Life Cycle Inventories of Wild Capture and Aquaculture

for the SRI project

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Background

The creation of reliable, consistent and transparent regionalised Life Cycle Inventories (LCI) represents a core purpose of the SRI programme. The LCI component of the SRI project provides a basis for informed decision-making on the sustainability of products and developments in other components of SRI project. The main goal is to establish and provide regional LCIs for the use in Life Cycle Assessment (LCA) studies, environmental product declarations, carbon footprinting and similar assessment tools. The ecoinvent Association, as the leading global supplier of transparent LCI data, is in charge of developing the basis for national LCI data in South America (Brazil, Colombia, Peru), South Africa, and India.

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Acknowledgments from data provider

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Data provider details

Data Provider is here defined as the association/s that created and submitted datasets to the ecoinvent Database in the context of the SRI project. The Data Provider are the authors of this report in collaboration of the ecoinvent Association.

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Seafood-related abbreviations

DHC	Direct human consumption
EEZ	Exclusive economic zone
EPO	Eastern Pacific Ocean
FAQ	Fair average quality (fishmeal)
FMFO	Fishmeal and fish oil
FUE	Fuel use efficiency: fuel consumed per landed tonne of fish
IHC	Indirect human consumption
LSW	Weight of a vessel including its gear but excluding all solid and liquid cargo

1 Introduction from the data provider

1.1 Introduction to the project

The project aims at constructing datasets of life cycle inventories representative of the capture, aquaculture and industrial processing of seafood in South America. A few “sister” fisheries from other locations were included, as their inventories were constructed following the same rules, and the data were available. The term “seafood” refers in this report to fish and other edible animals (molluscs, crustaceans) captured from or cultured in marine, brackish and freshwater environments, as well as industrial seafood-transforming processes. The following systems were modelled:

- Fisheries: steel and wood hulled purse seiners, steel hull trawlers; South Pacific anchovies and hake (including Patagonian grenadier), and Pacific tunas. Other global anchovy and hake “sister” fisheries, based on the same modelling approach.
- Aquaculture: pond and lake-based systems (including hatchery subsystems and industrial feed production); tilapia and trout.
- Seafood processing: canning, curing (salting-curing) and freezing of wild captured species, as well as fishmeal and fish oil (FMFO) production from wild anchovies.
- A special seafood product: fish sticks from Patagonian grenadier, including agricultural ingredients.

Across all concerned activities[1], a number of common subsystems were modelled as separate datasets, namely marine engines, electric motors and pumps, fuel use in fishing vessels, treatment of antifouling emissions (solid emissions to ocean), and fish rearing infrastructure (floating cages).

The countries represented are: Peru (cultured trout and tilapia, FMFO; fish freezing, curing and canning, wild caught anchovies and hake), Ecuador (wild captured tuna and tuna canning), Brazil (cultured tilapia), Chile (Patagonian grenadier is caught by foreign vessels from the Antarctic stock, and landed in Chilean ports), and South America (tilapia and trout aquafeeds). The additional modelled fisheries, namely anchovies and hake, represent Europe (mainly Spain) and Namibia.

1.2 Seafood production in South America

South America is an important seafood producing area, representing 10% of the global wild captures from marine, brackish and freshwater environments in 2015. In the same period, and historically, the continent’s aquaculture output is very small —3% of the world’s total production (FAO 2016)—, but certain countries are nonetheless important

[1] In this report, the term “activity” refers to transforming processes only. “In ecoinvent version 2 (except in the case of multi-output processes) both the activity which produces a certain product (such as steel production) and the product produced in that activity (such as steel) had the same name (such as "steel, converter, low-alloyed, at plant"). In ecoinvent version 3 the "activity" and the "product" are two separate entities. One product (such as steel) can be produced in different activities (such as "steel production, electric, low-alloyed" and "steel production, converter, low-alloyed"). The separation of the activity name from the process name allows a much simpler identification of different activities that produce the same product. It also allows the consistent creation of consumption mixes in the form of market activities, which group the suppliers of a product together.” From the ecoinvent FAQ “Differences between ecoinvent 2 & 3”.

global producers of specific seafood species, such as anchovies (Peru), tunas, mackerels and shrimps (Ecuador), salmonids (Chile) and tilapias (Brazil). These countries are all in the top 10 global producers of these species. In past decades, Peru alone contributed to up to 20% of wild marine captures due to the exploitation of South Pacific anchovies (*Engraulis ringens*) but, since the 1990s, fisheries management has rationalised its exploitation to more sustainable levels (Chavez et al. 2008).

The most common fishing methods in South America are purse seining and trawling, while the most common aquaculture systems are pond systems, seeding of artificial water bodies (e.g. dams) and cage systems in large water bodies.

