacts associated with the operation of a cold distribution chain if it has to be expended to the interior of the country, such an increase does not worsen the environmental performance of fresh and frozen products in comparison to the energy intensive canned and cured products (Avadí et al., 2014a). Hence, we recommend to public actors to favour the implementation of a cold chain, in partnership with the private sector.

Canned products are the more expensive to produce and thus feature a higher retailing price, yet remain a good overall alternative in most dimensions of analysis, except for their environmental performance. Alternative container technology (i.e. tetra pack) would improve environmental performance and lower transportation costs of such products (Labouze et al., 2008).

A general recommendation to decision makers is to consider all dimensions of sustainability when deciding a food policy. But the decision makers would face a dilemma in front of the presented results: should they favour the fish products that are the friendliest to the environment or the one that generate more employment, better nutritional properties and/or more gross profit? The decision would likely be politic in nature, depending on the current and future political priorities of the decision makers. In order to better contrast the various fish products rankings, according to the different dimensions of sustainability explored, we propose an example of dashboard presented in Table 9. Here we applied the same weight to the three pillars of sustainability, which in itself is a political choice, but different weighting factors can be applied. Such dashboards may be used as an element for steering decision-making.

4. Conclusions

The suggested sustainability assessment indicators' set depicts most of the main aspects of sustainability related to seafood products. The multi-criteria indicators' set presented illustrates the relative performance of various supply chains competing for the same basic raw material (*anchoveta*, either as raw material for processing into food products or for aquafeeds), in a holistic way that allows identification of eco-efficiency and socio-economic hotspots.[4] Regarding the *anchoveta* DHC industries, it is possible to conclude that the least energy-intensive industries (freezing and salting; less refined products) are less environmentally impacting and economically interesting, yet providing a roughly similar number of jobs and delivering nutritionally equivalent products than the more energy-intensive industries (canning and curing; more refined products); as synthesised in Fig. 2a. For Peruvian freshwater aquaculture products, environmental performance is largely related to the composition of aquafeeds (Avadí et al., 2014b), as seem to be the other dimensions of analysis (Fig. 2b). Moreover, aquaculture products display better performance than *anchoveta* DHC products regarding socio-economic indicators.

Finally, a good option can be encouraged only if it has a reasonable chance of succeeding from a market point of view, which takes into account additional factors such as demand and supply. For instance, in Peru supply (and to a lesser extent demand) favours canned over other *anchoveta* DHC and freshwater aquaculture products. It is difficult to claim an absolute superior sustainability performance for any product, even after a multi-disciplinary assessment as the one proposed, without taking into account additional socio-economical factors and political issues. The later depends on the priorities of the decision makers, whether they include improving nutrition, employment, gross profit generation, energy use and/or environmental performance. Nonetheless we advocate using this type of analysis as a tool in decision making for competing, alternative or potential food products.

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[4] Upcoming publications by our team will apply the proposed indicator set to a wider set of *anchoveta*-based supply chains products (including *anchoveta* fishmeal and oil, and hake fisheries), and will also compare policy-based scenarios for future exploitation of *anchoveta* by integrating ecosystem modelling into a LCA-based biophysical supply chain model.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2014.09.006.

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Supplementary Material

A set of sustainability performance indicators for seafood: direct human consumption products from Peruvian *anchoveta* fisheries and freshwater aquaculture

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A. Calculation of the ReCiPe single scores

Impact categories included in the single score are as follows, per area of protection (AoP):

- Human health, for which the endpoint indicators is expressed as disability-adjusted life years – DALY (Hofstetter, 1998): Climate change, Ozone depletion, Human toxicity, Photochemical oxidant formation, Ionising radiation, and Particulate matter formation.
- Ecosystems, for which the endpoint is expressed as the potentially disappeared fraction of species (PDF) integrated over area/volume and time (Goedkoop and Spriensma, 2001): Terrestrial ecotoxicity, Terrestrial acidification, Agricultural land occupation, Urban land occupation, Marine ecotoxicity, Freshwater eutrophication, and Freshwater ecotoxicity.
- Resources, for which the endpoint indicators is expressed as the marginal cost increase of extracting a resource (in year 2 000 USD): Metal depletion, Fossil depletion.

