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Life cycle assessment of three Peruvian fishmeal plants: Toward a cleaner production

Pierre Fréon [a], Hermine Durand [b], Angel Avadí [c, *], Sayda Huaranca [d], Rita Orozco Moreyra [e]

[a] UMR MARBEC, Institut de Recherche pour le Développement (IRD), Sète, France
[b] Ecole Normale Supérieure (ENS), Paris, France
[c] CIRAD, UPR Recyclage et risque, F-34398 Montpellier, France
[d] Universidad Nacional Agraria La Molina, Lima, Peru
[e] IMARPE, Chucuito, El Callao, Peru

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ABSTRACT

Fishmeal and fish oil are largely used as input to several animal feed industries all around the world, but there is a lack of life cycle assessments (LCAs) on Peruvian fishmeal plants, despite their predominance in the global supply. LCAs where performed on three different types of Peruvian fishmeal plants with the objective of comparing them and suggesting ways of limiting their impacts. The LCA results can be nested into LCAs of animal feed. Two system boundaries were used: one including the fishery and another excluding it in order to enable other practitioners to use our generic life cycle inventory (LCI) data and LCI analysis. The effects of different processing rates and qualities of fishmeal on environmental impacts were compared. We used the SimaPro software, the ecoinvent 2.2 database and the ReCiPe method. In contrast to many LCA studies, the construction and maintenance phases were considered. Despite the predominant impact of the use phase, in particular consumption of fossil energy, these two phases contribute significantly (>10% using the ReCiPe single score) when fishing is excluded from the system boundaries. Furthermore, existing screening LCAs of the use phase largely underestimate (~20%) its environmental impacts. The environmental benefit of using natural gas instead of heavy fuel as energy source, in terms of reduced impacts, is huge, reaching 41% of the ReCiPe single score when fishing is excluded and 30% when included. The comparison of environmental impacts between different qualities of fishmeal shows higher impacts of residual fishmeal, intermediate impact of standard fishmeal and lower impacts of Prime fishmeal, the difference between extreme values being more than twofold. Future studies on other fishmeal and residual fishmeal plants should take into account the construction and maintenance phases, and more items in the use phase than in historical screenings. There is room to decrease the environmental impact of this industry in Peru.

1. Introduction

1.1. Rationale and objective

Food production intensification is driven by the increase of foodstuff demand, itself driven by the human population growth and the increase of per capita foodstuff consumption. For at least the two last millennia, farmed terrestrial animals (livestock) have been the first source of protein in most countries, ranking just before (or sometimes just after) wild fish. World per capita apparent consumption of meat from feedstocks and fish (wild and farmed) increased dramatically during the last decades: from an average of ~24 kg in the 1960s to ~43 kg in 2012 for meat (FAOSTAT, 2016) and from an average of ~10 kg—~19 kg for fish during the same period (FAO, 2014). From the beginning of this millennium, nearly one fish out of two used for direct human consumption, that is excluding forage fish and trash fish reduced into fishmeal and fish oil (FM, FO, FMFO when referring to both), is a farmed fish (FAO, 2014).

Abbreviations: DHC, direct human consumption; BOD_5, biological oxygen demand after five days; COD, chemical oxygen demand; FAQ, Fair Average Quality; FM, fishmeal; FMFO, fishmeal and fish oil; FO, fish oil; FU, functional unit; IVQ, Individual Vessel Quota; LCA, life cycle assessment; LCI, life cycle inventory; LCIA, life cycle impact assessment.

* Corresponding author.

E-mail address: angel.avadi@cirad.fr (A. Avadí).

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Intensive or semi-intensive farming of livestock and aquatic animals (finfish and shrimps in particular) requires feeds with high protein and lipid contents, some of which must be of animal origin to supply essential amino and fatty acids. Those two ingredients are found in fishmeal and fish oil, respectively. Although the substitution of those two commodities by cheaper products of vegetal and animal origin is increasing (Tacon et al., 2011), the increase in farming of livestock and aquatic animals counterbalances these substitutions. There is also a growing demand of fish oil for human consumption (omega-3 fats). Because FMFO demand is still growing whereas the supply remains limited and variable, the prices of FMFO are increasing and volatile (Fréon et al., 2014a).

The food production intensification results in major concern regarding the environmental burden of food production (Garnett, 2014; Soussana, 2014). Environmental assessment approaches on food products, especially those using the life cycle assessment (LCA) approach, started to develop from the 1990s whereas such approaches regarding fisheries and aquaculture developed from the 2000s (Vries and de Boer, 2010; Avadí and Fréon, 2014). In the aquaculture sector, LCAs demonstrated that feed provision accounts for a large share in many of the environmental impacts in this sector (Henriksson et al., 2012, 2015). FMFO contribution within fish feed environmental impacts is substantial and usually ranks first in fish feed of carnivorous species such as salmon and trout (e.g. Pelletier et al., 2009; Avadí et al., 2015). Moreover, feeds for farmed herbivore fish such as *Cichlidae* and *Cyprinidae* often include small amounts of FMFO, thus representing a large aggregated consumption due to the large share of these families in the worlds' aquaculture output (Chiu et al., 2013; Henriksson et al., 2014a). Nonetheless the precision of FMFO impacts in most studies is hindered by the lack of a comprehensive life cycle inventory (LCI) of the FMFO production process. As far as we know, only Denmark benefits from a rough LCI of fishmeal plants, whereas Peru and Norway only benefit from an even more superficial screening. The Danish fishmeal plant LCI, available at http://www.lcafood.dk/, was performed in 2000 at the large (220,000 t of fishmeal per year) Triplenine plant, and most of its data were used as proxies for the other LCIs, in addition to few generic data for freshwater use and waste water (FAO, 1986; COWI, 2000). The Danish inventory includes only 9 inputs (including sandeel, *Ammodytidae* family, as primary material) and 8 outputs (including FMFO and three repeated outputs in different compartments). It excludes all items related to the construction, maintenance and end of life (EOL) phases. Beyond this LCI, there are only few fuel use and electricity consumption data by fishmeal plants compiled by Tyedmers (2000). These data are quite outdated whereas the technology improved substantially during the last decades, resulting in a cleaner production. According to Henriksson et al. (2014b) fishmeal environmental impacts could differ with two orders of magnitude depending upon its origin. Although Peru is the first producer and exporter of FMFO, there is still no publication of a detailed LCA on fishmeal plant but only papers that incorporate the results of such an LCA in different fish supply chain studies (e.g. Avadí and Fréon, 2014; Avadí et al., 2014a, 2015). The objectives of this work are, first, suggesting ways of limiting the environmental impact of different types of Peruvian fishmeal plants, and second, to provide Peruvian-specific and generic LCI data and LCI analysis usable by other LCA practitioners, as detailed in the Goal section.

1.2. The Peruvian FMFO sector

The Peruvian FMFO sector produces in average (2006–2015) 1.183 million t of fishmeal and 230,000 t of fish oil per year, which represent 24% and 23% of the global production, respectively. Peru exports most of this production which relies on the extremely high abundance of the Peruvian anchovy (*Engraulis ringens*), commonly referred to as 'anchoveta'. This species is also characterized by its high variation in abundance and condition (which is reflected by its oil content) at different time scales. The inter-annual volatility is mostly due to El Niño Southern Oscillation (ENSO) events, which can dramatically decrease the production and the fish condition (in the accepted biological sense) and, to a lesser extent, to La Niña events, which favour abundance and condition but often decreases catchability (Bertrand et al., 2004). Abundance cycles over decades and centuries are more pronounced than inter-annual variability, even in the absence of exploitation (Gutiérrez et al., 2009).

The production of FMFO is mostly supplied by the Peruvian industrial fleet of purse-seiners, which by law consists of vessels whose holding capacities are over 32.6 m^3 and land their catches exclusively for reduction into FMFO. This huge fleet subdivides into two major segments: steel vessels and wooden hull vessels (Fréon et al., 2014b). As of 2012, the wooden industrial fleet, nicknamed "Vikingas", consisted of nearly 700 vessels with holding capacities ranging between 32.6 and 110 m^3, whereas the steel industrial sub-segment consisted of 660 vessels with holding capacities ranging between ~90 and 870 m^3. There is also a Peruvian wooden small- and medium-scale (SMS) fleet of purse-seiners with holding capacity under 32.6 m^3. This fleet is subdivided by legislation into two sub-segments: small-scale proper, featuring up to 10 m^3 holding capacity, and medium-scale from 10 to 32.6 m^3 holding capacity and with an overall length of less than 15 m. SMS vessels are allowed by legislation to land anchoveta exclusively for direct human consumption (DHC), but from 2012, 10% of the small-scale anchoveta landings and 40% of the medium-scale one can be legally redirected to reduction under certain conditions. Up to 2008 the industrial fishery was regulated by a single quota whereas the SMS fishery benefited from a full open access. From 2009, an Individual Vessel Quotas (IVQs) system was fully implemented for the industrial fleet. From 2015, by law, a single quota should be implemented for anchoveta aimed at DHC but this measure is still not effective. Illegal, unreported, and unregulated (IUU) fishing is a recurrent problem in Peru (although improving), and in the SMS fleets operations it reached 200% over the officially reported figures. The most of the landing of the SMS fleet used also to be sent to fishmeal plants (324,000 t $year^{-1}$). As a result, the SMS fleet landings for FMFO reduction represented ~6% of total anchoveta catches in the period 2005–2010 and at that time it was fully illegal (Fréon et al., 2014b). In the meantime this figure is likely to have decreased due to new regulations and enforcement.

Three different categories of fishmeal were produced in Peru during the study period (2008–2012), where quality depends mainly on protein, lipid and salt content (Supplementary Material):

1) Standard fishmeal, also are referred to as "fair average quality" (FAQ), usually produced using direct hot air during the drying phase ("flame drying" or "direct-fire drying"), including the so-called "residual fishmeal", often of poor quality, produced from fish residues,
2) Prime fishmeal,
3) Super Prime fishmeal; for producing Prime fishmeal and Super Prime fishmeal, special driers are needed, where typically hot air is produced by circulation of steam in coils or tubes located inside the dryer ("indirect steam drying").

There is no clear definition of fish oil categories in Peru, except for the recent (2009) European sanitary regulation on fish oil importation. This UE regulation deals mostly with freshness of the raw material, and storage and hygiene conditions along the supply chain.

There are three main types of fishmeal plants operating in Peru:

1) Modern steam plants, which produce both Prime and Super Prime quality fishmeal (but often also have/had a separate production line of FAQ fishmeal) and use mostly whole anchoveta as raw material. These plants consume both heavy fuel and natural gas when available.
2) Traditional FAQ plants, which also use mostly whole anchoveta as raw material.
3) Residual plants which, in principle, are only allowed to process fish residuals and unsuitable fish of different species, namely anchoveta, jack mackerel (*Trachurus murphyi*), chub mackerel (*Scomber japonicus*), etc.; aimed at DHC. In practice, most of these plants process mostly IUU anchoveta. Both residual and traditional plants are producing only FAQ fishmeal and use mainly heavy fuel as energy source.

All traditional and modern steam plants belong to fishing companies that operate their own steel vessels and, in addition, buy fish from the wooden industrial vessels. In the recent period, the quality of the Peruvian FMFO increased, in particular in the biggest plants, and the production of FAQ fishmeal remains only in small plants.

There is a total of 207 fishmeal plants constructed in Peru, including 37 with cancelled permits, which correspond to an impressive total processing capacity of 11,400 t per hour (9350 excluding plants with cancelled permits) (Fig. 1). These plants are located all along the Peruvian coast, with concentrations close to the main fishing harbours of the largest coastal cities (Chimbote, Chancay, El Callao and Pisco). This concentration generated social conflicts between the industry and the local population regarding the nuisances of the plants (odour nuisance and costal water contamination), but the present situation is improved thanks to recent legislation and private initiative by the industrial sector. One important characteristic of nearly all the large plants is that they benefit from a floating transfer terminal located several hundred m offshore (locally known as “chata”), where the fish is pumped from the holds of fishing vessels and sent directly to the plant by an underwater pipe. This facility allows installing a fishmeal plant nearly everywhere along the coast and hence limits the travelling distance of the fishing vessels, resulting in substantial fuel savings.

The outline of this LCA paper is quite conventional, based on the for steps of LCA: Goal (Section 2.1) and scope (Section 2.2), life cycle inventory (Section 2.3) and its analysis (Section 3.1), life cycle impact assessment and finally its interpretation (merged in Sections 3.2, And 3.3 using different functional units (FUs)), In addition, Section 3.4 presents some considerations and recommendation about a cleaner production.

2. Material and methods

This whole section is based on the ISO-normed conventional LCA approach (ISO, 2006a,b).

2.1. Goal

The intended applications of our results are: 1) to provide data and related recommendations for environmental protection in Peru in order to allow a future greening of the FMFO supply chain; 2) to provide results of life cycle impact assessment (LCIA) that can be used in LCAs of any supply chains where Peruvian fishmeal or fish oil are key; and 3) to provide generic LCI data of fishmeal plants and corresponding LCI analysis and LCIA that can be used for non-Peruvian FMFO supply chains in combination with their national fishery data. The major limitations of this study are: 1) the limited number of sampled plants (one per category); 2) the usual inherent limitations of LCA when applied to fisheries; 3) the lack of characterization of the impacts of the production of certain substances and/or their subsequent released to the environment (oils, some antifouling substances, biological oxygen demand (BOD), etc.) including their odour nuisance in all cases; 4) our attributional approach, as well as its allocation and system boundary/cut-off decisions, leading by design to different conclusions than consequential or hybrid LCA approaches; and 5) as usual in LCAs, impact categories and associated characterization factors are often insufficient, subject to uncertainty and subjectivity in the weighting factors, and prone to biases and errors. Limitations 2) to 5) are discussed in Vázquez-Rowe et al. (2012) and in Avadí and Fréon (2013). How part of limitation 3) was overcame is detailed in Supplementary Material.

The reasons for this study are the above-mentioned issues related to: 1) the lack of LCIs and LCIAs of fishmeal plants in Peru and their scarcity worldwide limiting the LCIAs of FMFO-based supply chains; 2) the social concerns about contamination by FMFO plants. The target audiences are the Peruvian FMFO industrial sector and the Peruvian governmental political decision makers regarding goal 1), as well as the LCA practitioners regarding goals 2) and 3).

2.2. Scope

The studied system consists in two major processes: 1) capturing fish at sea and delivering it to the terminal of a fishmeal plant, and 2) transforming this raw material into FMFO. Because process 1) is already fully documented (Avadí et al., 2014a,b; Fréon et al., 2014b), this work concentrates on process 2) and its subprocesses. The function of the system is the procurement of the two commodities (FMFO).

In order to reach our three intended applications, two different types of functional units (FUs) were used: output-based and process-based. The first type of FU is the delivery of one metric tonne (t) of either of the two commodities at the gate of the plant, using three different criteria of allocation of impacts between those two coproducts (gross energy content, economic value and mass), considering two different main sources of energy (natural gas and heavy fuel) and considering separately three categories of commodities in the case of fishmeal: residual, FAQ and Prime or Super Prime. The output-based FUs allow reaching our first and second intended applications.

In order to fulfil our third intended application, a process-based FU was retained, namely the processing of 1 t of raw material delivered at the floating terminal of the plant (and used to produce the same three categories of fishmeal).

The reference flows are one t of Peruvian fish oil or Peruvian fishmeal of a specified quality for the output-based FUs. In the case of process-based FUs, the reference flow is one t of raw material as the major input of a plant aimed at producing two co-products (fish oil and fishmeal of a specified quality).

The system boundary of the study for the output-based FUs is “from cradle to gate” and includes the extraction of the raw material (fishing), its delivery at the plant terminal, its processing and conditioning in the plant. In contrast, the boundary for the process-based FUs is “from gate to gate” (in our case from the floating terminal to the gate), and excludes the fishing operation and delivery at the floating terminal (Fig. 2). The following three life cycle stages of the fishmeal plants were retained: construction, use and maintenance. The factory infrastructures (including the local warehouse), were considered, as well as the usual large storage area and the total land occupation. Manpower was excluded from the perimeter. The decommissioning, or end of life (EOL) stage, was ignored for the plant (not for the fishing vessels when using the output-based FUs) due to lack of previous experience of full dismantlement in Peru.

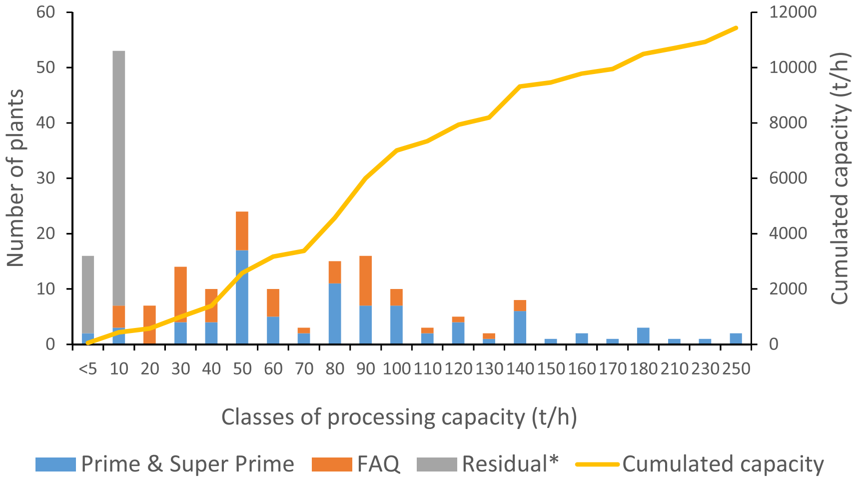

Fig. 1. Number of fishmeal plants in Peru according to their processing capacity in 2016. The statistics include 37 cancelled permits. The width of the class intervals of processing capacity is 10 t, except for the first one (<5 t/h), and the class name is its central value. Source: PRODUCE (Peruvian Ministry of Production, http://www.produce.gob.pe/index.php/shortcode/servicios-pesca/plantas-pesqueras).

Inventory data were collected by our team in the period 2010–2013 and encompass averaged fishery data from all the Peruvian anchoveta fleets and three fishmeal plants from anonymous companies for the period 2008–2012. These plants were numbered, chronologically, as Plant 1 for the traditional FAQ plant, Plant 2 for the modern steam plant producing prime fishmeal and Plant 3 for the residual plant (Table 1). Regarding Plant 3, only a screening LCI was performed on the field.

The LCIA method ReCiPe v1.07 (Goedkoop et al., 2009) was used as available in the LCA software SimaPro v7.3 (PRé, 2012), and the widely used LCI database ecoinvent v2.2 (Frischknecht et al., 2005) was used for background processes. Ecoinvent processes were modified to better represent Peruvian characteristics for the electricity mix, for biodiesel composition and for airborne emissions of boilers and drier using direct flame drying. The ReCiPe method was retained because it offers a wide set of 18 midpoint impact categories aggregated into three endpoint categories or areas of protection (human health, ecosystem diversity and resource availability) which is convenient for identifying most hotspots. It is worth noting that the marine eutrophication and water depletion impact categories are not considered in the ReCiPe single score, although they are in the midpoint method. The same applies for the "sea use" index and other additional indices we used in papers related to the impact of fishing (Avadí et al., 2014a,b; Avadí and Fréon, 2014). The egalitarian perspective of ReCiPe was retained for characterization and normalisation because it is the most precautionary one (Goedkoop et al., 2009). The default normalisation weighting of factors of ReCiPe at the world level (average weighting set) were retained, but no quantitative results are presented due to the limitations of this approach, and both the midpoint and endpoint levels where considered (Dong and Ng, 2014). Only the few largely dominating categories are indicated, if any. In addition to ReCiPe, we used the single issue method "cumulative energy demand" (CED) because the studied system is highly demanding in energy (fishing and processing). CED was calculated by means of the LCIA method CED v1.08, also implemented in ecoinvent (Hischier et al., 2010).

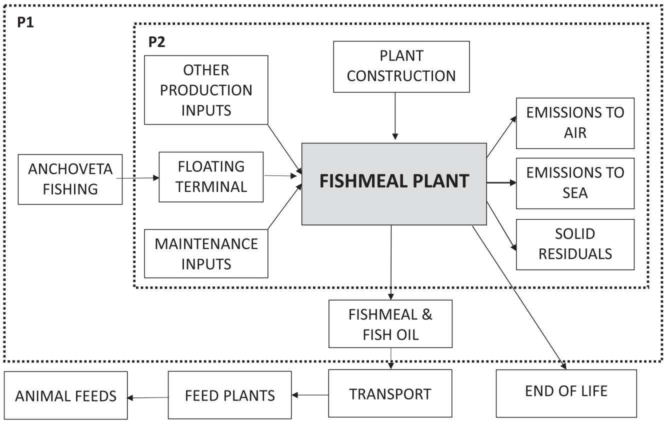

Fig. 2. System boundaries according to the functional units (FUs). In P1 the FUs are the delivery one metric tonne (t) of fishmeal or fish oil at the gate of the plant; in P2 the FU is the processing of 1 t of raw material entering at the floating terminal of the plant.