Seafood production can be segregated in two main types of supply chains: shorter chains aimed at "direct human consumption" (DHC) and longer chains aimed at "indirect human consumption" (IHC). DHC chains include fisheries where the product is consumed fresh or after one industrial process such as canning, while IHC includes seafood products that undergo various processing stages, such as cultured fish requiring industrialised fish inputs such as FMFO (Avadí and Fréon 2014).

Specific technology descriptions of each modelled system are included as short descriptions in section 2. Maps of seafood production in South America are presented in Appendix 1. Maps of seafood production centres in Latin America, whereas production statistics (showing certain trends) are presented in Appendix 2. Statistics of seafood production in Latin America.

1.3 Known sector hotspots

In fisheries, the main contributor to environmental impacts is widely known to be fuel consumption (Avadí and Fréon 2013; Parker and Tyedmers 2014), which is driven by a number of factors such as fish catchability (a function of abundance, aggregation, behaviour, etc.), distance to fishing grounds, vessel management (use of antifouling, engine management, shape of the hull) and fuel use strategies, the so-called "skipper effect" (Vázquez-Rowe and Tyedmers 2013). Other contributors include antifouling paint and gear materials. Recommended minimum LCIs have been proposed in the LCA literature (Fréon et al. 2014b).

Regarding industrial fish processing, the main contributors to impacts are energy consumption (electricity, heat) and the consumption of packaging materials (Avadí et al. 2014a; Fréon et al. 2017).

In aquaculture, and especially for carnivorous species, the main contributor to environmental impacts is the provision of feed (Pelletier et al. 2009; Henriksson et al. 2012; Avadí et al. 2015b), which is composed of a combination of agricultural, agro-industrial, animal husbandry by-products and fisheries inputs (Tacon et al. 2011). The feeding efficiency of an aquaculture system is often expressed in terms of its feed conversion ratio (FCR: the ratio between feed consumed and live weight of the produced seafood). FCR depends of the feed quality (e.g. its protein content, digestibility, etc.), the cultured species (herbivores, omnivores, carnivores), and the system management (stocking density, water quality, temperature, etc.). Other important contributors to impacts in aquaculture systems include fuel use, land use, water consumption and occasionally transportation of inputs.

2 Modelling approach

2.1 Introducing the new seafood sector in ecoinvent

The ecoinvent database includes food-related sectors such as agriculture, but until the completion of this project, lacked the seafood sector. Under the SRI project, additional agriculture, forestry and animal husbandry datasets are being created for Brazil, India and South Africa. It is desirable for future projects to enrich ecoinvent with seafood inventories representing other key fishing, seafood processing and aquaculture areas of the world, such as East Asia (representing more than 60% of global seafood production) and Northern Europe.

Under this project, to introduce the seafood sector into ecoinvent, we followed the following modelling strategy:

- Fishing activities are segregated by fishing gear (e.g. purse seining, trawling, long lining) and hull material (steel, wood, glass fibre), which are considered as determinant of fuel use efficiency (FUE: fuel consumed per landed tonne of fish) and thus of environmental performance.

- Fishing vessels show an array of different sizes, as expressed by their length, holding capacity or light ship weight (LSW: the weight of a vessel including its gear but excluding all solid and liquid cargo[2]); and featuring varying levels of FUE. Instead of creating different datasets representing the construction, maintenance, use (fishing) and end-of-life (EOL) of various vessel sizes or fleet segments, we expressed the construction, maintenance and EOL in terms of 1000 kg of LSW, and its use phase per 1000 kg of fish captured, using FUE as a key modelling parameter. FUE is determined as a landings-weighted mean of many vessels over many years of operation, to account for inter-annual and size-related variability.

- Aquaculture systems are segregated by the technology deployed (cage systems, pond systems, raceways, etc.) and the position of a system in the extensive-intensive continuum, which often determines its FCR. Only systems consuming commercial aquafeed are considered, because systems using artisanal feed are too heterogeneous and less documented, and are often sub-optimally managed. The use phase of aquaculture systems is expressed per 1000 kg of whole fish production, and its maintenance is included in the use phase. The construction and EOL are related to the production means for cages, while pond construction and maintenance are integrated into the use phase due to data paucity.

- Aquafeeds are modelled as the use phase of aquafeed plants, including in the feed processes an input from the technosphere representing capital goods, consisting of a standard mill infrastructure from ecoinvent, conveniently scaled by production volume. Only one feed was modelled per species, by averaging the compositions of various feeds. Averaged feeds were selected on the basis of the species-specific protein content requirements for the growing stage: ~30% for tilapia and ~42% for trout.

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[2] FAO definition in the 2009 Technical Paper No. 517 (http://www.fao.org/docrep/011/i0625e/i0625e00.htm).