In this study, the weighting set used was the Egalitarian/Average one, that is to say, the one where Human health contributes 40% to the single score, Ecosystems 40% and Resources 20%. Within AoPs, ReCiPe applies no weighting set among individual impact categories, but rather account for the contribution of each impact category's value to the unit in which each AoP is expressed.

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B. Calculation of Nutrient Rich Food scores

The Nutrient Rich Food (NRFn.3) index (Drewnowski and Fulgoni III, 2008), based on nutrient density (Darmon et al., 2005) and the LIM model of nutrients to limit (Maillot et al., 2007), was calculated for a 100 g portion of seafood. A weighted version of the index was tailored for the Peruvian population's nutritional requirements, considering the following nutritional deficiencies that were identified in previous works: mineral, vitamin and other macro- and microelement deficiencies, especially of vitamin A, iron and calories/protein (Creed-Kanashiro and Uribe, 2000; Romaña, 2005; Sacco et al., 2003).

Therefore we applied the following weighting set on a semi-arbitrary base:

- protein: 25%,
- Omega-3 fatty acids (EPA + DHA): 30%,
- other non-saturated lipids (including Omega-6 fatty acids): 10%,
- vitamin A: 10%,
- vitamins B-12 and D: 5% each;
- calcium, potassium and phosphorus: 5% each,
- iron: 10%,
- sodium: -5%, and
- saturated fatty acids: -5%.

The high weight of Omega-3 fatty acids is justified by the large health benefits to humans, when consumed, attributed to EPA and DHA (Bellows et al., 2010; Bourre, 2005; Pike and Jackson, 2010). The currently inexistent yet potentially interesting product "Anchoveta, fillets" (chilled) was also modelled. See section 2.2 in the paper for methodological details.

Table B.1 Unweighted and weighted Nutrient Rich Food scores

Protein products	NRF_n original	LIM original	$NRF_{n.3}$ original	NRF_n weighted	LIM weighted	$NRF_{n.3}$ weighted	Rank original $NRF_{n.3}$	Rank weighted $NRF_{n.3}$
Anchoveta, fillets	0.35	0.04	0.31	0.10	0.002	0.10	6	5
Hake, fillets	0.35	0.02	0.34	0.09	0.001	0.09	5	6
Trout, fillets	0.45	0.04	0.41	0.09	0.002	0.09	4	7
Black pacu, fillets	0.20	0.10	0.10	0.04	0.005	0.04	9	9
Tilapia, fillets	0.17	0.02	0.14	0.03	0.001	0.03	8	10
Frozen anchoveta (HGT)	0.87	0.04	0.83	0.25	0.002	0.25	2	2
Canned anchoveta	1.19	0.14	1.06	0.30	0.007	0.30	1	1
Salted anchoveta, gutted (unsalted)	0.94	0.30	0.64	0.26	0.015	0.24	3	3
Cured anchoveta, fillets	0.57	0.82	(0.25)	0.15	0.041	0.11	15	4
Chicken, lean	0.08	0.07	0.02	0.01	0.003	0.01	12	13
Pork, lean	0.05	0.17	(0.11)	0.01	0.008	(0.00)	14	15
Eggs	0.34	0.09	0.25	0.09	0.005	0.08	7	8
Beef, lean	0.16	0.10	0.07	0.02	0.005	0.02	10	12
Milk (no vitamin A added)	0.08	0.11	(0.02)	0.01	0.006	0.00	13	14
Fresh white cheese	0.10	0.42	(0.31)	0.01	0.021	(0.01)	16	16
Shrimp, edible portion	0.17	0.12	0.05	0.03	0.006	0.02	11	11

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C. Further comparison devices

Each indicator was compared respect to the single score. This approach shows that the best, most balanced option is salted anchoveta, and the worst canned *anchoveta* and aquaculture products (Fig. C.1).