Additional consideration on the goals and scope of the study, such as assumptions, inventory cut-off rules, representativeness of the data, data sources, justification of the attributional approach and of the allocation methods, and finally arithmetical relationships between the different FUs, are provided as Supplementary Material, along with the methods used for the direct monitoring of the environmental impacts of airborne emissions and emissions at sea.

2.3. LCI

The process tree for the system is given in Fig. 3 (excluding heat and self-generated energy) and described in Supplementary Material. From this description, it appears that fishmeal and fish oil share first various unitary processes (mostly from fishing to straining) before the separation between the solid and the liquid lines, which mostly result in the production of fishmeal and fish oil, respectively. Nonetheless, there are several bridges between these two lines, and also between some of the shared unitary processes and these lines. As a result, it is impossible to apply the subdivision principle during the LCI.

As for most other fishmeal plants in Peru, the three sampled plants are located in urban (FAQ plant) or semi-urban areas (Prime and residual plants). The land occupation is quite large (e.g. >34,000 m^2 for Plant 1) because, in addition to the settlement of the plant itself, it must have a large storage area, sometimes cemented (Plants 2 and 3) sometimes gravelled (Plant 1).

The LCI of Plant 1 resulted in the identification of 408 different items which in turn resulted in 138 different entries of raw material

Table 1
Major characteristics of the three sampled plants.

Characteristic	Plant 1: traditional FAQ	Plant 2: modern steam	Plant 3: residual
Type of fishmeal produced	100% FAQ	100% Prime from 2009	100% FAQ
Type of fuel used for heating	Heavy fuel	98% gas converted in 100% by simulation in the LCA	Heavy fuel
Number of production lines	2	3	1
Average instantaneous processing yield (t/h)	88	114	5
Average processing yield per working hours[a] (t/h)	70	100	4
Average annual working hours (h)	700	1400	1900 (estimated)
Fresh fish processed (t/y)	48,430	155,535	9600
Estimated mean lifespan (y)	30	30	30
Base years[b]	2008, 2009, 2010	2007, 2008, 2009, 2010	2012

[a] Taking into account daily maintenance (4 h per working day) and other delays.
[b] Dominating one underlined.

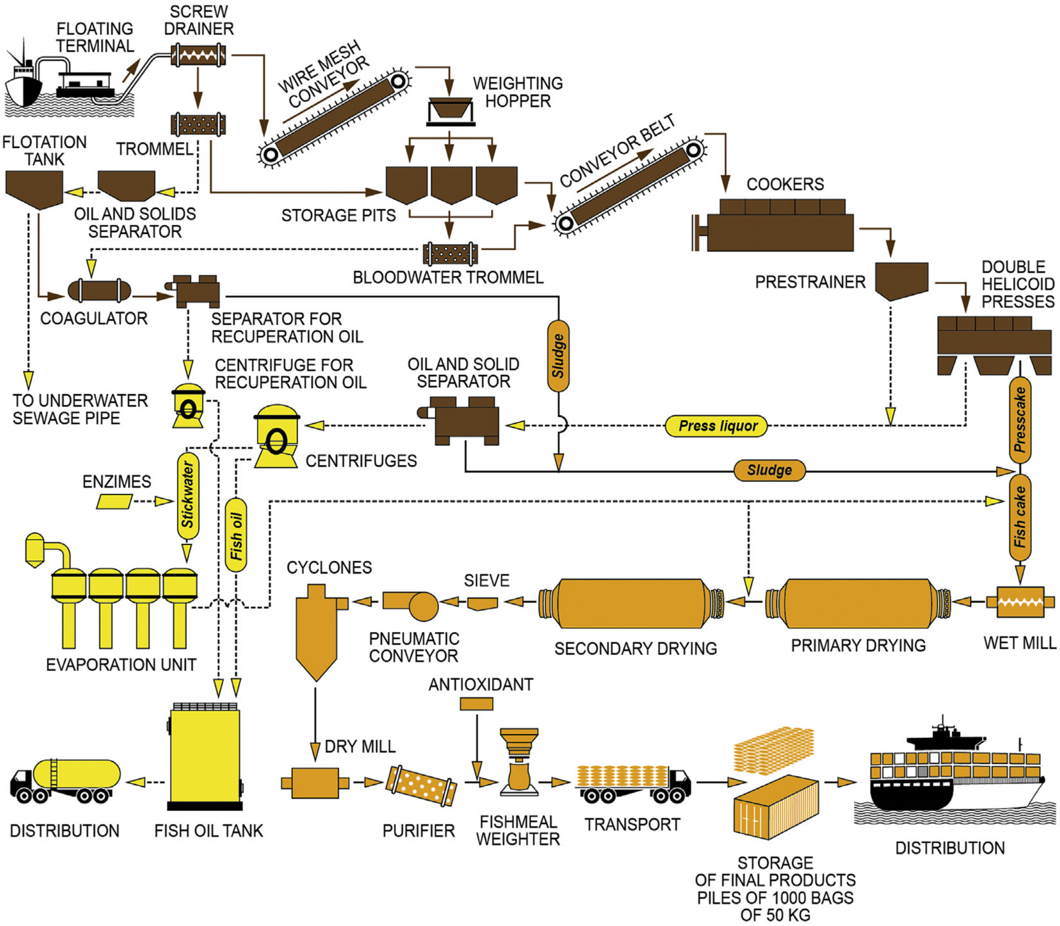

Fig. 3. Process tree for fishmeal Plant 1. Brown flows are common to fishmeal and fish oil production, orange flows are specific to fishmeal and yellow flows are specific to fish oil. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

or emissions in SimaPro (Table 2; more details in Supplementary Material).

3. Results and discussion

Because the Peruvian fishmeal production is increasingly dominated by Prime and Super Prime fishmeal, results of Plant 2 will be more detailed than the results of the other plants.

3.1. LCI analysis

The annual quantities of raw material processed by the three plants are much lower than their potential processing capacity. Considering 240 potential working days at full time (that is 20 h of processing and 4 h of cleaning and preheating per day), Plants 1, 2 and 3 could have processed in theory 422,400, 547,200 and 24,000 t per year, respectively (and the whole Peruvian industry 44.9 million tons in 2009, based on a 9350 t per hour national capacity). This means that Plants 1 and 2 used 11% and 28% of their potential full capacities, respectively, and the whole sector 13% of it, reflecting the large overcapacity of the Peruvian fishmeal industry. In contrast Plant 3 used 40% of its potential full capacity, which is a reasonable value due to the high variability in time and space of the resource. This good performance of Plant 3 is mostly due to more regular supply, both in fish residues from DHC plants and in fresh fish from IUU anchoveta. Overcapacity of the traditional FAQ and

Table 2
Number of items in the LCI of Plants 1, per phases of the LCA, and corresponding number of entries in SimaPro.

LCA phase	This work LCI items (n)	This work entries in SimaPro (n)	Danish lcafood LCI items (n)
Construction	258	29	0
Maintenance	100	51	0
Use	50	58	17
Total	408	138	17

modern plants (the dominant ones) is mostly due to the race for fish when the industrial fisheries were managed by a single quota and the annual duration of the number of fishing days fell below 50 days (Fréon et al., 2008). IVQs resulted in an increase of this duration to around 150 days and in a slow decrease of the capacity of the fleets, but not of the plants (+1% growth per annum from 2009 to 2016). As a result, the race to fish is now replaced by the race to buy fish from the freelance industrial wooden fleet (Fréon et al., 2014a). This situation worsened recently. The mean Peruvian TAC of anchovy decreased to an average value of 3.5 million t since 2012 due to a stricter management policy, whereas the potential capacity reaches now 54.9 million t. These values correspond to a national overcapacity (computed as 1-(TAC/actual capacity)) equal to 93% (92% when excluding cancelled permits).

The large overcapacity of the plants, and consequently their underuse (Table 1), increases the LCI expressed by FU, especially the construction phase. The maintenance phase is also affected, although to a lesser extent, whereas the use phase is only indirectly affected by likely lower daily processing rates, as detailed below.

Raw fish to fishmeal or fish oil conversion ratios mostly influence the process-based FUs. Because these ratios are fluctuating (especially the oil rate) according to the environmental condition experience by the anchoveta, the rates were based on average fish catches and FMFO national data for the period 2002–2011 for better representativeness. The resulting values were 4.21:1 and 21.3:1for Prime or FAQ fishmeal and fish oil yield respectively. These figures are slightly different from other values reported for Peruvian (4.45:1 and 28.45:1 respectively; Péron et al., 2010), Danish (4.66:1 and 22.2:1; www.lcafood.dk) and Norwegian (4.72:1 for fishmeal; Myrvang et al., 2007) industries. The main reasons for these differences are that Péron's reference period was shorter than the one associated with this study, and the Danish plant processed a different species than anchovy (sandeel), although a small bias in the Peruvian data resulting from under-reporting of fresh fish catches cannot be excluded. Regarding the residual plant, the conversion ratios retained were a) the same as the other plants when it processes whole anchoveta, and 1:5.5 when it processes fish residues (data from the residual plant).

The construction of the plants required huge quantities of infrastructure material (bricks, cement, concrete) and of metals, including those known for their high environmental impact (chromium steel and copper). When those quantities were prorated by FUs along the life cycle of the plants (Table 1), they become quite low but still significant (Table 3), due to the underuse of the plants.

The use and maintenance phases of the plant required large quantities of chemical products, particularly for inside cleaning the different devices every 20 h of use. Caustic soda is used nearly everywhere whereas sulfuric acid is mostly used for descaling the evaporation unit, along with other descaling agents. Different types of paint were used during these two phases (antifouling for the floating terminal, epoxy, oil- and water-based paints for the plant itself), resulting in airborne emissions of diluents. The LCI of the use phases of the plants are dominated by energy consumption, as it is the case for the fishery use phase (Avadí et al., 2014b; Fréon et al., 2014b, 2014c). Standardization of energy by the use of MJ show that the major sources of energy for the plants themselves are fossil fuels mostly used for heating (cooking of raw material, drying of fishmeal, evaporation plant) whereas the share of electricity is low (4.7% for Plant 1, 2.5% for Plant 2 and 1.7% for Plant 3; Table 3). Most of this electricity (Plant 1: 76%; Plant 2: 93%) comes from the Peruvian grid, the rest being self-generated. The monitoring of the emissions to the atmosphere at the exhaust chimneys of the cyclones attached to the dryers in Plant 1 resulted in higher concentrations of CO and particles than expected from data of combustion of heavy fuel in furnace found in ecoinvent (Supplementary Material). This excess of CO, not found at the

Table 3
Abridged inventory table of fishmeal production in Peru per process-based and output-based FUs.

Type of FU	Inputs/outputs	LCI main items (n)	Unit	Plant 2	Plant 1	Plant 3
Process-oriented FU (1 t raw material)	Inputs	Fuel use [a]	MJ	1498	1913	2406
		Electricity [b]	kWh	20.6	13.8	15.3 [c]
		Antioxidants	kg	0.17	0.25	0.10
		Concrete	L	13.7	1.97	2.54 [c]
		Sodium hydroxide	kg	0.59	0.58	0.68 [c]
		Sodium chloride	kg	0.40	0.59	0.59 [c]
		Metal manufacturing	g	387	220	44.0 [c]
		Copper wire	g	5.24	2.82	5.85 [c]
		Fishmeal bags	kg	0.609	0.592	0.513 [c]
	Outputs	Suspended solids	kg	3.70	6.92	7.69 [c]
		Oil and fat	kg	3.14	3.94	4.38 [c]
		BOD_5	kg	9.17	17.8	15.2 [d]
Output-oriented FU (1 t fishmeal)	Additional inputs [e]	Fresh fish [f]	t	4.21	4.21	2.11
		Fish residues [i]	t	0	0	2.75
	Additional outputs [e]	Fish meal	t	1.00	1.00	1.00
		Fish oil	t	0.19	0.19	<0.19

[a] Heavy fuel oil (R500) or natural gas used for heating (excluding fuel use for self-generated electricity and fishing).
[b] Excluding self-generated.
[c] Estimated from Plant 1.
[d] From Plant 1 data, rescaled by yield rate.
[e] In addition to above inputs that must be rescaled by fish input (see example in Supplementary Material).
[f] Fish caught by the industrial steel fleet (81%) and the industrial wooden fleet (19%) for Plants 1 and 2, and the small- and medium-scale fleets (100%) for Plant 3.
[i] Considering a 43% inclusion of fresh fish coming from IUU landing for reduction (range 30–50%), which results in a 50:50 ratio in fresh fish and fish residue in the origin of FM given their different conversion ratios (1:4.21 vs 1:5.5).

Table 4
Comparison of available original LCI data for Prime fishmeal. The functional unit is the processing of one t of raw fish. Generic data from FAO and COWI do not specify the location. Denmark data are from www.lcafood.dk, Norway data from Myrvang et al. (2007), old Peruvian data from (S&T)2 (2004) and present Peruvian data from Plant 2.

	Material/fuel	Unit	Generic data	Denmark	Norway	Peru (2004)	Peru (this work)
Input	Heating energy	MJ	1760 [a]	1478 [d]	1890	1518	1498
	Electricity	kWh	33 [a]	40.77	57.69	30	21
	Antioxidant	kg	N/A	0.066	N/A	N/A	0.17
	Sodium hydroxide	kg	N/A	1.03	N/A	N/A	0.59
	Formaldehyde	kg	N/A	2.32	N/A	N/A	0.02
	Sulfuric acid	kg	N/A	0.45	N/A	N/A	0.07
	Nitric acid	kg	N/A	0.11	N/A	N/A	0
	Hydrochloric acid	kg	N/A	0.08	N/A	N/A	0
	Fresh water	kg	300 [b]	N/A	N/A	N/A	1790 [e]
Output	COD	kg	42 [c]	0.12	N/A	N/A	
	BOD_5	kg	N/A	N/A	N/A	N/A	9.17
	N-tot	kg	N/A	0.35	N/A	N/A	0.35 [f]
	P-tot	g	N/A	7.77	N/A	N/A	7.77 [f]
	Waste water	m^3	21 [c]	N/A	N/A	N/A	N/A

[a] FAO (1986) plant 100–200 t/h with evaporation plant and waste heat recovery, assuming 40 MJ per kg of heavy fuel. More heating energy data available in FAO (1986) and Tyedmers (2000, Table 28).
[b] COWI (2000); other data available in FAO (1986) partly aggregated with sea water use.
[c] COWI (2000).
[d] Value derived from the heat production using a Danish mean conversion factor from steam in MJ to natural gas in MJ of 1.111.
[e] No proper LCI data, Plant 1 data used as proxy.
[f] No proper LCI data, Danish data used as proxy.

exhaust chimneys of boilers burning the same fuel, can be attributed to an incomplete combustion that may result from insufficient ventilation in the dryers and/or insufficient input of oxygen from the air. The excess of particles comes from the fishmeal itself.

Emissions to the ocean resulted mostly from the use phase and were dominated by the large quantities of suspended solids (mostly fish residues; ~29 kg/FU in Plant 1) and the associated Biological Oxygen Demand after five days (BOD_5). Oily components, also wasted in large quantities, originated mostly from fish residues but also from oil and grease used in the plant.

The comparison between our LCIs and others shows similar results and, beyond the fact that our inventory is much more detailed, shows quite similar values regarding the use of fossil energy, but quite different results regarding other items (Table 4). Electricity consumption from the grid is twice lower in our study and this is only partly explained by the used of self-generated electricity (7% in Plant 2). The use of chemical products inventoried in the Peruvian plants is much lower than those inventoried in the Danish plant, but this is certainly due to the fact that other descaling agents are used (and inventoried) in Plant 2. The consumption of fresh water is higher in Plant 1 (used as a proxy for Plant 2) than in COWI (2000) data, possibly due to economies of scale in this last plant, probably larger than Plant 1. Our BOD data are lower than the COD data of COWI (2000), which is expected because COD must be greater than BOD. In contrast, our BOD data are much higher that the COD data of the Danish plant, which is difficult to explain.

Henriksson et al. (2014a) performed LCA studies of Asian aquaculture systems including the impact of fishmeal production. Unfortunately only limited information on this last point is presently available. The authors indicate that some of the smaller Chinese fishmeal plants use up to 500 kg of coal per tonne of low quality fishmeal produced, which result in a corresponding energy impact 4.6 fold higher than the impact of FAQ Plant 1, and 2.5 fold higher for this same plant simulated as if it was using natural gas. Henriksson et al. (2014b) added that the emissions from fishmeal factories are roughly twice as high in China compared to Thailand, assuming that a more efficient wastewater treatment occurs in Thailand compared to China.

3.2. LCIA using process-based FUs

The dominant ReCiPe endpoints in Plant 2 are by far human health and resources (Fig. 4). As expected, most of the environmental impacts during the life span of fishmeal plants are due to the use phase, more specifically to the consumption of fossil energy. Nonetheless the construction and maintenance phases, largely ignored in other studies, contribute significantly. The ReCiPe single score of the use phase at the endpoint level is 87% in Plant 2, whereas the shares of the construction and maintenance phases are 10 and 2.5% respectively. Nonetheless, at the midpoint level, the contributions of some specific impact categories reach currently values of 10–40% in one or two of these two phases in Plant 2 (Fig. 5). As a result, the remaining contribution of the use phase varies from values as low as 19–77% in ten midpoint impact categories of ReCiPe. Because the share of the construction phase in the LCIA was shown to be significant, and a similar quantity of materials used in construction will, in turn, require EOL processes, ignoring the EOL phase is likely result in a substantial underestimation of LCIA using the process-based FUs.

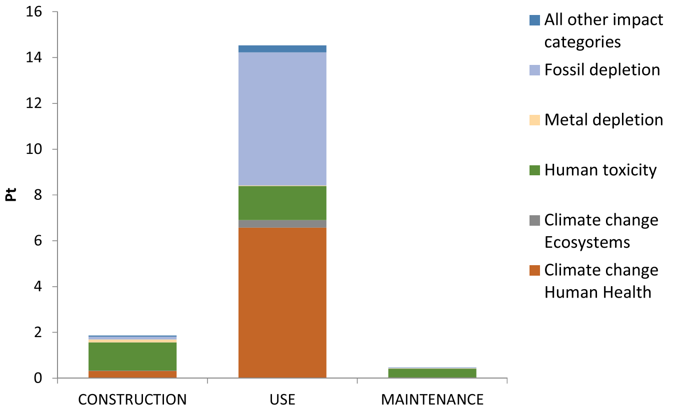

Fig. 4. Fishmeal plant 2 LCA: endpoint environmental impacts using the ReCiPe method. The functional unit is the processing of one t of raw material. “All other impact categories” refer to those retained in ReCiPe endpoint.

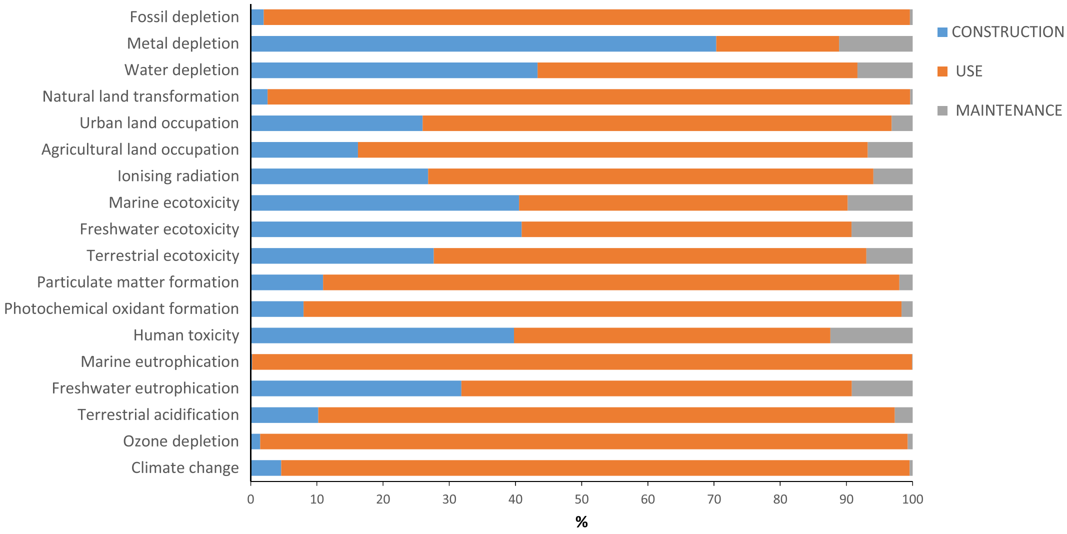

Fig. 5. Fishmeal plant 2: LCA midpoint environmental impacts using the ReCiPe method. The functional unit is the processing of one t of raw material.

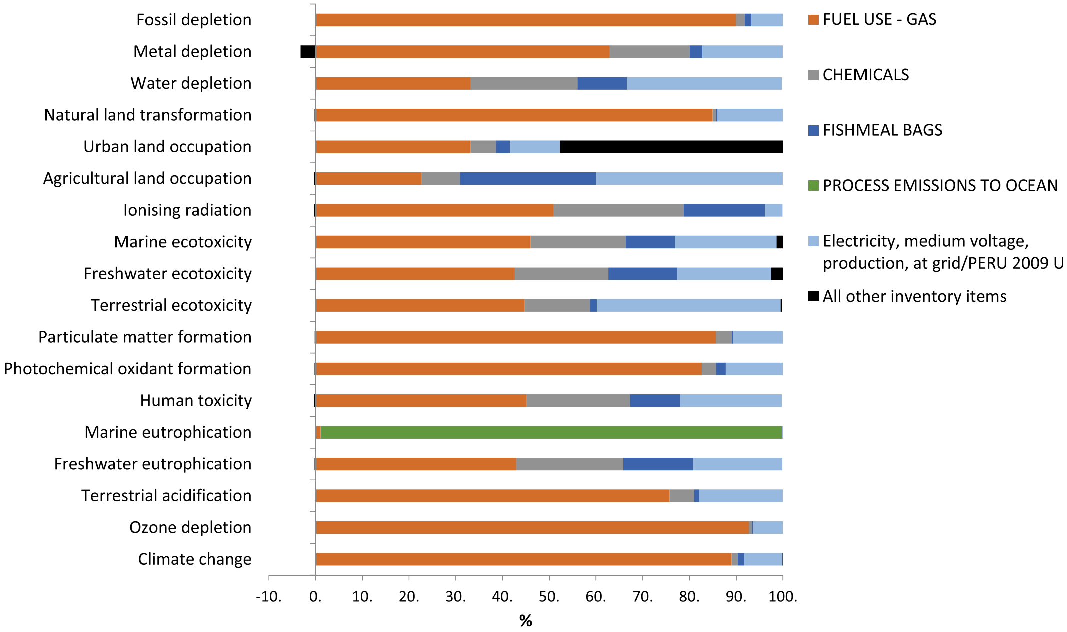

Fig. 6. Fishmeal plant 2: use phase midpoint environmental impacts using the ReCiPe method. The functional unit is the processing of one t of raw material. LCI items in upper case correspond to self-made systems or regroup different items.

After normalisation, the dominating impact categories used by the endpoint level are fossil depletion and climate change effect on human health and human toxicity, whereas at the midpoint level they are human toxicity and marine ecotoxicity.

Within the use phase, fuel use (mostly natural gas) dominates most of the midpoint impact categories for Plant 2 (Fig. 6), with the notable exceptions of marine eutrophication (where ocean emissions dominate), freshwater eutrophication, agricultural land occupation and water depletion. The dominance of fuel use in industrial processes is a common finding (e.g. Hall and Howe, 2012). This dominance is even stronger in Plants 1 and 3 (not shown), due to the use of heavy fuel which is more impacting than natural gas. As a result, the relative importance of the use phase is higher in Plants 1 and 3 (91% and 93% of the single score respectively) than in Plant 2 (87%).

The construction phase of Plant 2 is dominated by the impact of concrete fabrication, the manufacturing of metals and the fabrication of unalloyed steel (cast iron) and chromium steel in most midpoint categories (Supplementary Material). Although the LCI showed that the dominating metal is unalloyed steel, its impact per mass unit is much lower than the one of chromium steel. The results of Plant 1 and 3 differ from Plant 1 by the lower share of concrete because the floor covering of the storage area is made of gravel instead of concrete, resulting in a lower impact.

The maintenance phase is dominated by the impact of chemical products (Supplementary Material). Among them, those coming first in many midpoint impact categories are chlorine dioxide, epoxy paint and a variety of inorganic chemicals products used for cleaning. Although chlorine is used in small quantities (18 g per FU) compared to other products, its impacts are so high that it often overpasses the use of others chemical substances used in larger quantities such as inorganic chemicals (82 g per FU, with an impact

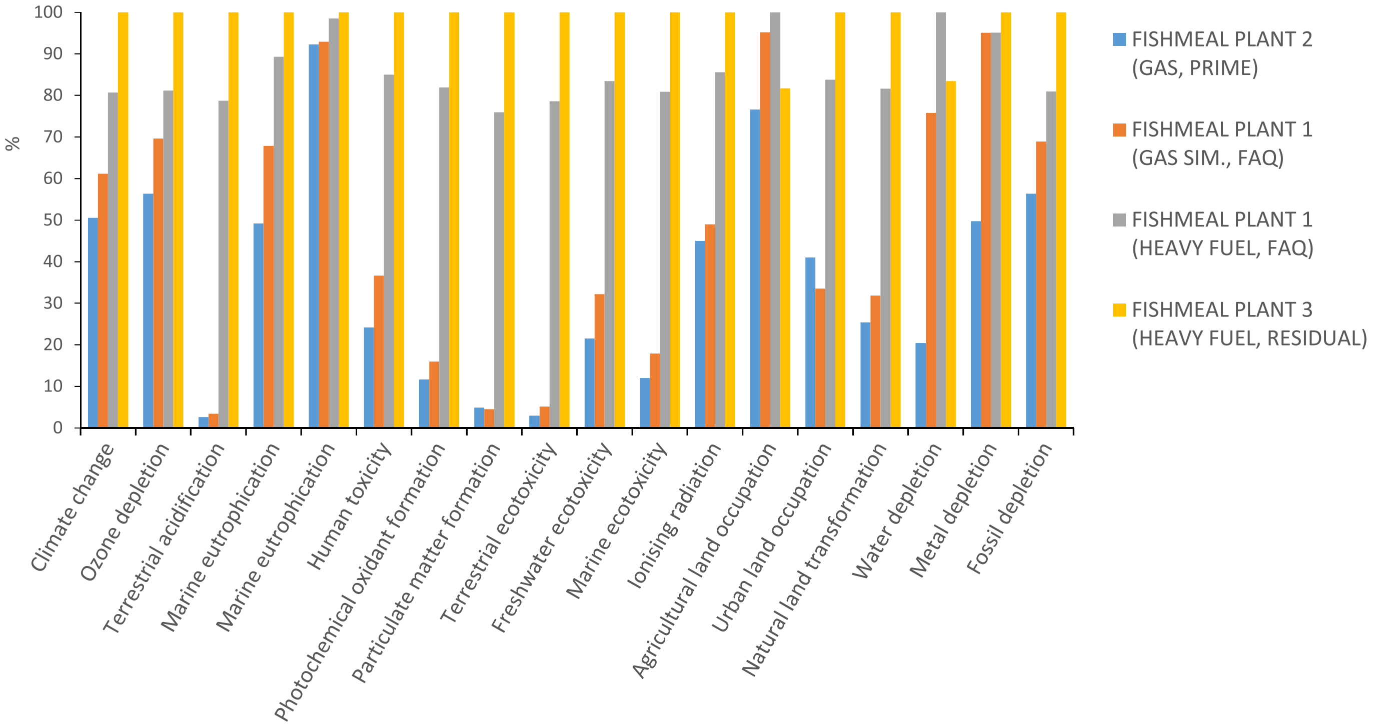

Fig. 7. Comparison of LCA midpoint environmental impacts of the three fishmeal plants (with addition of a simulation of Plant 1 using natural gas) using the ReCiPe method. The functional unit is the processing of one t of raw material.

close to chlorine dioxide in many categories). Copper also have a relatively strong impact.

The comparison of the LCIAs of the three plants at the midpoint and single score levels shows that Plant 2 is the cleanest in nearly all impact categories, Plant 3 the less environmental friendly, whereas Plant 1 falls in between (Fig. 7). The difference between extreme values of the ReCiPe single score is more than twofold. The interpretation of these results is straightforward for most categories. First, Plant 2 benefits from the use of natural gas as its main energy source whereas, Plants 1 and 3 use heavy fuel. Second, Plant 2 average working hours per annum are double than those of Plant 1 (but lower than those of Plant 3), which result in a lower impact per FU in the construction and maintenance phases (especially for metal depletion), as explained earlier (see simulation in Supplementary Material). Third, there are certainly economies of scale along the life cycle that benefit to Plant 2 and largely disadvantage Plant 3. In order to refine this comparison, we simulated the life cycle of Plant 1 using natural gas instead of heavy fuel. Because the requested changes in the capital goods are negligible, there were ignored. In all impact categories except metal depletion, the move to gas supply results in substantial or large decreases of impact, as detailed latter on. As a result, the impacts of the simulated Plant 1 falls most of the time in-between those of Plant 1 (original) and 3, or close to those of Plant 2.

The comparison between our LCIA and other work is hindered by large difference in the LCIs, mostly due to the use of different cut-off rules. The effects of this difference in LCIs on the LCIA are evidenced by comparing Plant 2 current results with simulated results based on the same limited number of entries as the Danish LCI. The ReCiPe single score of Plant 2 is 20% higher when its LCI is detailed than when it is as coarse as the Danish one (Supplementary Material). This is partly due to the absence of the construction and maintenance phase in the latter case, but also to the lack of several items in the inventory of the use phase, such as fishmeal bags and other chemical products than those inventoried in the Danish plant. It worth noting that at the midpoint level this comparison shows increases >100% in the categories human toxicity, freshwater ecotoxicity, marine ecotoxicity, urban land occupation and water depletion, and >470% in metal depletion (Supplementary Material).

Plant 2 LCIA results resulting from the simulation of a paucity of data, were compared with the Danish plant results, assuming that its heat production uses natural gas, based on ecoinvent data. The ReCiPe single score of the Danish plant is 28% higher than the score of Plant 2 when using the same coarse LCI (Supplementary Material). This result is surprising because the two plants use similar quantities of fossil energy, the major source of impact in Plant 2 (Table 4). The LCIA of the Danish plant (not shown) shows that the share of electricity represents nearly 30% of its direct energy consumption, versus 9% for Plant 2. This is not only because the Danish plant use twice the amount of electricity than the Peruvian plant. It is also because the Danish electricity production is more impacting than the Peruvian one due to the relative contribution of coal–powered generation.

3.3. LCIA using output-based FUs

The results of the three allocation approaches for the relative impacts of FM and FO are extremely contrasted (2.5 fold between the two extremes values; Supplementary Material) due to the differences in corresponding ratios of allocation factors (expressed in % for FM and FO): 34:66 when using the criterion of gross energy content, 50:50 with the economic value (average value 2008–2012), and 84:16 with the mass. Mass allocation, which at the end results in the same environmental burden of FM and FO when expressed by FU, appears to be the less realistic one because FO production requires the catch and processing of five times more fish than FM. The choice between the criteria of energy content and

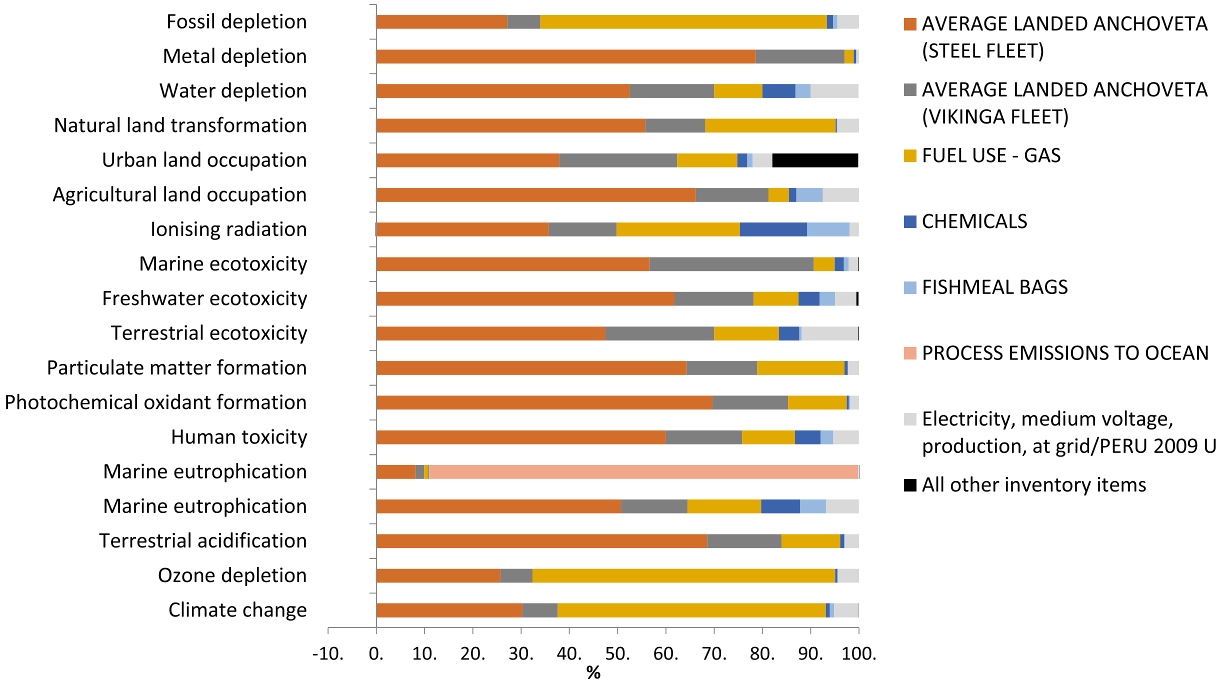

Fig. 8. Fishmeal plant 2: use phase midpoint environmental impacts using the ReCiPe method. The functional unit is the delivery of one t of prime fishmeal. LCI items in upper case correspond to self-made systems or regroup different items.

economic value remain debatable (e.g. Avadí and Fréon, 2013), but it is worth noting that the later approach results in large temporal variation of the allocation factor (e.g. from 36:64 to 63:37 during the study period), unrelated to the environmental burden. We thus retained the energy content as allocation criterion.

The share of anchoveta supply in the ReCiPe single score impact of Plant 2 life cycle is 49%. The dominant endpoints are by far human health and resources (Supplementary Material). As expected, the relative contribution of the construction and maintenance phases of the plant decreases substantially in most impact categories when considering the output-based FUs. The same would happen to the EOL phase if it would have been considered. At the midpoint level, all these contribution are lower than 15%, except for water depletion (20%), ionising radiation and human toxicity (16% each). As a result the remaining contribution of the use phase varies from 76 to 100% (Supplementary Material). After normalisation, the dominating impact categories are the same as those found for the process-based FU.

Within the use phase, the supply of raw material by the two industrial fleets dominated most of the midpoint impact categories in Plant 2 (Fig. 8), followed by fuel use, with the notable exceptions of marine eutrophication. It is worth noting that fuel use impact also dominates in most categories of the supply of raw material (Avadí et al., 2014b; Fréon et al., 2014b, 2014c). As a result, fuel use is by far the most impacting issue in the output-based FUs.

The comparison of the relative environmental impacts of the Peruvian plants at the endpoint and midpoint levels (Supplementary Material, Fig. 9 and Table 5) are similar to those obtained using the process-based FU. In contrast, the single issue CED indicator displays a different pattern than the ReCiPe single score. First, the CED output-based FUs of the Plant 1 according to the type of fuel used shows a less contrasted difference than did the single score (Table 5) which is expected because the energy use is unchanged. Second, the CED output-based FU of the residual plant shows an even more contrasted difference with the other plants than did the single score (Table 5) which is due to the higher proportion of non-renewable biomass (wood) used by the SMS fleet for the construction and maintenance of the hull. The CED method consider that 100% (a debatable proportion) of the wood cut in rainforest is non-renewable.

3.4. Towards a cleaner production

The environmental benefit of using natural gas instead of heavy fuel as energy source in Plant 1 is quantified first by the single score of the process-based FUs that shows a decrease of 41% (Fig. 9) when considering a process-based FU (30% when considering an output-based FU). Second, at the midpoint level, were all categories decreased by more than 24%, except metal depletion, agricultural land occupation, marine eutrophication, and ozone depletion (Fig. 7, Table 5). These results advocate the conversion from heavy fuel use to natural gas (simple change of burners in boilers and in dryers if flame drying is used) when the natural gas network can reach the plant. Similarly, the benefit resulting from the production of Prime fishmeal instead of FAQ is obvious, although not precisely quantifiable from Figs. 7 and 9 because, even after simulation of Plant 1 using natural gas as Plant 2, the production of these two commodities still comes from two different plants with different capacities, etc. But at least the consensual value of heavy fuel use according to the final product, as provided by Peruvian engineers, is highlighting: 190 L for FAQ fishmeal vs 144 L for Prime fishmeal.

It is noteworthy that when a plant line works at its daily average processing rate, as it was mostly the case for Plants 2 and 3 (but less true for Plant 1 in 2009), the fuel consumption is optimal. In contrast, when a line does not produce fishmeal but expects fish delivery for the next days, it carries on consuming fuel either for keeping warm its major equipment (cooker and drier) or for pre-heating them at the end of the daily 4-h cleaning. Using a 9-days limited dataset of Plant 2 during which the mean daily processing rate increased from 60 to 138 t/h, Durand (2010) showed that fuel use decreased from 8.0 to 5.7 GJ per t of fishmeal produced. These results show that the processing overcapacity combined with the

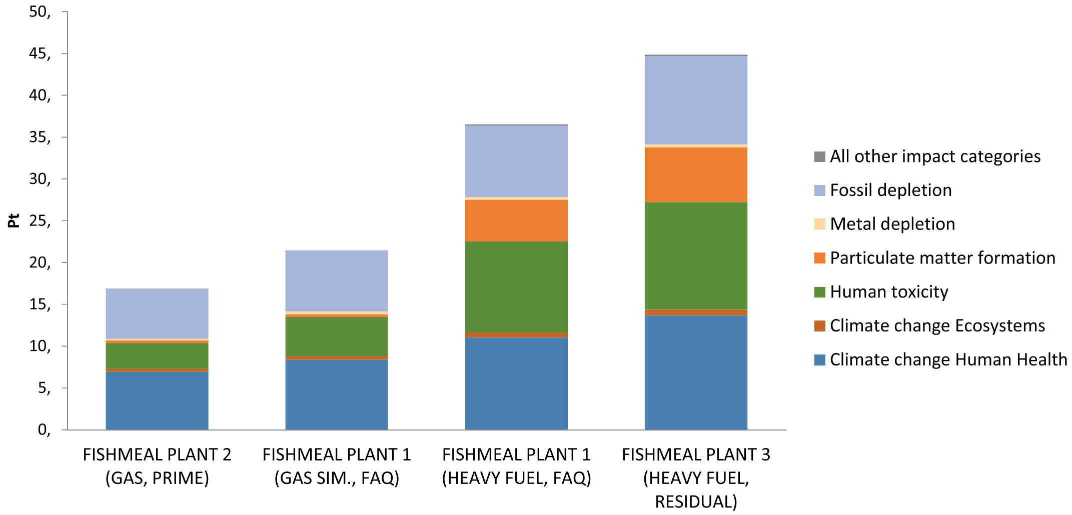

Fig. 9. Comparison of endpoint environmental impacts of the fishmeal produced by Plants 1, 2 and 3 using the ReCiPe method. The functional unit is the processing of one t of raw material. “All other impact categories” refer to those retained in ReCiPe endpoint.

Table 5
Characterization at the midpoint and single score levels of the life cycle impacts of the production of 1 t of fishmeal of different categories with different main sources of energy and using the energy content allocation factor of 34% (upper values) and of the processing of 1 t of raw material (lower values).