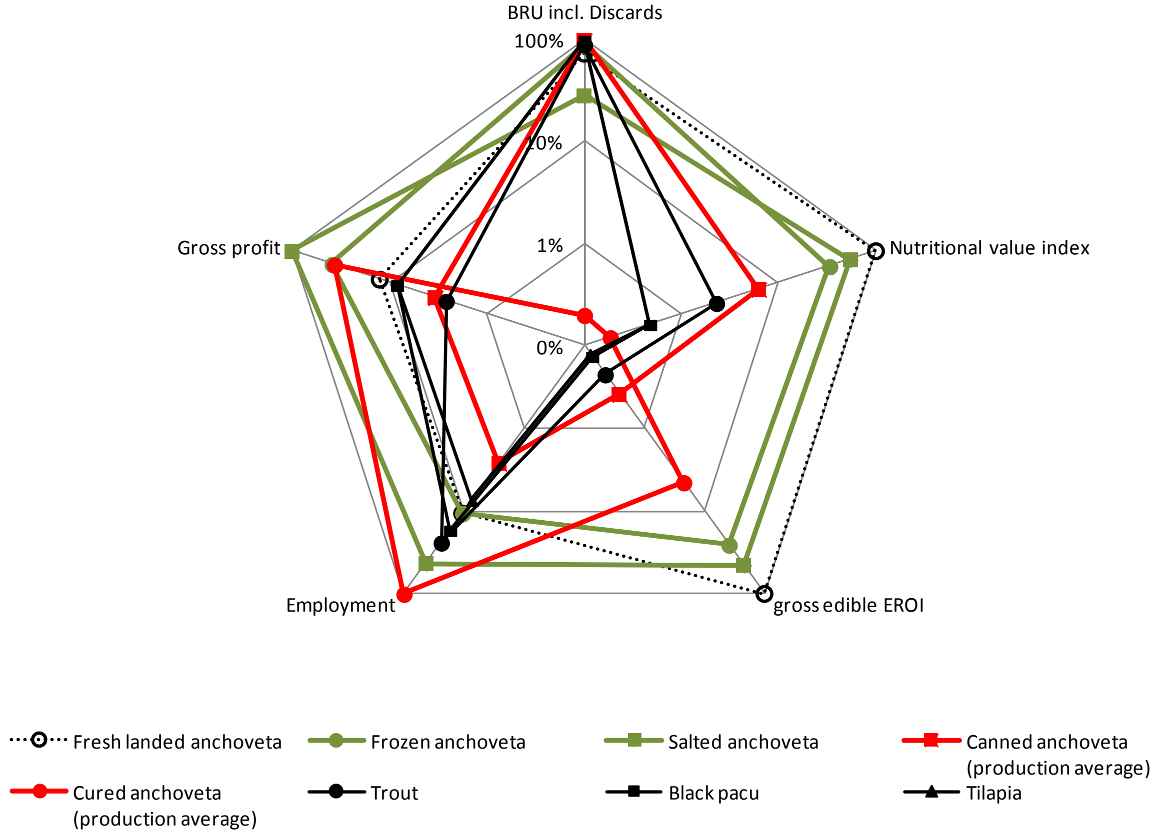

Fig. C.1 Relative sustainability performance of Peruvian *anchoveta* DHC products and aquaculture products, based on ratios of each indicator to the ReCiPe single score (per tonne of final product, including national distribution)

The environmental performance of each product was re-scaled in relation to its nutritional value, and its gross rent generation potential to its embodied energy efficiency (EROI) (Fig. C.2). It is noticeable that aquaculture products are better balanced than anchoveta products. Cured *anchoveta* generates much higher gross rent related to their embodied energy than any other *anchoveta* product, followed by canned products. In these ratios, the relation between numerator and denominator does not skew the results, because each product results are scaled respect to all others.