Impact category	Unit	Plant 2 (Gas, prime)	Plant 1 (Gas simul., FAQ)	Plant 1 (Heavy fuel, FAQ)	Plant 3 (Heavy fuel, residual)
Climate change	kg CO2 eq	2.65E+02	3.01E+02	3.66E+02	5.76E+02
		1.18E+02	1.43E+02	1.88E+02	2.33E+02
Ozone depletion	kg CFC-11 eq	3.45E−05	4.00E−05	4.48E−05	7.26E−05
		1.64E−05	2.03E−05	2.36E−05	2.91E−05
Terrestrial acidification	kg SO2 eq	1.25E+00	1.33E+00	7.83E+00	1.20E+01
		1.57E−01	2.08E−01	4.75E+00	6.03E+00
Freshwater eutrophication	kg P eq	1.85E−02	2.19E−02	2.58E−02	3.81E−02
		6.23E−03	8.59E−03	1.13E−02	1.27E−02
Marine eutrophication	kg N eq	6.29E−01	6.33E−01	6.68E−01	8.24E−01
		3.96E−01	3.99E−01	4.23E−01	4.29E−01
Human toxicity	kg 1,4-DCB eq	9.50E+02	1.15E+03	1.91E+03	2.89E+03
		2.65E+02	4.02E+02	9.32E+02	1.10E+03
Photochemical oxidant formation	kg NMVOC	1.51E+00	1.60E+00	2.96E+00	4.91E+00
		1.68E−01	2.30E−01	1.18E+00	1.45E+00
Particulate matter formation	kg PM10 eq	4.48E−01	4.40E−01	1.98E+00	3.15E+00
		7.32E−02	6.82E−02	1.14E+00	1.51E+00
Terrestrial ecotoxicity	kg 1,4-DCB eq	7.33E−02	9.49E−02	8.14E−01	1.25E+00
		2.03E−02	3.53E−02	5.38E−01	6.84E−01
Freshwater ecotoxicity	kg 1,4-DCB eq	5.58E−01	6.57E−01	1.13E+00	1.67E+00
		1.40E−01	2.09E−01	5.41E−01	6.48E−01
Marine ecotoxicity	kg 1,4-DCB eq	1.76E+03	1.91E+03	3.48E+03	6.86E+03
		2.10E+02	3.13E+02	1.41E+03	1.75E+03
Ionising radiation	kg U235 eq	7.39E+00	7.78E+00	1.14E+01	1.90E+01
		3.09E+00	3.37E+00	5.88E+00	6.87E+00
Agricultural land occupation	m^2a	2.84E+00	3.00E+00	3.04E+00	5.10E+00
		4.56E−01	5.67E−01	5.95E−01	4.87E−01
Urban land occupation	m^2a	5.66E−01	5.19E−01	8.37E−01	1.70E+00
		1.82E−01	1.49E−01	3.71E−01	4.43E−01
Natural land transformation	m^2	1.31E−01	1.42E−01	2.25E−01	3.70E−01
		2.97E−02	3.72E−02	9.52E−02	1.17E−01
Water depletion	m^3	4.92E−01	1.12E+00	1.39E+00	1.57E+00
		1.61E−01	5.98E−01	7.89E−01	6.58E−01
Metal depletion	kg Fe eq	3.25E+01	3.66E+01	3.66E+01	3.79E+01
		3.10E+00	5.93E+00	5.93E+00	6.23E+00
Fossil depletion	kg oil eq	9.49E+01	1.09E+02	1.22E+02	1.93E+02
		4.41E+01	5.39E+01	6.33E+01	7.82E+01
Single score	Pt	4.43E+01	5.09E+01	7.25E+01	1.12E+02
		1.69E+01	2.15E+01	3.65E+01	4.49E+01
Cumulative energy demand	MJ	5,74E+03	6,39E+03	6,85E+03	1,71E+04
		2,13E+03	2,58E+03	2,90E+03	3,57E+03

increased fishing season due to the implementation of IVQs generates difficulties to optimize daily processing rate, which result in a substantial waste of energy. The large fishing companies that own several plants along the Peruvian coast try to limit this waste by

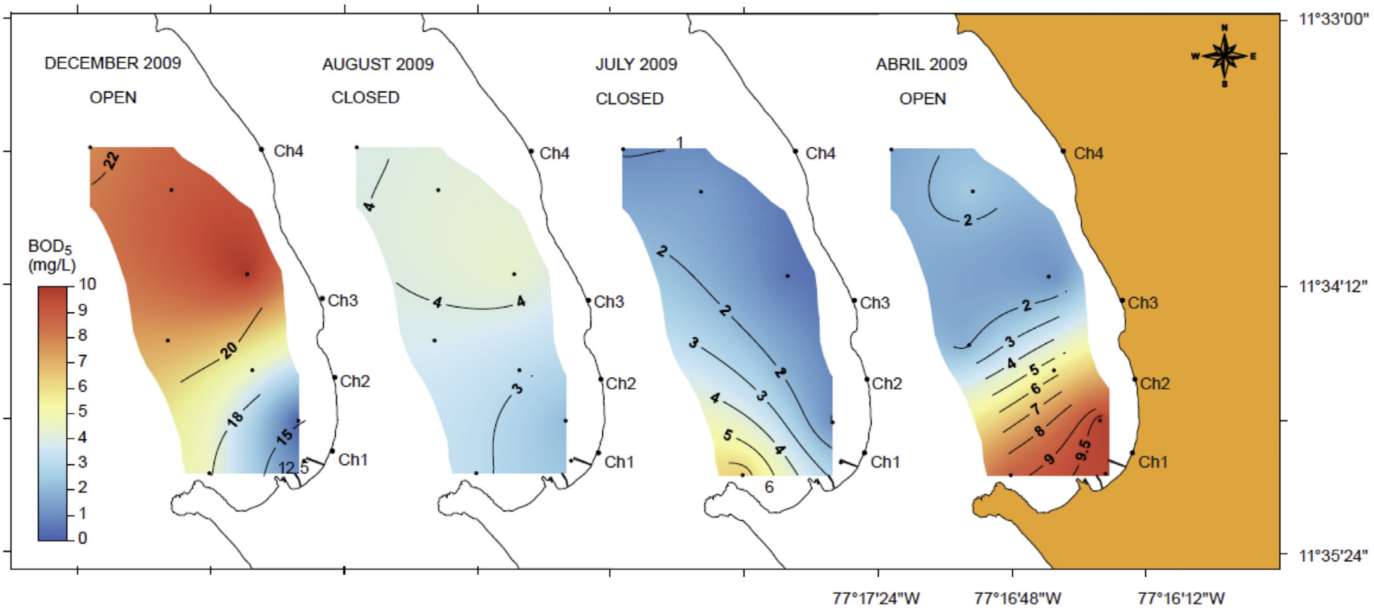

Fig. 10. Biological oxygen demand in the bay of Chancay, where Plant 1 and 6 other fishmeal plants were located, according to fishing activity during the four fishing seasons of 2009 and 2010, whose annual landings were 0.38 and 0.20 million t, respectively. Dots along the coast line and at sea correspond to the position of sampling stations.

closing for several days or weeks some of their plants. Nonetheless, the large spatial and temporal variability of the anchoveta distribution makes this exercise difficult and risky, and often results in a counterproductive increase of the travelling distance of the fishing vessels from fishing grounds to the active plants. In addition, overcapacity results in an increase of the impact of the construction and maintenance phase due to a lower production of FUs along the life cycle (see simulation in Supplementary Material).

The impact of the production of 20 bags of 50 kg each for every t of fishmeal is substantial, although it could be avoided in many cases. Indeed at the time of this work >90% of the fishmeal production was bagged whereas most of it was transported in bulk from the plants to its final destination. The bags were emptied manually either within the plant or at the Peruvian harbour of Lima, taking advantage of low cost of manpower in Peru. Using much larger bags (e.g. the existing ones of 1200 kg) or storing the fishmeal directly in shipping containers at the plant should reduce the environmental burden.

The vessels of the Peruvian fleets landing anchoveta for reduction are not equipped with a refrigeration system, with the exception of few of the largest steel vessels which, up to recently, did not use it (Fréon et al., 2014b). As a result, fish rapidly deteriorates on board and in the storage pits of the plants, leading to softening of the flesh and resulting in an increase of the amount of protein and oil content of the blood water and in the formation of histamine. Furthermore, soft fish may clog up the outlets of the press. To limit these processes that result in poor fishmeal quality, chemical products (e.g. formaldehyde) are used when necessary. Cleaner production and improved quality of final products can be obtained by chilling the fish on board when necessary. Furthermore, dry unloading by pneumatic off-loader can also result in cleaner production due to the elimination of unloading blood water (COWI, 2000). Oldest plants, especially residual ones, could benefit from renovation aimed at reducing energy lost by recycling the steam. For instance waste heat from the evaporators and dryers can be used to pre-heat the material. Additional saving can come from eliminating steam leaking, and from increased descaling frequency to limit inhibition of heat transfer. Finally, a better processing of blood water should result in reaching the legal maximum limits regarding the emissions of suspended solids, oil (Supplementary Material) and the BOD concentration at sea, which is not always the case presently, despite governmental incentives (e.g. Ministerial Resolution N°181-2009-PRODUCE, but see the remarkable initiative in the bay of Pisco at http://www.apropisco.org/).

Most of these measures should contribute to a decrease of the physicochemical parameters of the seawater in coastal areas, especially in some bays where the reduction industry tend to concentrate (Fig. 10 and Supplementary Material).

4. Conclusion

This is, as far as we know, the first detailed LCA of fishmeal plants in the world, beyond existing screening LCAs. It considers the construction and maintenance phases, which distinguish it from many other LCA studies, and it might provide generic life cycle inventory (LCI) data of fishmeal plants and LCI analysis by using a process-based functional unit (FU) along with a conventional output-based one. The LCIs of the construction and maintenance phases represented by far the heaviest work, although their corresponding environmental impacts were much lower than that of the use phase (87% of the ReCiPe single score of the process-based FUs, dominated by fuel use). The share of these two phases in the Peruvian case, particularly the construction one, is exacerbated by the processing overcapacity. Ideally, future studies on fishmeal and residual fishmeal plants should include not only a screening of the construction, maintenance and EOL phases (infrastructure construction, metals manufacturing and production, with a focus on chromium steel and copper), but also an improvement of the LCI of the use phase, particularly the impact of fishmeal bags and other chemicals than those inventoried. According to our simulation, the Danish plant LCA screening, the most documented one available, is likely to have underestimated its environmental impact by more than 15% at the single score level, and by more than 100% in some midpoint impact categories.

There is room to decrease the environmental impact of this industry (use of natural gas instead of heavy fuel, reduction of overcapacity (see Supplementary material for simulations), modernisation of the oldest plants, production of higher fishmeal quality, improvement of sanitary condition, etc.). Because the use of natural gas instead of heavy fuel as the main source of energy results in large decreases of environmental impacts (Figs. 7 and 9), it is recommended to favour this move by extending the natural gas network all along the Peruvian coast. Presently this network covers only a fourth of the Peruvian coast line. A feasibility study of the extension of the national natural gas network was performed recently (Tamayo et al., 2014) but its concretisation suffers from delays. It demonstrated the positive economic impact of this extension for the public (cheaper energy), the industries (e.g. energy for steel plants; production of explosives), the agriculture sector (production of fertiliser) and the public sector (improvement of the Peruvian balance of trade hydrocarbon, production of cheaper and cleaner electricity compared to heavy fuel thermal plants). The fishmeal industry will immediately react in the expected direction if this extension were to be implemented due to lower costs of this energy per MJ and policy dispositions (Ministerial Resolution N°621·2008-PRODUCE). Similarly, the move from the production of FAQ fishmeal to the production of Prime fishmeal, already started (Ministerial Resolution N°242·2009-PRODUCE), should continue to be encouraged by the legislation. These two measures are beneficial both from the environmental and economic points of view. Regarding overcapacity, if it was decreased by a factor two, the share of the construction phase would decrease by about the same amount. A final recommendation for the Peruvian industrial sector is to enforce the present policy regarding management and sanitary conditions in order to address “black fishing”, illegal and unregulated fishmeal plants in operation and the lack of compliance with environmental regulations (although recent progresses in these domains have been observed). These last recommendations should result in the production of less impacting FAQ and Prime fishmeal produced in large plants than residual fishmeal of poor quality produced in small, insanitary and often illegal residual plants.

Acknowledgments

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Appendix A. Supplementary material

Supplementary material related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2017.01.036.

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Supplementary Material for the paper:

Life Cycle Assessment of three Peruvian fishmeal plants: toward a cleaner production

Pierre Fréon[1], Hermine Durand[2], Angel Avadí[3*], Sayda Huaranca[4] , Rita Orozco Moreyra[5]

[1] UMR MARBEC, Institut de Recherche pour le Développement (IRD), Sète, France
[2] Ecole Normale Supérieure (ENS), Paris, France
[3] CIRAD, UPR Recyclage et risque, F-34398 Montpellier, France
[4] Universidad Nacional Agraria La Molina, Lima, Peru
[5] IMARPE, Chucuito, El Callao, Peru
[*] Corresponding author: Email: angel.avadi@cirad.fr

Content

1 The FMFO process tree

Let us describe briefly the process tree for the baseline system as presented in Fig. 3 of the paper itself. The following description is based on two key references (FAO and FID, 1986; COWI Consulting Engineers and Planners AS, 2000) and adapted to the Peruvian case. After reception of the fishing boat at the floating terminal the fish is pumped out of the vessel’s hold and conveyed to the plant mixed with seawater in a proportion close to 1 m^3 per t of fish (0.7 m^3 in Plant 1 in 2009). There the fish is separated from the mix of water, fish residues and blood (bloodwater) through a screw drainer. The drained bloodwater is processed in a rotating screen in order to remove the solid residues (flesh, scale, etc.) that are then conveyed to the “solid line” (described below), and the remaining water is processed first in an oil and solids separator and then in a flotation tank where oil is recuperated thanks to its positive buoyancy. The oil is conveyed to the “liquid line” (described below) whereas the remaining water is discharged at sea through a long underwater pipe (e.g. one-km long in Plant 1[1]). In modern plants, the flotation process is accelerated by the release of fine air bubbles at the bottom of the flotation tank. The remaining bulk of the fish is then conveyed by a wire mesh conveyor belt to an automated weighting hopper and then released into large storage pits. From there fish is conveyed to a cooker using a conveyor, whereas additional bloodwater is processed into a specific trommel. There a continuous cooking occurs by means of an internal rotary screw conveyor, at a temperature of 95 to 100°C in order to coagulate the proteins. The cooking process is indirect, thanks to steam-heated jacket surrounding the conveyor, but still generates odorous fumes. From the cooker the product is conveyed to strainer (or first to a pre-strainer and then to double helicoid press) that allows draining a mix of oil, protein (dissolved and suspended) and water from the solid mass, thanks to the previous cooking step. From the straining process starts the major separation between the liquid line (oily water or “press liquor") and the solid line (presscake), but with further bridging connections.

The processes in the liquid line consists in a further separation between oil, water and protein coming from different paths. The press liquor, along with the bloodwater, is first transferred by pipe to a oil and liquid separator (or decanter) which is a horizontal centrifuge. After two to three separation phases, the oil and liquid separator returns the remaining solid (sludge) to the solid line whereas the liquid goes to a vertical disk centrifuge. The centrifugation process allows further separation between fish oil and the aqueous phase named “stickwater”. Stickwater is concentrated in a multi-stage (two to four) evaporation unit, prior to enzyme addition aimed at reducing its viscosity. The unit must be cleaned at regular interval, usually using caustic soda, to maintain its thermal efficiency. This is because the evaporator tubes where steam circulates are quickly fouled. The final phase of the liquid

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[1] In the bay of Pisco, thanks to a joint initiative of the fishing companies, the emissions of the seven fishmeal plants are first stored in two large tanks of 1 150 m^3 each and from there sent 13.8 km offshore through a underwater pipe (http://www.apropisco.org/).

line is oil polishing, which is carried out in special separators and facilitated by using hot water, which extracts impurities from the oil (resulting in additional stickwater) and thus ensures stability during storage. This phase ends with the transfer of the stickwater to the evaporation unit and with the pumping of the refined oil into storage.

The presscake along with the sludge from the oil and liquid separator is conveyed first to a wet mill and then to a rotating dryer. As indicated earlier, direct-fire dryers or indirect steam dryers can be used and will result in different qualities of fishmeal. The drying process also generates smells and particles, especially in the case of direct-fire dryers. The raw dry meal (“scrap”) first passes through a sieve to remove large extraneous material mostly collected during the purse-seining operation (wood, rope, plastic residues, etc.). Then the meal is pneumatically conveyed to a cyclonic tower to extract fish meal particles from the drying air. In the sampled plant of FAQ fishmeal, the air emission of the cyclone was processed in a scrubbing tower where water is pulverised in order to limit particles and odours emissions. The fishmeal is then milled in a dry mill. Follows a centrifuging purifier that allows a final elimination of small extraneous material. Finally anti-oxidant is added before automatic weighting and conditioning into plastic bags for distribution.

Steam is produced in a series of boilers and distributed throughout the plant by insulated pipes, forming close circuits in order to save energy. Steam condensate is also returned to the boiler through a piping systems.

The energy source in boilers is either natural gas when available or heavy fuel. In the past fish oil was recycled in boiler burners because its commercial value was very low.

Electricity from the Peruvian grid is used most of the time, except during peak hours (or power breakdowns) where it is supplied by a series of powerful electric generators fuelled by light fuel. This strategy is used to reduce production costs because self-generated energy is cheaper than the grid energy during peak hours.

2 Main characteristics of the Peruvian fishmeal categories

Three commercial categories of fishmeal were used in Peru during the study period (2008-2012; Table 2-A). Recently, two new categories of improved standard of fishmeal are currently produced in Peru: the so-called “Taiwan” one at the top, followed by the “Thailand” one, both produced in modern steam lines.

Table 2-A. Main characteristics of the Peruvian fishmeal categories in 2011. All terms and conditions refer to GAFTA[2] 118 and arbitration rule n°125 (Jean-François Mittaine, Fishmeal Experts Office, France, pers. comm.)

Name of product	Item	Limit (%)	Ref.	Comment
1) FAQ	Protein	65	min	can be 64/63
	Fat	12	max	
	Moisture	10	max	
	Salt/sand	5	max	
	Salt alone	2	max	
	Antioxidant	150	min	
2) Standard	Protein	65	min	can be 67/66/65
	Fat	10	max	
	Moisture	10	max	
	Salt/sand	5	max	
	Salt alone	2	max	
	Antioxidant	150	min	
2) Super-prime	Protein	67	min	must be 67

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[2] Grain and Feed Trade Association (www.gafta.com).

Fat	10	max	
Moisture	10	max	
Salt/sand	5	max	
Salt alone	2	max	
Antioxidant	150	min	
FFA	10	max	Free fatty acids
Histamine	500	max	
TVN	120	max	Total Volatile Nitrogen
Ash	14	max	

3 Additional information related to the goals and scope of the study

3.1 Commissioner of the study and other influential actors

This work was not really commissioned, but needed by the Anchoveta Supply Chain (ANCHOVETA-SC, (http://anchoveta-sc.wikispaces.com/) project. It is also a contribution to the International Join Laboratory "Dynamics of the Humboldt Current system" (LMI DISCOH) coordinated by the Institut de Recherche pour le Développement (IRD) and the Instituto del Mar del Perú (IMARPE), and gathering several other institutions. This study is of an accounting character and does not imply a direct decision-support but aims at analysing the system in isolation.

3.2 Assumptions

Regarding the output-based FUs, we make the assumption that the production of Prime and Super Prime quality do not differ significantly in terms of environmental impact[3], but rather depends on the quality of the raw material (freshness), its conditions of manufacture (in particular the control of temperature) and of storage (temperature and wetness). Because we do not consider any category of fish oil in the definition of the corresponding FU, the assumption is made that here as well there is no significant difference in the environmental impact according to the quality of the oil. The recommended duration of use of FMFO is <6 months because of the continuous acidification of fishmeal and the decrease in its protein and fat contents, and of the continuous oxidation and esterification of oil in fish oil, despite the addition of antioxidants and enzymes (Kamasastri and Ramananda Rao, 1962; Su Pak, 2005).

Regarding the process-based FUs, we made the same assumption as above regarding Prime and Super Prime fishmeal, plus an additional one. Here we assumed that, within the processes of production of the three types of fishmeal, the environmental impacts are not significantly different according to the type of raw material and its fat content[4]. This assumption may appear not so true for residual fishmeal because we considered that In Peru the raw material processed by residual plants was in average made of 57% of fish residues and 43% of IUU anchoveta resulting in an average ratio raw material:fishmeal of 5.5 (against 4.2 for FAQ and Prime or Super Prime qualities which process only whole fish). Higher ratios might be obtained when processing only fish residual and this would result in higher environmental impact per FU, beyond the fact that more raw material is processed. But the fact that our process-based FUs consider the raw material input rather than the outputs takes into account most of the consequences of changes in the conversion ratio according to the raw material, providing that the LCA practitioner that use this kind of FUs knows the actual value of the conversion

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[3] Although the rough analysis performed on a 7-day dataset of Plant 2 when it was producing FAQ fishmeal in proportion of 1 to 32% did not show significant difference (Durand, 2010), it is likely that the production of Super Prime fishmeal would request a bit more of energy to dry than the Prime fishmeal.

[4] Although we did not find data to support this assumption, it is likely that the oiliest it is the raw material, the less energy will be needed per FU to extract the oil.

ratio of his/her case study. If not, data from the literature can be used. Here the method of allocation of environmental impacts of the two coproducts can be elected by the practitioner. The duration of validity of the process-based FU can be estimated at around 10 years from date because the LCI was performed in 2010 and the technology is not expected to change significantly in a near future, despite continuous improvements, in particular in the oldest plants which tend to modernise their processes, mostly to improve the quality of the products and to reduce operational costs, in particular energetic ones.

We made the assumption that EOL environmental impact is limited base on: 1) the large duration of life of the equipment (at least 30 years) allowed by an excellent maintenance, at least for the large plants; 2) the results of other LCA studies of good production; 3) the expected environmental benefits of the recycling of dominant items in the inventory (metals).

In order to allow LCIA comparisons between the three plants, the initial screening LCI of residual Plant 3 was expanded by assigning to the missing LCI parts of Plant 3 rescaled corresponding items from Plant 1. The full construction phase was arbitrarily rescaled by a factor 1/5, taking into account economies of scale and the fact that Plant 3 is less sophisticated than Plant 1 (no evaporation unit; rough treatment of blood water). The missing items in the use phase were rescaled in proportion to the ratio of the fishmeal production rates of the two plants (5.5:4.21) whereas the maintenance phase was rescaled according to the ratio of the average effective processing rates (4:70). This last rescaling factor may appear excessive

3.3 Type of LCA and allocation

Because our goals are mostly retrospective, accounting and descriptive ones, the retained LCI modelling framework is an **attributional** one. Although we address the consequences of a change of the main energy source from heavy fuel to natural gas, consequential LCA was not used because existing Peruvian data allows this comparison (see also considerations exposed by Yang (2016) on the use of the attributional approach for comparison). Because we deal with multifunctional processes resulting in two co-products (fishmeal and fish oil) whose respective production paths cannot be fully subdivided in corresponding single operation unit processes (see details below), the subdivision approach cannot be used. The whole fishmeal plant was considered as a single black box unit process. The system expansion approach is systematically used in the Danish LCAfood database and in the case of FMFO, it is considered that fish oil production avoids rapeseed oil production. Nonetheless this approach has not been retained here for several reasons: 1) in this case it generates negative flows that are not easy to interpret or justify; 2) it is a highly debated approach (e.g. Suh et al., 2010; Weidema and Schmidt, 2010); 3) in the real life, it is unlikely that the production of rapeseed oil result in an avoided production of fish oil because the former became cheapest than the latest during the last decades; in contrast rapeseed oil and soybean oil are more and more used as substitutes of fish oil, although they poor concentration in n-3 highly unsaturated fatty acids (essential to animal growth) limits this substitution in some cultivated species (e.g. Turchini et al., 2009). The allocation approach was retained, based on three different classes of relationships that were compared: energy content as a physical relationship, following in that the recommendation of Ayer et al. (2007); mass allocation as a conventional one, and economic as a non-physical relationship commonly used by LCA practitioners.

3.4 Cut-off rules and most relevant items in the LCI

Because these were the first detailed inventory of fishmeal plants, common sense and the conventional cut-off criteria that were retained in the LCIs of Plants 1 and 2, using deliberately low thresholds of mass (> ~0.1 % of plant total weight) and monetary value (> ~US$500, that is > ~0.01 % of the total price of the plant), and rough estimates of environmental significance (expert knowledge with help of environmental impact databases when necessary). Therefore the inventory phase considered combustibles (heavy fuel or natural gas, light fuel), electricity use, water use, the major pieces of equipment detailed below, all pipes within the plant and those linking the plant to the discharge platform, infrastructures, and finally all known production and maintenance inputs and outputs such as chemicals, fishmeal bags, industrial salt, soda, antioxidants, airborne emissions (CO2, H2S, NOx…), releases to water and solid residues (see below). In contrast we excluded small and medium pipes (diameter < 16'), office furniture (except computing hardware) and very small machines (except motors and pumps because they were numerous).The cut-off rules used for the fishing process are detailed in Fréon et al. (2014a,b).

The most relevant items for the fishing sub-system are fuel consumption, vessel building and vessel maintenance materials (steel, other metals, wood, antifouling paints, etc.) and fishing gear. For the fishmeal plant sub-system these items are heavy fuel or natural gas consumption, electricity consumption, lubricants consumption, emissions to water, plant building and plant maintenance material (metals and their manufacturing, different categories of paints and their solvents). Fossil energies, electricity mix and materials consumed by the fishing fleet or the plant, and combustion of fuels in industrial boilers were modelled specifically for Peru. Nitrogen outputs from the plants were not available in Peru, therefore values per FU of the Danish LCAfood database were retained. Some discrepancies, real or apparent, were observed between the input and output ex-post data, or between the ex-ante and ex-post data (in particular measured emissions). These discrepancies were due to different reasons (packaging in the background, no access to stock inventory, variability or error in punctual measurements of emissions, etc.). In these cases, the most conservative values were retained.

3.5 Use of this study for other cases

Although in both cases the processes occur in Peruvian plants, the process-based FU can be used for processing of different raw material in other countries (see technical details below) because nowadays the technologies for producing FMFO are similar in most countries (Péron et al., 2000; but see Henriksson et al. (2014) for China where up to 500 kg of coal is used to produce one t of fishmeal). Photos of a fishmeal plant and of the final products are available at http://www.indigo.ird.fr/fr/spotlight/31375/fabrication-de-farine-et-d-huile-de-poisson-dans-une-usine-peruvienne-pierre-freon/page/1/SN/REPORTAGES.

3.6 Data sources and representativeness of the sample

The major LCI datasets for the fishing sub-system were provided by the major fishing companies (details in Fréon et al., 2014b), whereas for the processing sub-system data regarding Plants 1 and 2 were provided by a single fishing company (anonymous). In both cases we had access to reliable data, including to detailed accounting databases in the case of these two plants. In addition, plant engineers helped us, when necessary during our stays of several days in these plants, to fulfil a detailed questioner (see below). Our goal was to obtain the weight, the composition (percentage of each material) and the origin (brand and country) of each object (e.g. a wall, a press...) either from the available documentation in the two plants or on Internet, or from its dimensions. Visual estimations were used only in a limited number of cases for these two plants, such as for small objects and part of the infrastructure (walls, roofs and floor coverings). In contrast the datasets from the residual plant were limited and less complete and precise.

The technological representativeness of the fishery sub-system is quite good, especially for the industrial fleet of steel vessels that provide the bulk of the catch and which fuel consumption was exhaustively available (Fréon et al., 2014b), whereas this representativeness is correct for the rest of the fleet (Avadí et al., 2014; Fréon et al., 2014a). Because only one fishmeal plant was sampled in each of the three categories, the technological representativeness is limited. Nonetheless, and despite a large range of processing capacities in each category of plant (detailed below), the technology is quite the same in FAQ and prime plants that produce the bulk of the catch. This is not so true for the residual plants. The geographical representativeness looks good at the national scale because, as far as we know, there are no geographical changes. Beyond the national level, the Peruvian plants seems very similar to those found in the major countries producing FMFO, in particular Chile, but might be non-representative of other countries, including China.

From the description of the categories of FMFO available in the Introduction, it is clear that there are no obligatory properties of the two commodities, but only positioning properties.

3.7 *Overcoming the limitation of characterisation*

Some material used in the construction (and maintenance) were not represented as such in ecoinvent but were approximated by equivalent material or raw material. This was the case for the high-density polyethylene of the one-km long underwater pipe used for waste water that was approximated by polypropylene granulate. It was also the case for different chemical substances approximated by substances from the same family when possible. Emissions at sea of nitrogen (N) by the Peruvian plants occur in coastal zone through an underwater pipe. Nonetheless, if those emissions are declared in the "ocean" compartment, their eutrophication impact is no characterized by ReCiPe (probably because N emissions offshore are diluted and difficult to quantify). In contrast, when declaring N emission in an unspecified compartment, the midpoint impact category "Marine eutrophication" is characterized. Therefore coastal N emissions were declared to an unspecified compartment.

4 Data collection in Plant 1 and 2

4.1 *Extract from the LCI questionnaire*

9. Pressing														
Equipment	Reference number	Number of items	Material weight (kg)						Life expectancy (years)		Maintenance	Brand, Country	Data source	Preliminary data processing
			Steel	Inox steel	Copper	Bronze	Aluminium	Refractory plastic	theorical	practical				
Press		2	49300	5800		2900			10	15 to 20	Change of bearings, lubrication	STORD, Norway	Technical manual, production chief engineer	Percentage
Press motor (2*150 HP)		2	657		438				15 to 20	-	-	STORD, Norway	Technical manual	Linear regression
Helicoidal conveyer (out of press)	12	1		293					25	-	Lubrication	Made at plant, Peru	Technical manual and personal measurements	Helicoidal conveyer weight calculation method
Helicoidal conveyer (to mill)	13	1		444					25	-	Lubrication	Made at plant, Peru	Technical manual and personal measurements	Helicoidal conveyer weight calculation method
Mill		1	692						10	15 to 20	Mere cleaning	Peru	Personal measurements	Approximation by rectangular box
Mill motor (100 HP)		1	223		149				15 to 20	-	-	Peru	Technical manual	Linear regression

4.2 *Construction data*

We considered both the infrastructure of the plant and the equipment itself. Our goal was to obtain the weight, the composition (percentage of each material) and the origin (brand and country) of each object. To that end, we first studied the equipment technical data available in the plant's office. When we did not find out the information needed, we held the inquiry in the plant together with engineers or workers. In this case, for each object (e.g. a wall, a press...) we took down its dimensions, its main materials and we calculated its approximate weight and composition, with a rough uncertainty factor. We also considered the office computer hardware.

4.3 *Use data*

Thanks to annual reports, we made an inventory of all production inputs and outputs of the factory.
The major inputs of the plant are: fuel, chemicals, water, fishmeal bags, industrial salt, soda, antioxidants and electricity. The inputs to the chemical laboratory of the plant were inventoried because they are mostly highly impacting products in absolute, but at the end they were eliminated

because their low amount per FU resulted in a negligible impact. We assigned the origin of electricity in its thermal and hydraulic components according to the Peruvian Department of Energy and Mines. The outputs major of the plant are: gas emissions (CO_2, H_2S, NO_x…), solid waste (dangerous and non-dangerous) and liquid effluents (carrying chemicals and solid residuals).

4.4 Maintenance data

For each object, we collected information about the maintenance frequency, the type of inputs and their chemical composition. We also had access to the annual maintenance buying reports. Thus, the main inputs in volume and/or costs were found to be paint, lubricants, grease, water and spare parts.

4.5 Resulting LCI

The LCI of the construction phase of Plants 1 resulted in the identification of 258 different items (similar values were obtained for Plant 2), where main raw materials were identified and their corresponding weights estimated. This construction LCI resulted in 29 different entries in SimaPro dominated, in mass, by metals and infrastructure material and their manufacturing. The maintenance phase inventories, based on detailed accounting databases (>6,000 entries for Plant 1 and >8,000 entries for Plant 2), allowed the identification of ~100 of major items that resulted in 51 entries in SimaPro, including 15 for raw material (dominated in mass by chemical products resulting from paints, but copper wire was substantial) and six major emissions (dominated by organic substances emitted to the atmosphere, resulting from some paints diluents). The use phase inventory resulted in the identification of 50 different items and 58 corresponding entries in SimaPro including three related to the raw material, four to energy sources (modified to reflect Peruvian specificity), 18 to the production of chemical products (including the chemical laboratory), nine emissions to ocean, three emissions to stratosphere (particles and CO) and 14 waste flows, including four recycling-related. The use phase is dominated by the use of energy, in particular fuels (heavy fuel in Plants 1 and 3, mostly natural gas in Plant 3). Follows fishmeal bags, chemical products, in particular salt for consumed by the water softening plant, water itself, caustic soda and products used for treating deteriorated raw material (formic aldehyde and organic chemicals).

4.6 Specificities of Plant 2's inventory

In order to compare different scenarios of production techniques (FAQ versus Steam) or combustion processes (oil versus natural gas), we used the same detailed data inventory as in Plant 1 but we considered several base years, each one of them corresponding to a different production process. We focused on the progressive changes made on the equipment, and on the variation of material and energy flows (that is to say production and maintenance, inputs and outputs).

4.7 End of life data

Due to due to lack of previous experience of full dismantlement in Peru, end of life is not modelled. Nonetheless, part of relevant data was collected for assessing the average life expectation of the plants (30 years). With the help of the maintenance chief engineer, we took down the theoretical life expectancies of each piece of equipment and we compared them to their real shelf lives. We also collected information from visual observations of waste disposal and inquiries of different workers at the factory and headquarters. Due to a tradition of recycling (formal and informal) in Peru, the impact of the EOL phase should be minored.

5 Preliminary data processing

5.1 Construction data (Plant 1):

Calculations were made to estimate the weight of some pieces of equipment.

- *Pumps and motors.* Only the electric motors of motor pumps were considered, ignoring the pumps themselves due to low expected environmental impact of the other materials. The weight of each motor was estimated with a linear regression made from a technical document. Then, we considered that a motor was made of 60% steel and 40% copper.

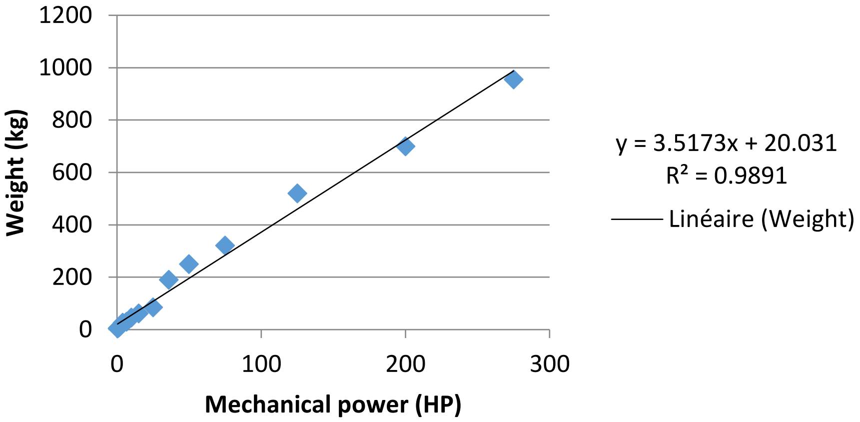

Figure 5-A. Estimate of motors' weight. Source: Triphasic engines, speed 1800 rpm, Siemens Andina S.A.

- *Helicoid conveyers.* Their exact weight was calculated from technical data.
- Some machines were assimilated to their external structure. When precise dimensions were missing, their volume was considered that of their closest external geometrical form (e.g; a rectangular box or a tube, with or without lid). However, the thickness of the material was always exactly known, reducing the margin of error. This was the case for: mills, hoppers, pools, prestrainers and balance (rectangular boxes); tanks, trommels and compressors (tubes).
- When technical documents indicated precise dimensions, we were able to calculate the weight of the external structure, considering its thickness and its material composition. This was the case for the cyclones.
- When technical document indicated the weight of the equipment but not its material composition, we estimated the percentage of each material in the machine with the help of a chief engineer and we deduced its weight. This was the case for: presses, energy transformer, fishmeal purifier, preliminary fish driers, centrifuges and separators.

All uncertainty factors were assessed, according to the data source and the computation method (see below).

In order to allocate the construction of the plant to our functional unit (1t of fishmeal leaving the plant), we considered thanks to historical data on the fishing season (Fréon *et al.*, 2008) that in average the production took place 700 hours a year for 30 years with a mean production yield of 70 t/h in Plant 1, and 1,400 hours a year for 30 years with a mean production yield of 100 t/h in Plant 2.

5.2 Use data

After data collection, we built 7 categories related to use: fuel production and consumption, chemicals production inputs, chemicals laboratory inputs, electricity, emissions to air, emissions to sea and waste.

- *Fuel production and consumption.* We had to convert fuel US gallons and natural gas cubic meters into Mega Joules in order to use the ecoinvent database. Moreover, we modified dryers and boilers' air emissions (CO, NOx, SO2, particulates…) in the combustion data (heavy fuel oil) according to local bibliography (Alva Aliaga 2007).
- *Other production inputs and electricity*. No pre-processing was needed, as the units used were already SimaPro-compatible.

- *Emissions to air*. Those emissions are already taken into account in the process "fuel production and consumption", which is the unique source of gas emissions.
- *Emissions to sea*. Average concentration of particulates and residual oils in emissions to sea was deduced from monthly data.
- *Waste*. No pre-processing needed.

5.3 Maintenance data

We analysed Plant 1's and Plant 2's annual maintenance reports using to a dynamic table in Excel. From a 5 000-line file, we produced a list of the 10 major maintenance inputs in quality and quantity.

5.4 Specificities of data pre-processing in Plant 2

As it was not possible to approximate Plant 2's equipment global weight from Plant 1 data in a simple way, we had to find the weight of Plant 2's major equipment. When not available, we estimated it from their dimensions and the weight of Plant 1's corresponding equipment, as detailed below.

- *Equipment whose weight was found in technical documents.* This was the case for dryers, boilers, cookers, presses, preliminary fish driers, centrifuges and separators. Then we considered that the chemical composition of the machines was the same as in Plant 1 and therefore for each material we applied the same percentage.
- *Equipment whose weight was calculated from dimensions.* This was the case for fuel and fish oil tanks.
- *Motors and pumps.* We used the same linear regression as for Plant 1 motors (see Fig. 4.)
- *Helicoid conveyers.* As their exact weight was calculated from technical data in Plant 1, we were able to design a linear regression and apply it to Plant 2 helicoid conveyers.

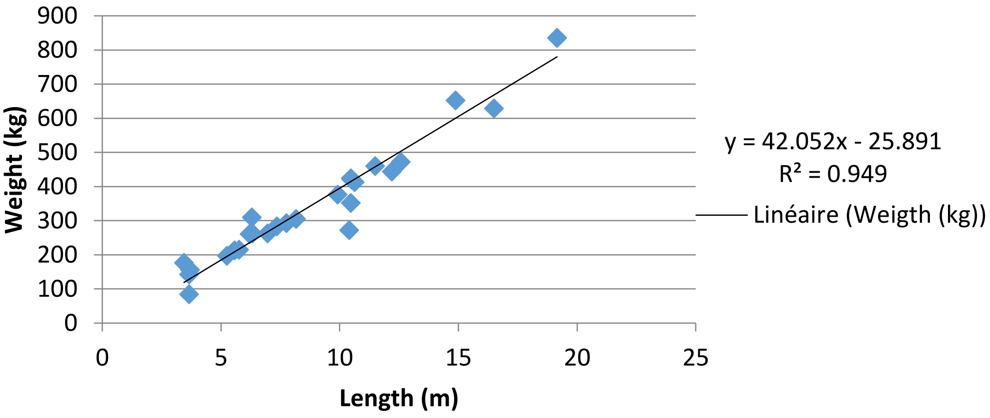

Figure 5-B. Estimate of helicoid conveyers' weight

6 Limits of data collection and processing

Although the inventory was quite complete, we had to face a certain number of difficulties.

6.1 Incomplete or imprecise technical information

Since very few studies have been carried on about fishmeal factories, we had to collect all the technical information by ourselves. Reading the technical manuals did not always provide us with the information we were looking for (e.g. weight and chemical composition of each piece of equipment). Questioning chief engineers and workers was often very instructive, because some of them knew very well the equipment and provided us with additional data, and some others told us the historical changes made in the factory. Uncertainty on estimated values was noted (usually a range) as follows and in some cases implemented in SimaPro.

6.2 *Uncertainty factors on data collection and pre-processing*

According to the data source or the calculation method, we assessed uncertainty factors on data collection and data processing as shown below.

Table 6-A. Uncertainty factors on data collection and pre-processing

		Source		**Uncertainty factor**
Data collection	At plant	Technical manuals		0%
		Engineers and workers		± 15%
		Annual reports and studies		± 1%
	Others	Peruvian energy department		± 1%
		Calculation method		**Uncertainty factor**
Data processing – Construction		Motors		±15%
		Rectangular box		± 20%
		Tube		± 15%
		Calculation with exact dimensions from technical data		± 10%
		Calculation with exact weight and percentage of each material		± 10%
		Additional uncertainty on equipment weight in Plant 2 due to approximation from Plant 1 equipment		± 10%
		Category	**Source/Calculation method**	**Uncertainty factor**
Data processing – Use		Fuel equivalence in MJ	SimaPro	± 10%
		Emissions to sea	SGS studies	± 5%
		Emissions to air (dryers)	Inspectorate Services Peru S.A.C., 2009	± 15%
		Emissions to air (boilers)	Alva-Aliaga, 2007	± 15%
		Object		**Uncertainty factor**
Data processing – Maintenance		Selection of major inputs (dynamic table in Excel)		+ 5%
Others		Total production time of the factory		± 20%

7 Electricity production in Peru

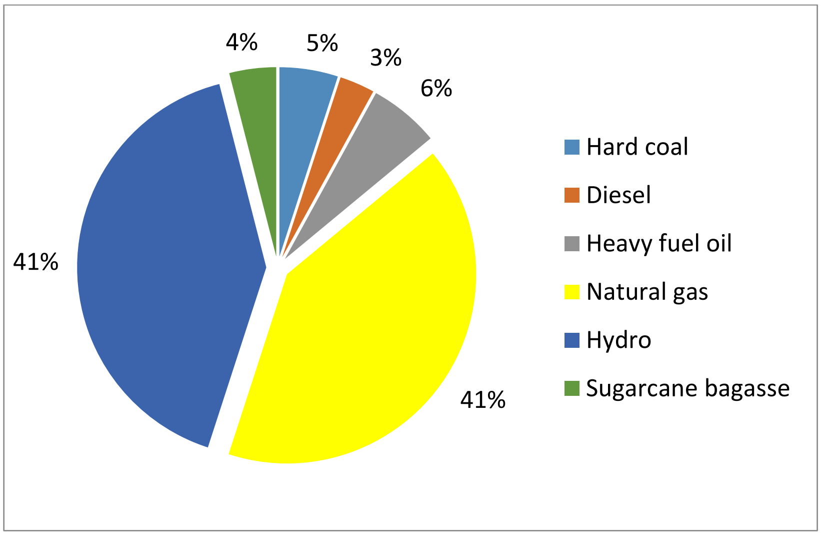

Figure 7-A. Peruvian electricity mix in 2009. Source: Peruvian Ministry of Energy and Mines.