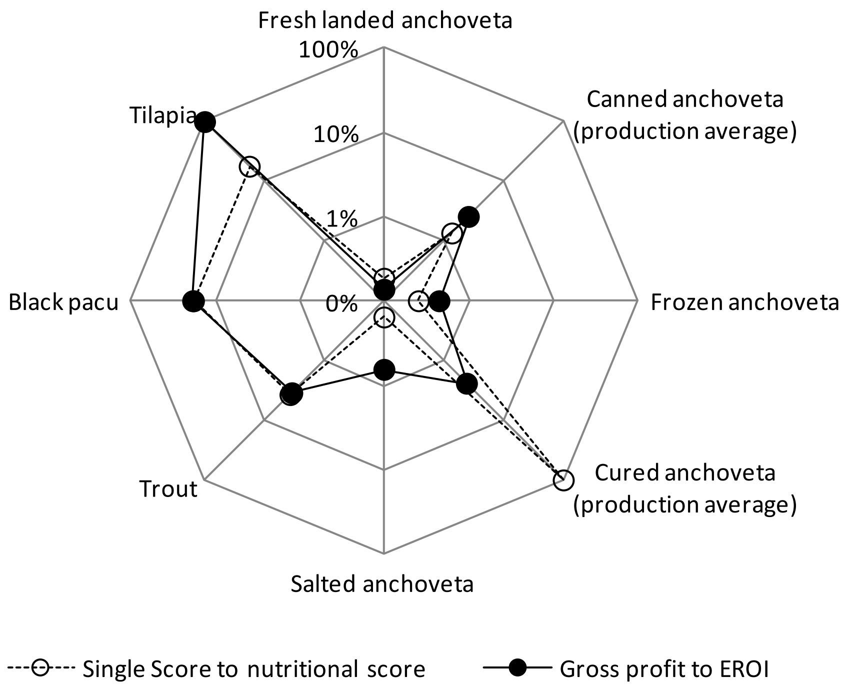

Fig. C.2 Additional score ratios of the *anchoveta* and aquaculture DHC products: environmental performance to nutritional value and gross rent to embodied energy efficiency (per tonne of final product, including national distribution)

Table C.1 Detailed dashboard of fish products rankings by various criteria (dimensions of sustainability)

	Ecological		Environmental				
Ranking→ Product↓	$I_{BNR,sp}$	$I_{BNR,eco}$	BRU, including discards	LCA/ReCiPe single score	LCA/CED	LCA/Toxicity /CML	LCA/Toxicity /USEtox
Fresh *anchoveta*	2	1	1	1	1	1	1
Frozen *anchoveta*	2	1	1	1	1	1	1
Canned *anchoveta*	3	1	1	1	4	1	1
Salted *anchoveta*	7	4	5	1	1	1	9
Cured *anchoveta*	9	5	4	1	5	1	3
Cultured trout	1	9	9	5	4	6	1
Cultured black pacu	1	2	2	6	5	6	3
Cultured tilapia	1	3	3	9	9	9	3

	Nutrition		Energy efficiency		Economic			Social
Ranking→ Product↓	Gross Energy Content	Nutrient Rich Food	gross edible EROI	edible protein EROI	Production costs	Value added	Gross profit generation	Employment
Fresh *anchoveta*	1	2	1	5	1	9	9	9
Frozen *anchoveta*	5	1	9	1	5	8	7	8
Canned *anchoveta*	6	2	2	8	3	6	6	9
Salted *anchoveta*	7	9	9	1	7	2	8	7
Cured *anchoveta*	6	3	3	8	7	2	5	8
Cultured trout	6	6	9	9	9	1	8	1
Cultured black pacu	5	9	9	9	7	1	2	1
Cultured tilapia	7	8	9	9	6	3	1	4

Notes. 1 = best. Abbreviations: BRU: Biotic Resource Use; CED: Cumulative Energy Demand; LCA: Life Cycle Assessment; $I_{BNR,sp}$: Impact on the biotic natural resource at the species level; $I_{BNR,eco}$: Impact on the biotic natural resource at the ecosystem level.

For all columns, rankings were obtained by scaling all values within each column in relation to the best value among all products (thus the rankings correspond to values between 0% and ~100%). Individual product ranks were obtained by clustering calculated positions into homogenous classes of 10%.