8 Additional results of LCIA

8.1 Process-based FUs

8.1.1 Plant 2 (natural gas, Prime fishmeal)

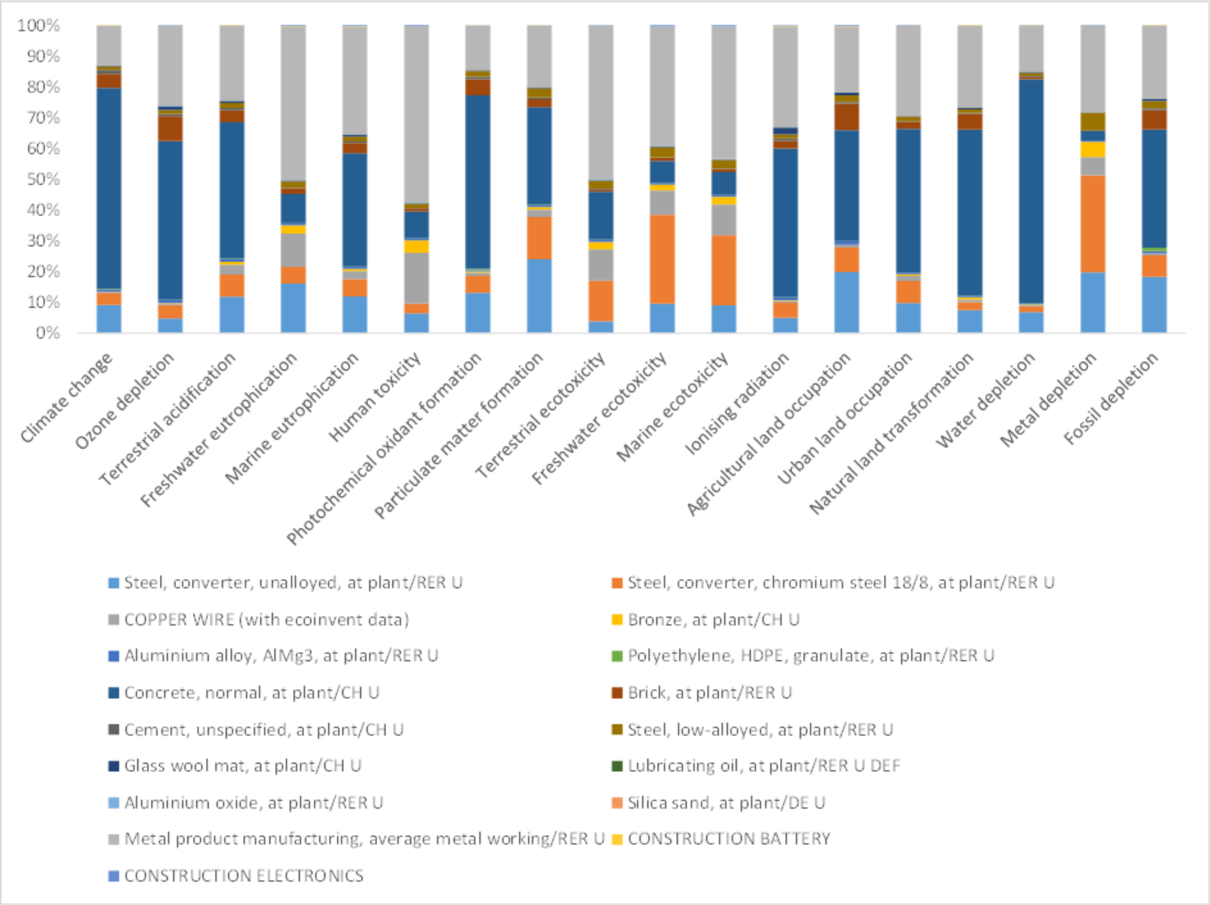

Figure 8-A. Fishmeal plant 2: construction phase midpoint environmental impacts using the ReCiPe method. The functional unit is the processing of one t of raw material. LCI items in upper case correspond to self-made systems or regroup different items.

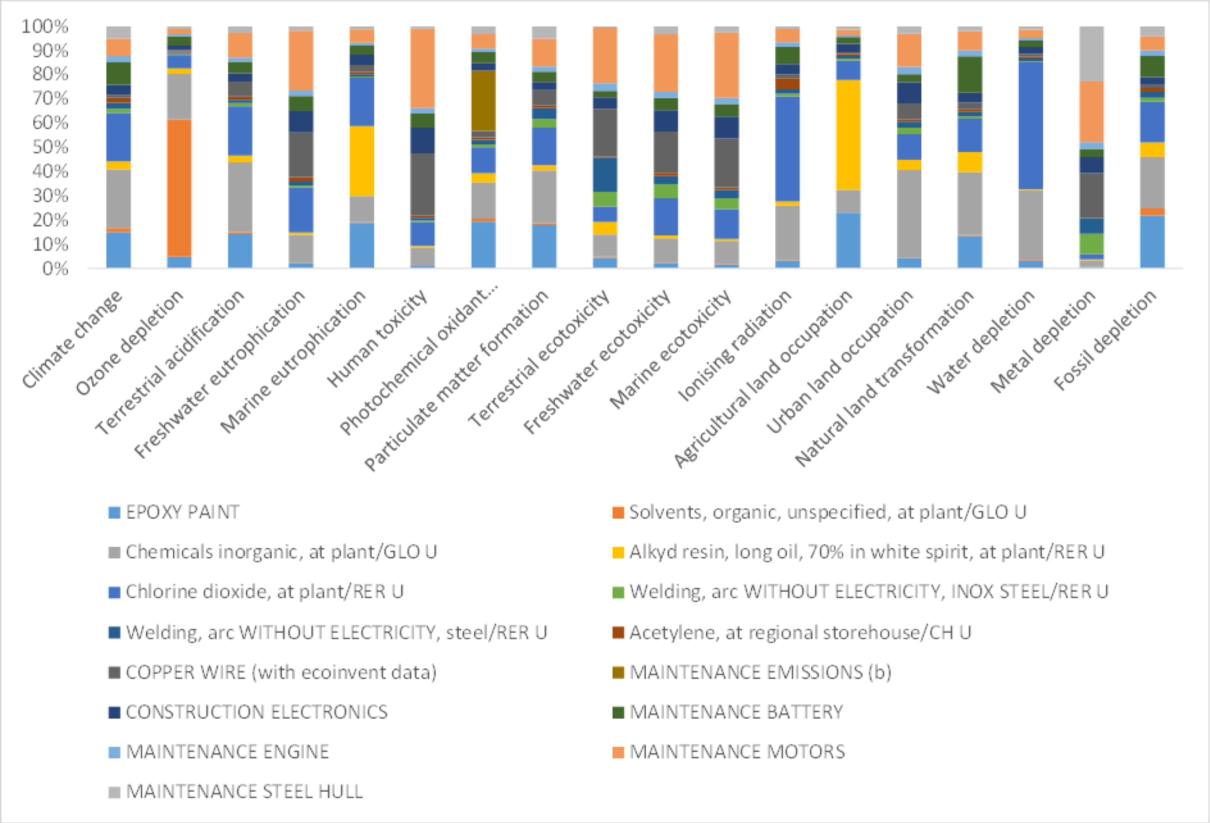

Figure 8-B. Fishmeal plant 2: maintenance phase midpoint environmental impacts using the ReCiPe method. The functional unit is the processing of one t of raw material. LCI items in upper case correspond to self-made systems or regroup different items.

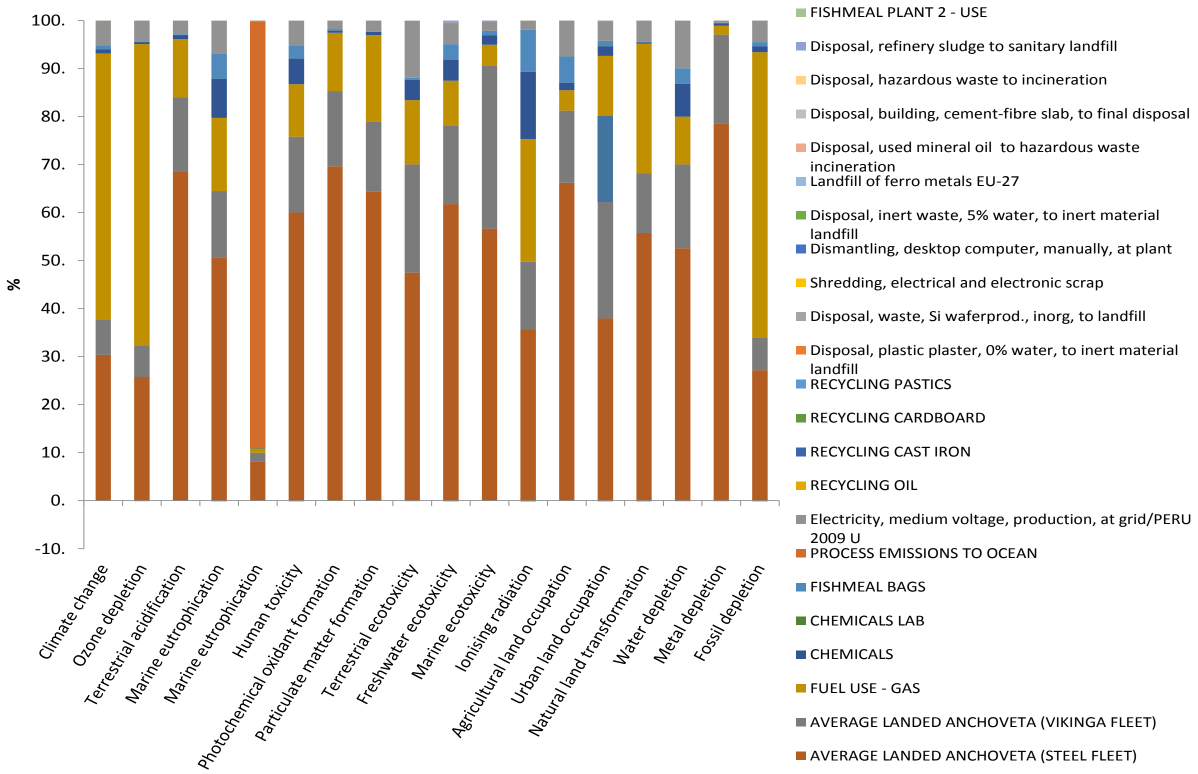

Figure 8-C. Fishmeal plant 2: use phase midpoint environmental impacts using the ReCiPe method. The functional unit is the delivery one t of prime fishmeal. LCI items in upper case correspond to self-made systems or regroup different items.

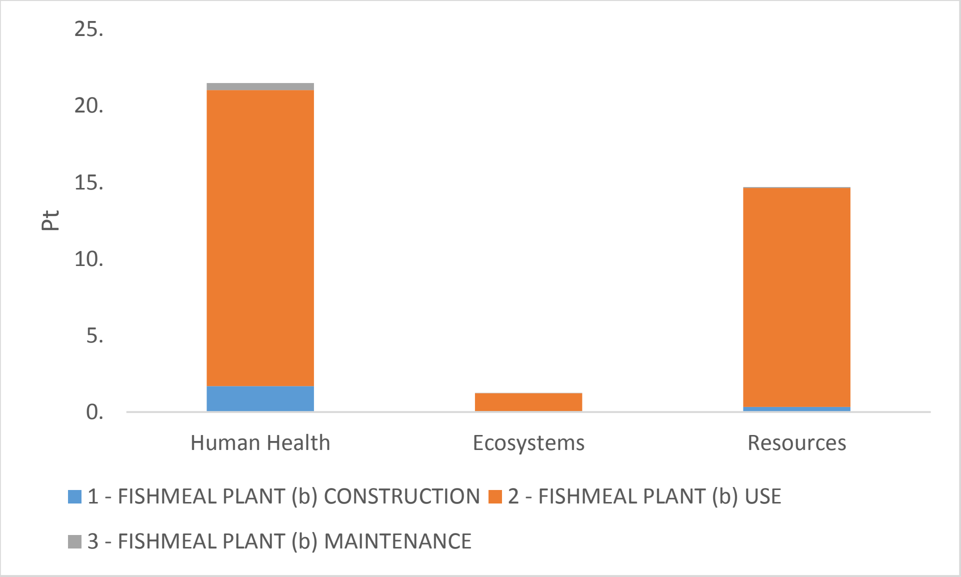

Figure 8-D. Fishmeal plant 2: LCA endpoint environmental impacts using the ReCiPe method. The functional unit is the 1 t of prime fishmeal.

8.1.2 Comparisons between fishmeal plants

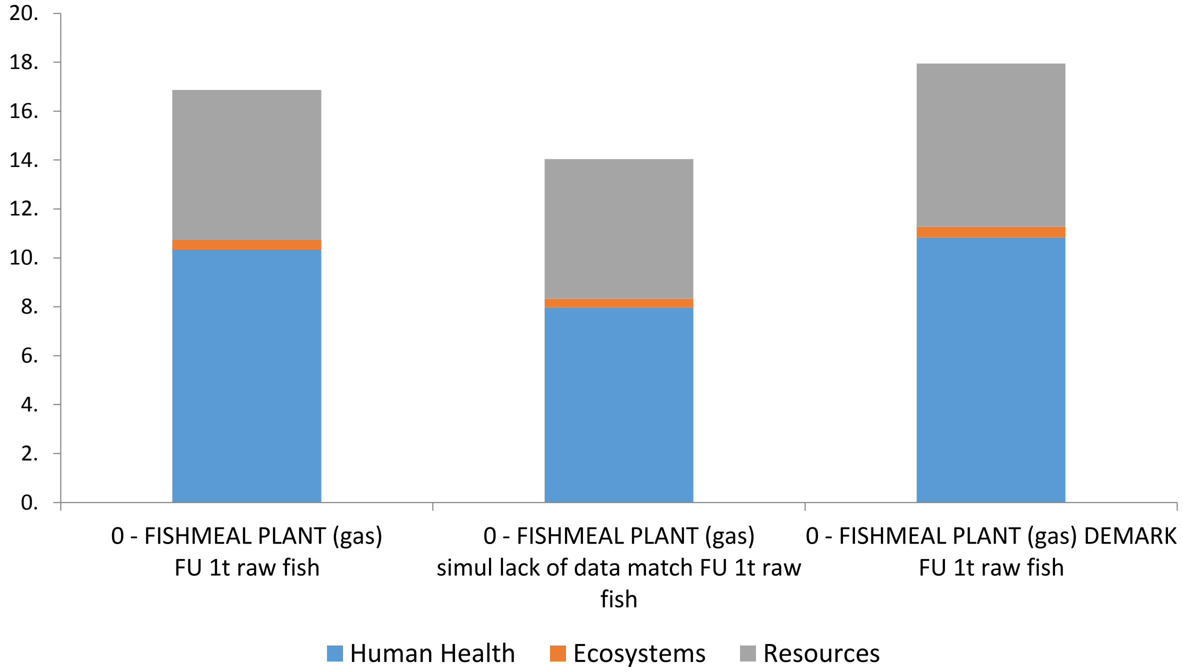

Figure 8-E. Comparison of LCA endpoint environmental impacts of the Danish fishmeal plant and Plant 2 (using our detailed LCI and simulating the lack of data as in the Danish plant) using the ReCiPe method. The functional unit is the processing of one t of raw material.

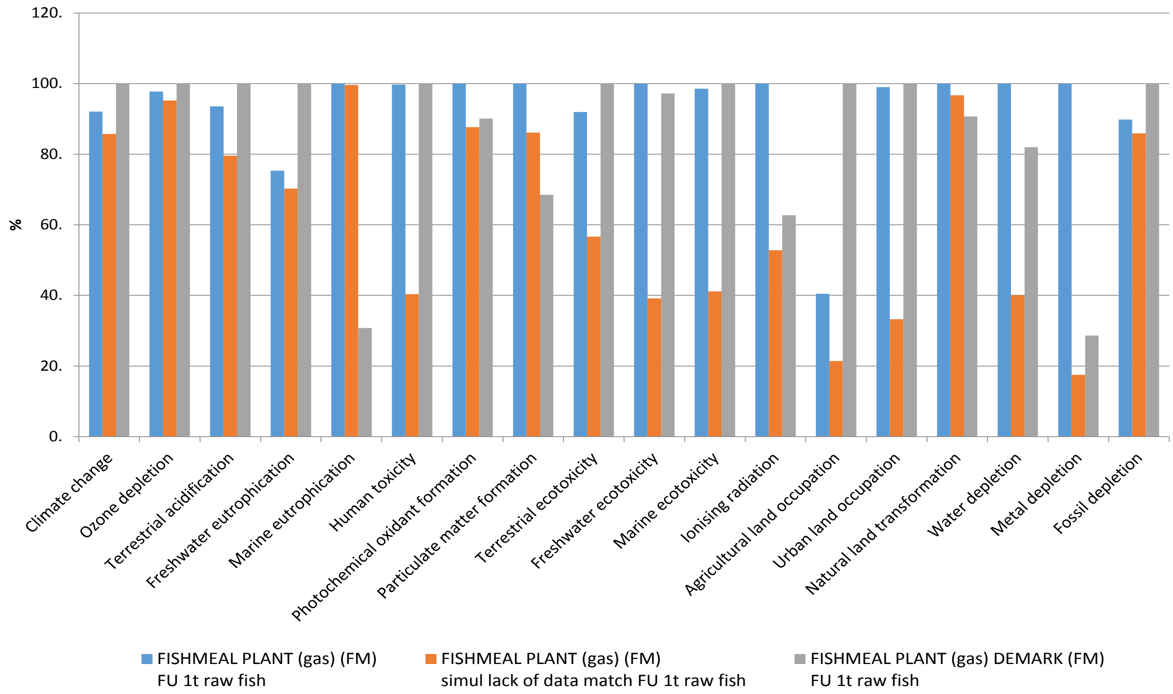

Figure 8-F. Comparison of LCA midpoint environmental impacts of the Danish fishmeal plant and Plant 2 (using our detailed LCI and simulating the lack of data as in the Danish plant) using the ReCiPe method. The functional unit is the processing of one t of raw material.

Table 8-A. Characterisation at the midpoint and single score levels of the impacts of the processing of 1 t of raw material for the construction phase with different main sources of energy and different size of plants. The ReCiPe method with the World egalitarian and average weighting was retained.

Impact category	**Unit**	**Plant 2 (Gas, Prime)**	**Plant 1 (Gas simul., FAQ)***	**Plant 1 (Heavy fuel, FAQ)**	**Plant 3 (Heavy fuel, residual)****
Climate change	kg CO2 eq	5,41E+00	3,44E+00	3,44E+00	4,44E+00
Ozone depletion	kg CFC-11 eq	2,35E-07	1,92E-07	1,92E-07	2,48E-07
Terrestrial acidification	kg SO2 eq	1,60E-02	1,57E-02	1,57E-02	2,03E-02
Freshwater eutrophication	kg P eq	1,98E-03	3,06E-03	3,06E-03	3,94E-03
Marine eutrophication	kg N eq	8,12E-04	8,86E-04	8,86E-04	1,14E-03
Human toxicity	kg 1,4-DB eq	1,05E+02	1,65E+02	1,65E+02	2,13E+02
Photochemical oxidant formation	kg NMVOC	1,35E-02	1,05E-02	1,05E-02	1,36E-02
Particulate matter formation	kg PM10 eq	8,00E-03	9,75E-03	9,75E-03	1,26E-02
Terrestrial ecotoxicity	kg 1,4-DB eq	5,60E-03	8,41E-03	8,41E-03	1,09E-02
Freshwater ecotoxicity	kg 1,4-DB eq	5,72E-02	9,65E-02	9,65E-02	1,24E-01
Marine ecotoxicity	kg 1,4-DB eq	8,52E+01	1,42E+02	1,42E+02	1,83E+02
Ionising radiation	kg U235 eq	8,29E-01	7,44E-01	7,44E-01	9,60E-01
Agricultural land occupation	m^{2}a	7,39E-02	7,89E-02	7,89E-02	1,02E-01
Urban land occupation	m^{2}a	4,72E-02	4,57E-02	4,57E-02	5,90E-02
Natural land transformation	m^2	7,54E-04	6,22E-04	6,22E-04	8,02E-04
Water depletion	m^3	6,98E-02	3,98E-02	3,98E-02	5,14E-02
Metal depletion	kg Fe eq	2,18E+00	3,90E+00	3,90E+00	5,03E+00
Fossil depletion	kg oil eq	8,71E-01	9,05E-01	9,05E-01	1,17E+00
Single score	Pt.	1,87E+00	2,55E+00	2,55E+00	3,29E+00

* Same LCI as for the original Plant 1 (using heavy fuel) because LCI changes from heavy fuel to gas are considered as negligible.

** Very rough estimation obtained by dividing by 5 the LCI equipment data of Plant 1 (but using specific production of this residual plant).

Table 8-B. Characterisation at the midpoint and single score levels of the impacts of the processing of 1 t of raw material for the use phase with different main sources of energy and different size of plants. The ReCiPe method with the World egalitarian and average weighting was retained.

Impact category	**Unit**	**Plant 2 (Gas, Prime)**	**Plant 1 (Gas simul., FAQ)***	**Plant 1 (Heavy fuel, FAQ)**	**Plant 3* (Heavy fuel, residual)****
Climate change	kg CO2 eq	1,12E+02	1,38E+02	1,84E+02	2,28E+02
Ozone depletion	kg CFC-11 eq	1,60E-05	1,97E-05	2,31E-05	2,88E-05
Terrestrial acidification	kg SO2 eq	1,37E-01	1,87E-01	4,73E+00	6,00E+00
Freshwater eutrophication	kg P eq	3,67E-03	4,70E-03	7,41E-03	8,66E-03
Marine eutrophication	kg N eq	3,95E-01	3,97E-01	4,21E-01	4,27E-01
Human toxicity	kg 1,4-DB eq	1,27E+02	1,84E+02	7,14E+02	8,79E+02
Photochemical oxidant formation	kg NMVOC	1,52E-01	2,15E-01	1,17E+00	1,43E+00
Particulate matter formation	kg PM10 eq	6,38E-02	5,59E-02	1,13E+00	1,49E+00
Terrestrial ecotoxicity	kg 1,4-DB eq	1,32E-02	2,45E-02	5,27E-01	6,72E-01
Freshwater ecotoxicity	kg 1,4-DB eq	6,96E-02	9,10E-02	4,23E-01	5,22E-01
Marine ecotoxicity	kg 1,4-DB eq	1,04E+02	1,38E+02	1,24E+03	1,56E+03
Ionising radiation	kg U235 eq	2,08E+00	2,46E+00	4,97E+00	5,89E+00
Agricultural land occupation	m^2a	3,51E-01	4,13E-01	4,41E-01	3,80E-01
Urban land occupation	m^2a	1,29E-01	9,50E-02	3,18E-01	3,83E-01
Natural land transformation	m^2	2,88E-02	3,64E-02	9,44E-02	1,16E-01
Water depletion	m^3	7,79E-02	5,50E-01	7,41E-01	6,05E-01
Metal depletion	kg Fe eq	5,76E-01	9,57E-01	9,59E-01	1,15E+00
Fossil depletion	kg oil eq	4,30E+01	5,26E+01	6,20E+01	7,69E+01
Single score	Pt.	1,45E+01	1,81E+01	3,32E+01	4,15E+01

*Screening

Table 8-C. Characterisation at the midpoint and single score levels of the impacts of the processing of 1 t of raw material for the maintenance phase with different main sources of energy and different size of plants. The ReCiPe method with the World egalitarian and average weighting was retained.

Impact category	**Unit**	**Plant 2 (Gas, Prime)**	**Plant 1 (Gas simul., FAQ)***	**Plant 1 (Heavy fuel, FAQ)**	**Plant 3 (Heavy fuel, residual)****
Climate change	kg CO2 eq	5,455E-01	8,707E-01	8,707E-01	4,310E-02
Ozone depletion	kg CFC-11 eq	1,217E-07	3,579E-07	3,579E-07	1,772E-08
Terrestrial acidification	kg SO2 eq	4,190E-03	5,651E-03	5,651E-03	2,797E-04
Freshwater eutrophication	kg P eq	5,721E-04	8,388E-04	8,388E-04	4,152E-05
Marine eutrophication	kg N eq	3,539E-04	6,825E-04	6,825E-04	3,378E-05
Human toxicity	kg 1,4-DB eq	3,294E+01	5,322E+01	5,322E+01	2,634E+00
Photochemical oxidant formation	kg NMVOC	2,805E-03	4,666E-03	4,666E-03	2,310E-04
Particulate matter formation	kg PM10 eq	1,470E-03	2,528E-03	2,528E-03	1,251E-04
Terrestrial ecotoxicity	kg 1,4-DB eq	1,412E-03	2,450E-03	2,450E-03	1,213E-04
Freshwater ecotoxicity	kg 1,4-DB eq	1,291E-02	2,113E-02	2,113E-02	1,046E-03
Marine ecotoxicity	kg 1,4-DB eq	2,063E+01	3,380E+01	3,380E+01	1,673E+00
Ionising radiation	kg U235 eq	1,837E-01	1,636E-01	1,636E-01	8,096E-03
Agricultural land occupation	m^2a	3,100E-02	7,529E-02	7,529E-02	3,727E-03
Urban land occupation	m^2a	5,768E-03	7,874E-03	7,874E-03	3,898E-04
Natural land transformation	m^2	1,079E-04	1,589E-04	1,589E-04	7,865E-06
Water depletion	m^3	1,342E-02	8,110E-03	8,110E-03	4,015E-04
Metal depletion	kg Fe eq	3,443E-01	1,069E+00	1,069E+00	5,289E-02
Fossil depletion	kg oil eq	1,821E-01	3,396E-01	3,396E-01	1,681E-02
Single score	Pt.	4,717E-01	7,982E-01	7,982E-01	3,95E-02

In order to investigate the effects of different intensities of use between Plant 1 (700 h per year) and Plant 2 (1 400 h per year), and also to investigate the effects of overcapacity in the sector, we compared the following three different intensities of use of Plant 1:

- Current intensity (700 h)
- Simulated intensity equal to the intensity of use of Plant 2 (1400 h)
- Simulated optimal intensity (3 000 h) which correspond to 150 working days at full time, that is 20h of processing and 4 of maintenance. The value of 150 working days takes into account the fishery closure during the two reproductive seasons and the spatial and temporal variability of the fishing activity around the area where the plant is located.

In our simulations, the above changes in intensity of use of Plant 1 affected only the construction phase. The likely effect on the maintenance and use phases, although certainly lower than those affecting the construction phase, are too uncertain (for instance a lower intensity of use may result in the decrease of some items of the LCI per FU, but increase some other items). The three LCIA results of Plant 1 were compared to the LCIA result of Plant 2 under current intensity (1400 h) and optimal intensity (3 000 h), using the process-based FU.

The results show a slightly decrease in the ReCiPe single score value of Plant 1 (36.5 to 34.6 points) when increasing its intensity of use from 700 h per year to 3 000 h (Fig. 8-G). Nonetheless and as expected, the decrease in the impact category "metal depletion" was substantial when expressed in relative value (51%), but low in absolute (0.35 to 0.17 points; Fig. 8-H).

The large differences initially observed between Plant 1 and Plant 2 LCIAs still holds when using the same intensity of use (1400 h) for both plants (35.3 vs 16.9 points, respectively). Similarly to what was found for Plant 1, the increase of its intensity of use from 1400 h to 3 000 h result in a low decrease of the ReCiPe single score (Fig. 8-G), but a substantial one in the impact category "metal depletion" and, to a lower extent, "natural land transformation" (Fig. 8-H).

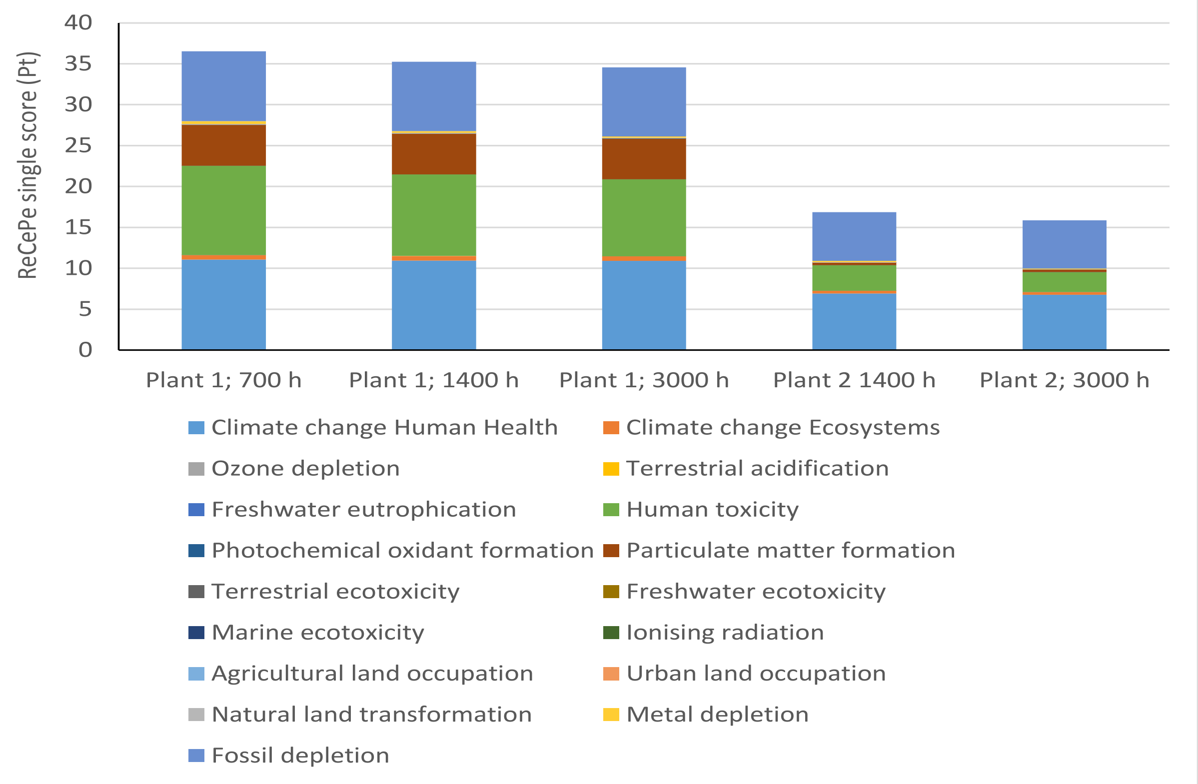

Figure 8-G. Effect on LCA endpoint environmental impacts using the ReCiPe method of different intensity of use of Plant 1 (700, 1400 and 3 000 h per year) and comparison with Plant 2 (1400 h and 3 000 h per year). The functional unit is the 1 t of prime fishmeal. The effect is limited to the construction phase.

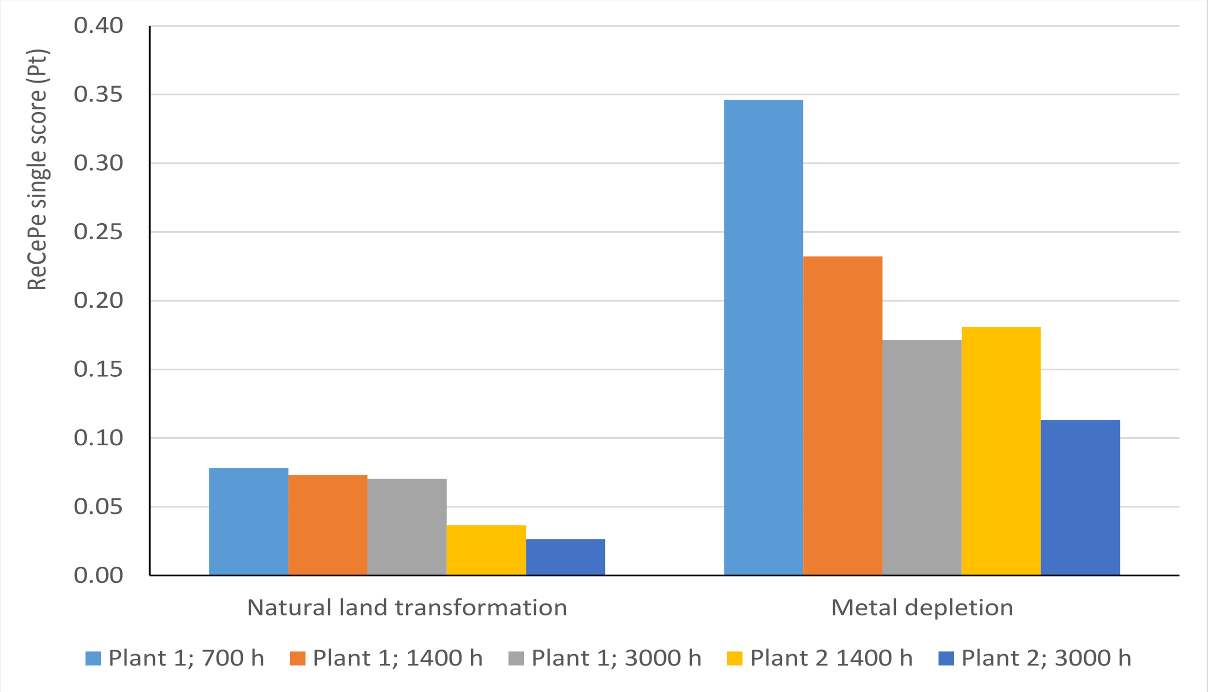

Figure 8-H. Effect on the LCA endpoint environmental impacts of two selected impact categories using the ReCiPe method of different intensity of use of Plant 1 (700, 1400 and 3 000 h per year) and comparison with Plant 2 (1400 h and 3 000 h per year). The two impact categories have been selected for their large (>25%) differences in impacts of Plant 2 according to its intensity of use, despite low contribution to the single score. The functional unit is the 1 t of prime fishmeal. The effect is limited to the construction phase.

8.2 Output-based FUs

Table 8-D. Characterisation at the midpoint and single score levels of the life cycle impacts of the production of 1 t of fish oil of different categories with different main sources of energy and different size of plants. The ReCiPe method with the World egalitarian and average weighting was retained.

Impact category	**Unit**	**Plant 2 (Gas, Prime)**	**Plant 1 (Gas simul., FAQ)**	**Plant 1 (Heavy fuel, FAQ)**	**Plant 3 (Heavy fuel, residual)**
Climate change	kg CO2 eq	2,71E+03	3,07E+03	3,73E+03	5,87E+03
Ozone depletion	kg CFC-11 eq	3,52E-04	4,08E-04	4,57E-04	7,40E-04
Terrestrial acidification	kg SO2 eq	1,28E+01	1,35E+01	7,97E+01	1,22E+02
Freshwater eutrophication	kg P eq	1,88E-01	2,23E-01	2,62E-01	3,89E-01
Marine eutrophication	kg N eq	6,41E+00	6,45E+00	6,80E+00	8,40E+00
Human toxicity	kg 1,4-DB eq	9,68E+03	1,17E+04	1,94E+04	2,94E+04
Photochemical oxidant formation	kg NMVOC	1,54E+01	1,63E+01	3,02E+01	5,00E+01
Particulate matter formation	kg PM10 eq	4,56E+00	4,49E+00	2,02E+01	3,21E+01
Terrestrial ecotoxicity	kg 1,4-DB eq	7,47E-01	9,67E-01	8,30E+00	1,28E+01
Freshwater ecotoxicity	kg 1,4-DB eq	5,69E+00	6,70E+00	1,15E+01	1,70E+01
Marine ecotoxicity	kg 1,4-DB eq	1,79E+04	1,94E+04	3,55E+04	6,99E+04
Ionising radiation	kg U235 eq	7,53E+01	7,93E+01	1,16E+02	1,93E+02
Agricultural land occupation	m^2a	2,89E+01	3,05E+01	3,09E+01	5,20E+01
Urban land occupation	m^2a	5,77E+00	5,28E+00	8,53E+00	1,73E+01
Natural land transformation	m^2	1,33E+00	1,44E+00	2,29E+00	3,77E+00
Water depletion	m^3	5,01E+00	1,14E+01	1,42E+01	1,60E+01
Metal depletion	kg Fe eq	3,31E+02	3,73E+02	3,73E+02	3,86E+02
Fossil depletion	kg oil eq	9,67E+02	1,11E+03	1,25E+03	1,97E+03
Single Score	Pt.	451,921	518,952	738,698	1141,031

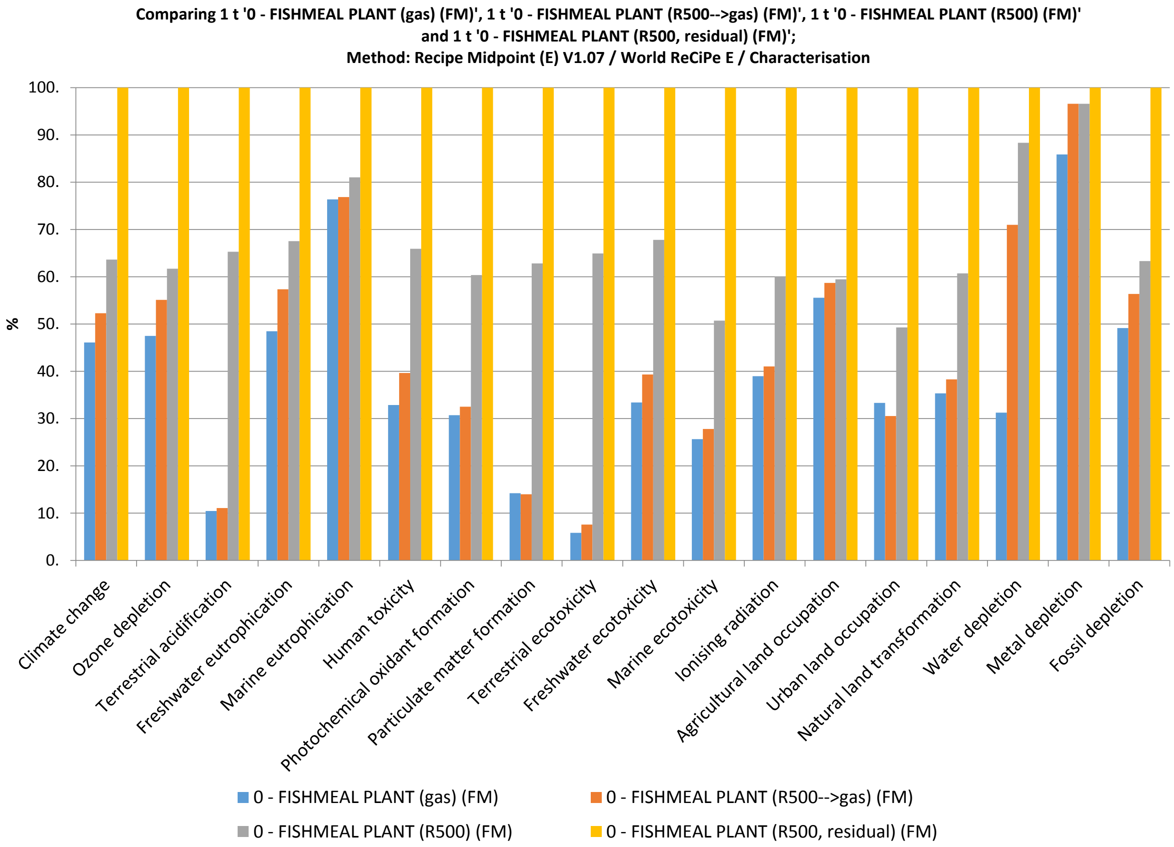

Figure 8-I. Comparison of midpoint environmental impacts of the fishmeal produced by Plants 1, 2 and 3 using the ReCiPe method. The functional unit are the delivery one t of FAQ fishmeal for Plant 1, one t of Prime fishmeal for Plant 2, and on t of residual fishmeal for Plant 3. Plant 1 simulation with use of natural gas instead of heavy fuel is also displayed.

9 Simple arithmetic related to characterisation conversion factors

Let us use the following notations related to characterisation and allocation:

- CF_alloc$_n$ stands for any characterisation factor (at the midpoint, endpoint or single score) of 1 t of fishmeal or fish oil using fishmeal or fish oil allocation n (GEC allocation, economic value allocation or mass allocation)
- CF_alloc$_{n'}$ same as above for a n' allocation different from n
- CF_FM_allocFm$_n$ stands for any characterisation factor (at the midpoint, endpoint or single score) of 1 t of fishmeal using allocation number n
- CF_FO_allocFo$_n$ same above for fish oil
- Alloc$_n$ stands for the allocation factor n of environmental impact to fishmeal or fish oil
- Alloc$_{n'}$ same as above for a different allocation factor n'.
- AllocFm$_n$ stands for the allocation factor of environmental impact to fishmeal.
- AllocFo$_n$ same as above for fish oil. Because there are only two coproducts, the allocation factor devoted to fish oil is always equal to 1 – AllocFm$_n$.
- ProdRateFm stands for fishmeal production rate
- ProdRateFo stands for fish oil production rate

9.1 *From fishmeal characterisation to fish oil characterisation and vice versa*

$$\text{CF\_FO\_allocFm}_n = (\text{CF\_FM\_alloc}_n / \text{AllocFm}_n / \text{ProdRateFm}) * \text{AllocFo}_n * \text{ProdRateFo} \quad (1)$$

$$\text{CF\_FM\_allocFm}_n = (\text{CF\_FO\_alloc}_n / \text{AllocFo}_n / \text{ProdRateFo}) * \text{AllocFm}_n * \text{ProdRateFm} \quad (2)$$

For example, knowing that the ReCiPe single score of 1 t of prime fishmeal produced by Plant 2 is equal to 37.4 when using a GEC allocation factor equal to 0.34 for fishmeal and a fishmeal production rate of 4.21 one can calculate the single score of 1 t of fish oil produced by the same plant with a production rate of 22.16 (4.21/0.19 according to Table 3 of the main body of this paper), by using eq. (1):

$CF\_FO\_allocFm_n = (37.4 / 0.34 / 4.21) * 0.66 * 22.16 = 382$ Pt.

and inversely using eq. (2):

$CF\_FM\_allocFm_n = (382 / 0.66 / 22.16) * 0.34 * 4.21 = 37.4$ Pt.

9.2 *From one type of allocation to another*

$$CF\_alloc_{n'} = CF\_alloc_n / Alloc_n * Alloc_{n'} \quad (3)$$

For example, knowing that the ReCiPe single score of 1 t of prime fishmeal produced by Plant 2 is equal to 37.4 when using a GEC allocation factor equal to 0.34 for fishmeal one can calculate the same single score for a mass allocation factor of 0.84, by using eq. (3):

$$CF\_FM\_allocFmn' = 37.43 / 0.34 * 0.84 = 92.47 \text{ Pt.}$$

Using the same equation one can obtain the ReCiPe single score of 1 t of prime fishmeal produced by Plant 2 using an economic value allocation factor of 0.50 and obtain:

$$CF\_FM\_allocFmn' = 37.43 / 0.34 * 0.50 = 55.04 \text{ Pt.}$$

The above results show the high sensitivity of the characterisation factors that varies from 37.43 to 92.47 Pt., that is 2.5 folds between the two extremes.

10 Using the Peruvian results as proxies for other countries

Here we present the steps that a practitioner should follow for combining our process_based FUs to his/her own fishery characterisation factors in order to obtain an output_based FUs. If necessary, the average use of the fishmeal plant along its life cycle can be modified. This is likely to be necessary due to the overcapacity of the Peruvian fishmeal plants. Let us use the following notations, in addition to part of the notations presented in the above section:

- CF_Process_LC stands for any characterisation factor (at the midpoint, endpoint or single score) of the processing of 1 t of raw material along the life cycle of the plant, excluding its end of life (EOL) phase.
- CF_Process_Construc., same as above but only for the construction phase.
- CF_Process_Use, same as above but only for the use phase.
- CF_Process_Maint., same as above but only for the maintenance phase.
- CF_Output_LC stands for any characterisation factor (at the midpoint, endpoint or single score) of 1 t fishmeal or fish oil using any fishmeal or fish oil allocation, along the life cycle of the commodity, including the fishing impacts but excluding the EOL of the plant.
- CF_Fishery_LC stands for the characterisation factor (at the midpoint, endpoint or single score) or the capture and delivery at the fishmeal plant terminal of 1 t of raw material.
- Proc.Yield stands for the effective average processing yield per working hours (t/h, taking into account daily maintenance and other delays)
- Hours stands for the average annual working hours (h/y)
- Years stands for the expected lifespan of the plant (y)
- LC_t stands for the total number of t of raw material processed along the life cycle of the fishmeal plant.
- Rescal.Fac stands for an empirical rescaling factor using to correct the difference in size between the Peruvian plant and the foreign plant. It should reflect the economies of scale related to the size of the plant. Therefore foreign plants larger than the Peruvian ones should

benefit from a rescaling factor < 1 in order to minimize the characterisation factors, and vice versa.

- ProdRate stands for fishmeal or fish oil production rate.
- Index letter $_P$ added at the end of any of the above notations is used to indicate any of the Peruvian plant.
- Index letter $_F$, same as above for any equivalent foreign plant.

The following set of equations can be applied to any of the three categories of Peruvian plants (and if necessary also to our very realistic simulation of Plant 1 using natural gas) in order to approximate characterisation factor of fishmeal or fish oil of any foreign plant of the same category:

$$LCt_P = Proc.Yield_P * Hours_P * Years_P \tag{4}$$

LCt_F can be computed as above ($Proc.Yield_P * Hours_P * Years_P$) or in different ways.

$$CF\_Process\_Construc._F = CF\_Process\_Construc._P * (LCt_P / LCt_F) * Rescal.Fact \tag{5}$$
$$CF\_Process\_Use_F = CF\_Process\_Use_P \tag{6}$$
$$CF\_Process\_Maint._F = CF\_Process\_Maint._P * Rescal.Fact \tag{7}$$
$$CF\_Process\_LC_F = CF\_Process\_Construc._F + CF\_Process\_Use_F + CF\_Process\_Maint._F \tag{8}$$
$$CF\_Output\_LC_F = (CF\_Process\_LC_F + CF\_Fishery\_LC_F) * ProdRate_F * AllocFm_n \tag{9}$$

Obviously the allocation factors of the elected coproduct should be the same in eq. (9). If necessary different allocation can be applied to the final results using eq. (3).

Let us take as an example a virtual foreign plant with characteristics similar to those of Plant 2 (large plant using natural gas as its main source of energy and producing prime fishmeal). Let us suppose that this plant would have an effective average processing yield of 80 t per working hours (whereas the Peruvian one is 100 t for Plant 2), would work two times more hours per year than Plant 2 (2 800 h instead of 1 400) and would have a lifespan of 25 years instead of 30). This virtual plant would process the following number of t of raw material along its life cycle, according to eq. (4):

$$LCt_F = 80 * 2\,800 * 25 = 5.6 \text{ million t},$$

instead of 4.2 million t for the Plant 2. Considering that the two plants are not too much different in size, the rescaling factor can be approximated by 1.1. Therefore, using eq. (5) the characterisation factor of the construction phase of the foreign plant, expressed in single score of ReCiPe for the processing of 1 t of raw material, can be approximated as follows from the initial value (1.481 Pt.) of Plant 2:

$$CF\_Process\_Construc._F = 1.481 * (4.2 / 5.6) * 1.1 = 1.222 \text{ Pt.}$$

Equation 6 shows that the characterisation factor of the use phase of a foreign plant can be approximated directly by the equivalent value of the Peruvian plant. This is because here, in contrast to the construction phase, no substantial economies of scale are expected. Therefore, using the initial value of 12.54 Pt.for the single score of ReCiPe of the use phase of Plant 2 for the processing of 1 t of raw material, one can approximate the characterisation factor of this phase for the foreign plant as by:

$$CF\_Process\_Use_F = 12.54 \text{ Pt.}$$

Because the maintenance phase can benefit from the economies of scale, Eq. 7 makes use of a rescaling factor that can be the same as the one used for the construction phase. Therefore the characterisation factor of the maintenance phase of the foreign plant, expressed in single score of ReCiPe for the processing of 1 t of raw material, can be approximated as follows from the initial value (0.3665 Pt.) of Plant 2:

$$CF\_Process\_Maint._F = 0.3665 * 1.1 = 0.4032 \text{ Pt.}$$

At the end, the characterisation factor of the processing of 1 t of raw material along the life cycle of the plant, excluding its EOL phase for the foreign plant exemplified above can be approximated using eq. 8 as follows:

$$CF\_Process\_LC_F = 1.222 + 12.54 + 0.4032 = 14.17 \text{ Pt.}$$

Let us now approximate the characterisation factor at the single score level of 1 t fishmeal of the same foreign plant as above along the life cycle of the commodity, that is including the fishing impacts (but again excluding its EOL phase). This can be done as follows using eq. (9), the value of the fishmeal production rate of the foreign plant (let say 4.50), the fishmeal allocation factor retained for all the above computations (let say 0.34) and the characterisation factor or the capture and delivery at the fishmeal plant terminal of 1 t of raw material (let say 20 Pt. instead of ~14 Pt. for the Peruvian fishery, in order to take into account the fact that the latest is the most fuel efficient worldwide;):

$$CF\_Output\_LC_F = (14.7 + 20) * 4.50 * 0.34 = 53.09 \text{ Pt.}$$

Figure 10-A presents the results of the ReCiPe single score of FM and FO according to three allocation criteria and two accounting periods.

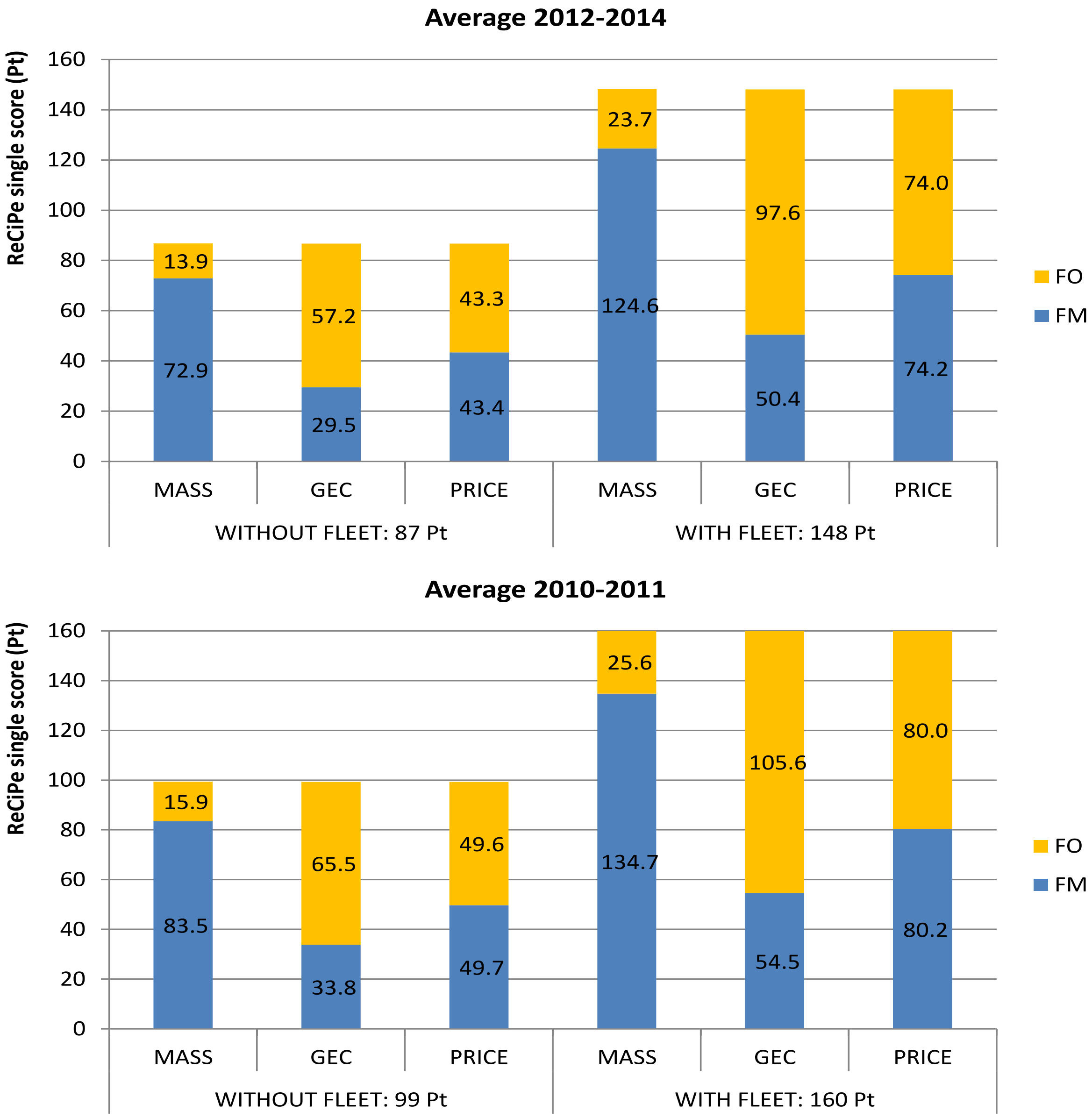

Figure 10-A. ReCiPe single score of FM and FO according to three allocations for two different periods.

11 Direct measurement of the environmental impact

11.1 Wastewater from fish meal plants

Table 11-A. Total suspended solids emitted by Plant 1 in 2009 for the production of 11 897 t of fishmeal.

Type of effluent	Mean concentration (g/t)	Total emissions (t)	Emissions per t of fishmeal (kg)
Pumping water from terminal	5,126	335	28,170
Other emissions	177.5	11.6	98
Total	**-**	**347**	**29**

Table 11-B. Total suspended solids emitted by Plant 2 in 2009 for the production of 37 093 t of fishmeal.

Type of effluent	Mean concentration (g/t)	Total emissions (t)	Emissions per t of fishmeal (kg)
Pumping water from terminal	5,070	552	14.9
Other emissions	237	25.8	0.7
Total	**-**	**578**	**15.6**

11.2 Airborne emissions from fish meal plants

Specific entries of emissions to air (stratosphere) were created in SimaPro to take into account differences between measured emissions (Tables 11-C and 11-D) and ecoinvent data regarding CO and particles emissions, avoiding double counting. In contrast to CO, SO_2 was not found during the monitoring of exhaust chimneys of the cyclones attached to the dryers in Plant 1 (no data available for Plants 2 and 3) but default values from ecoinvent were retained.

Table 11-C. Airborne emissions of the direct-fire drying drier of Plant 1 as measured at the exhaust of its cyclone for a total volume of 25 066 300 m3 in 2009.

Material emitted	Concentration (mg/m^3)	Total emission (kg)	Emission per MJ (g/MJ)	Ecoinvent emissions (g/MJ)
Particulate matter	349	8748	0,452	0,05
Carbon monoxide	109	2732	0,141	0,007
Nitrogen oxides	44	1103	0,057	0,1
Sulfur dioxide	0	0	0	0,4

Table 11-D. Airborne emissions of a boiler in a Peruvian plant of 150 t/h of processing capacity (anonymous) as measured at its exhaust chimney (source: Alva Aliaga, 2007) compared with ecoinvent data.

Emissions to air - Boilers CHANCAY (PETROLEO). Base year 2009					
Source	Alva Aliaga (2007) Fishmeal plant with a processing capacity of 150 t/h			ecoinvent Heavy Fuel Oil (HFO) in Industrial Furnace	Ecoinvent HFO in boiler
Item/ unit	kg/h	kg in 2009[a]	kg per MJ used [b]	kg per MJ	kg per MJ
SO2	264.67	183,893	3.222E-3	4E-4	4.684E-5
SO3	3.37	2,341	4.103E-05	0	0
NO2	30.91	2,1476	3.763E-4	1E-4	2.75E-5
CO	2.81	1,952	3.421E-05	7E-6	7.5E-6

PM[c]	5.62	3,905	6.842E-05	3.5E-5	5E-7

[a] *694.8 working hours in 2009 (reference year)*
[b] *57,071,515 MJ in boilers in 2009*
[c] <2.5 microns

11.3 Peruvian legal maximum limits regarding the waterborne emissions of suspended solids and oil

According to the Supreme Decree N°10-2008-PRODUCE emitted by the Peruvian Ministry of Production, the legal maximum limits regarding the waterborne emissions of fishmeal plants (all types) are those presented in Table 11-E.

Table 11-E. Legal maximum limits (LMLs) regarding the waterborne emissions of fishmeal plants (all types) emitted inside and outside the littoral protected area.

Parameter	Unit	LMLs inside the littoral protected area from 2012	LMLs outside the littoral protected area from 2012	LMLs outside the littoral protected area from 2014
Oil and grease	(mg/L)	20	1,500	350
Suspended solids	(mg/L)	100	2,500	700
pH	-	6-9	5-9	5-9
DBO_5	(mg/L)	≤60	*	*

* to be defined later on.

11.4 Peruvian national standards of environmental quality of superficial sea water

According to the Supreme Decree N°15-2015-MINAM emitted by the Peruvian Ministry of Environment, the national standards of environmental quality of superficial sea water are those presented in Table 11-F.

Table 11-F. National standards of environmental quality of superficial sea water (selection of relevant items directly related to this work).

Parameter	Unit	Category and sub-category of marine waters			
		Category 2: Extraction, cultivation & other activities			Category 4: Conservation areas
		Extraction and aquaculture of mollusks (C1)	Extraction and aquaculture of other species (C2)	Other activities (C3)	Marine (E3)
Oil and grease	(mg/L)	1.0	1.0	2.0	5.0
Suspended solids	(mg/L)	80	60	70	30
BDO_5	(mg/L)	**	10	10	10
Thermotolerant (44.5°C) coliforms	MPN*/ 100 ml	≤30	1000	200	2000

* Most probable number ** No value available

11.5 Peruvian legal maximum limits regarding the airborne emissions of fishmeal plants

According to the Supreme Decree N°11-2009 MINAM emitted by the Peruvian Ministry of Environment, the legal maximum limits regarding the atmospheric emissions of fishmeal plants (all types) are those presented in Table 11-G. Because the measurement protocol of those emissions was emitted only in August 2010 (Ministerial Resolution-194-2010-PRODUCE), these emissions monitoring was not implemented at the time of our study.

Table 11-G. Legal maximum limits regarding the airborne emissions of fishmeal plants (all types).

Contaminant	**Maximum concentration (mg/m^3)**
Hydrogen sulfur, sulfurs	5
Particular matters	150

11.6 Changes in physicochemical parameters in the Chancay bay during fishing seasons

Sea water sample collection occurred in the bay of Chancay, where there is a concentration of 6 fishmeal plants. Eight sampling points were defined within the bay, and four along the shore (Fig. 10 in the paper itself), following the protocol define in the Ministerial Resolution N° 003-2002-PE issued by the Peruvian Ministry of Production[5]. The following methods were used for the measurements of physical-chemical parameters:

- Total suspended solids: standard method 2540D. APHA-AWWA-WEF (2005)
- Oil and grease: standard method 5520B. APHA-AWWA-WEF (2005)
- Biological oxygen demand (BOD_5): Standard International ISO 5815 (1991).
- Quantification of the coliform bacteria using the multiple-tube fermentation (MTF) technique: APHA (2005)

The results show that the legal maximum limits (LML) of total suspended solids was slightly overpassed only once (out of four) fishing seasons whereas the BOD limit was largely overpassed during all four fishing season (and during one of the closure period, which is likely due to a remanent effect). The oil and grease concentrations also largely overpassed the LML values during three fishing seasons out of four whereas the total coliforms values were always largely over the LML values except during one closure period.

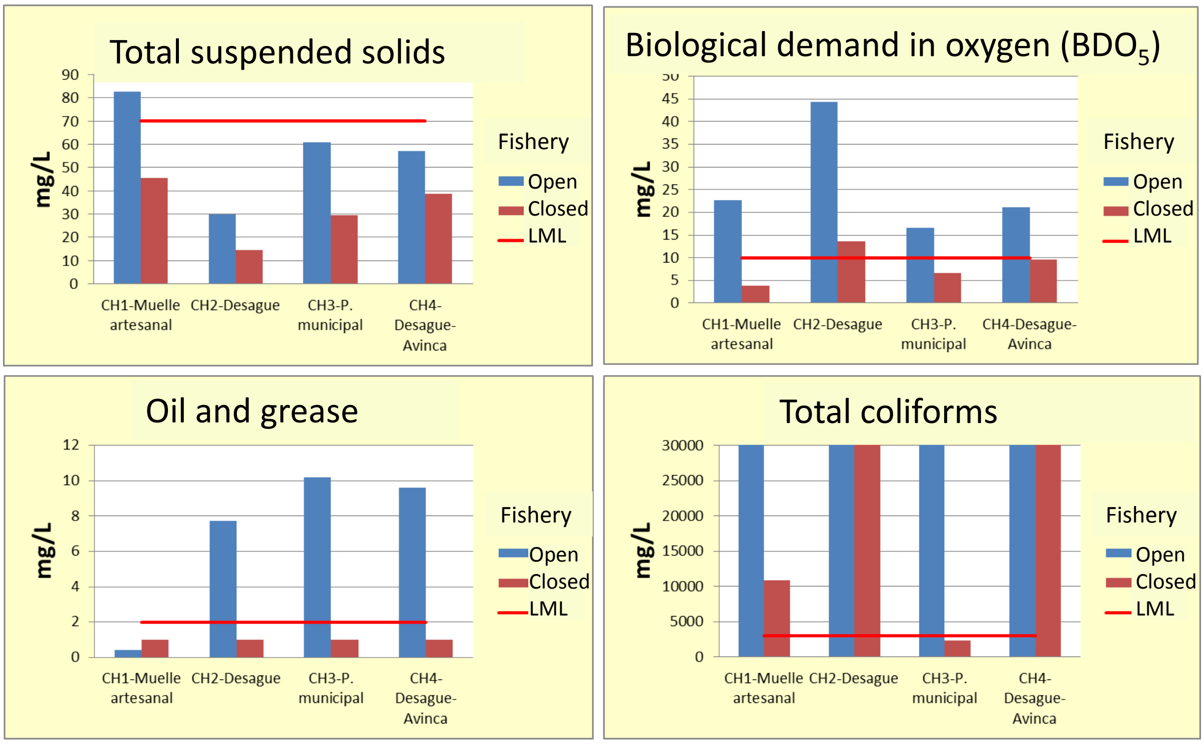

Figure 11-A. Changes in physicochemical parameters in the four coastal monitoring stations in the Chancay bay during fishing seasons 2009-2010 and legal maximum limits (LML). Refer to Fig. 10 in the main body of the paper for the location of the monitoring stations (CH1 to CH4).

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[5] This protocol was updated in 2013 (Ministerial Resolution N° 293-2013-PE)

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