- Fish processing systems are segregated by the final product, namely a canned, frozen or cured product, or FMFO. Some products, such as fish sticks or canned fish, are multi-ingredient. FMFO is further segregated by fishmeal quality, expressed in its protein content, which is roughly correlated with the processing method and type of fuel used: heavy fuel-powered direct heat drying for the lesser qualities and natural gas-powered indirect drying for the higher qualities. All fish processing plants (construction, maintenance and EOL) are expressed per 1000 kg of processing capacity, to account for size-related variability. This approach deviates from established ecoinvent practice of representing processing plants as one unit of plant with a specific (yet not always clearly communicated) installed capacity, but we found our functional unit to be better adapted for seafood processing facilities, which are usually modular and for which a linear extrapolation of material and energy requirements seems suitable. Their use phase is expressed per 1000 kg of production.

- Packaging and infrastructure products (when explicitly modelled, such as for aquaculture cages) were modelled in terms of their basic materials and energy expenditure required for production. For instance, metal cans were modelled as tinplate or aluminium sheets, including a margin for production scraps, plus average metalwork. Plastic containers, plastic film and bags, and glass containers were modelled in a similar way (plastic raw materials plus energy expenditures for extrusion or thermoforming). Packaging materials constitute a main input in food and seafood processing. Thus, we considered essential to include these materials in fish processing inventories, modelling them as services delivering the "processed and packed" fish and fishmeal. Literature demonstrates that important eco-efficiency gains may be achieved by optimising packaging strategies for food products (Pardo and Zufía 2012; Avadí et al. 2014a).

- Specific direct emission calculation models were used for fisheries (antifouling solids emitted to ocean) and aquaculture (direct nutrient emissions to water from fish faeces, mortalities and uneaten feed).

- For all production activities, a single co-product was identified as the determining product, and all other co-products as by-products. For instance, all by-catch from fisheries was modelled as by-product, while fish oil was modelled as a by-product of fishmeal.

- Activities that are part of DHC supply chains, namely canning, freezing and curing, exclude the provision of fish (fishery phase); they are modelled as "services", in ecoinvent's terminology. This guarantees that users will be able to combine these transformation processes with their own fisheries. Fish as input, nonetheless, is included in those activities as an input from the ecosphere. Modelled FMFO includes the South American fisheries providing raw materials, but the activities are easily modifiable for users to include their own fisheries or other raw material-providing activities.

2.2 Data sources and data collection

Most required raw materials were obtained from ecoinvent, namely gear materials, most agricultural, animal husbandry and chemical aquafeed inputs, including industrial heat and water. FMFO, which was explicitly modelled in the project, was also used as input to modelled aquafeeds.

The majority of data consists of primary data collected in the context of the Anchoveta Supply Chain project (http://anchovetasc.wordpress.com/) and other research projects involving the Association Team (e.g. Vázquez-Rowe 2011). These data were collected by means of field visits, questionnaires, interviews with industry representatives and local pundits, as well as from data mining extensive unpublished datasets owned by research institutions such as the Instituto del Mar del Perú - IMARPE (http://www.imarpe.gob.pe/). The majority of data used have been previously published in scientific papers on: the Peruvian anchovy fishery (Avadí et al. 2014b; Fréon et al. 2014b), the Peruvian hake fishery (Avadí et al. 2017), the Peruvian FMFO industry (Fréon et al. 2017), the Peruvian fish canning, freezing and curing industries (Avadí et al. 2014a), the Ecuadorian tuna fishery and processing industry (Avadí et al. 2015a), the Peruvian trout and tilapia aquaculture including aquafeed production (Avadí et al. 2015b), the production of Patagonian grenadier fish sticks (Vázquez-Rowe et al. 2013), and sister European and African anchovy and hake fisheries (Vázquez-Rowe 2011; Vázquez-Rowe et al. 2014b; Laso et al. 2018). Key sampling metadata and production volumes associated with all constructed datasets are presented in Appendix 3. Metadata for the primary data used for all datasets constructed.

Primary data were complemented with ancillary data from secondary sources, most of which are also listed in the main Anchoveta Supply Chain project deliverable (Avadí 2014) and a PhD thesis (Vázquez-Rowe 2011), such as:

- Protein, lipids, nitrogen and phosphorus content of fish tissue and aquafeed, which are parameters of the calculation model used to determine direct nutrient emissions to water from aquaculture (see section **Error! Reference source not found.**).
- Material requirements for packaging products.
- Direct emissions to air from the generation of heat in industrial boilers and furnaces, for which available ecoinvent processes were used.
- Various feed compositions for South American tilapia and trout aquaculture.
- Direct emissions from the combustion of fuel (diesel) in marine engines, obtained from the EMEP/EEA air pollutant emission inventory guidebook 2016 (EMEP/EEA 2016).

Other secondary data were collected and used to extend the (mainly) Peruvian aquaculture data to represent production in Brazil and the rest of South America:

- Specific characteristics of aquafeed for tilapia. These data were based on average data reported by a set of Peruvian companies.
- Nutrient agents used in ponds, namely poultry manure, ammonium sulphate or potassium fertiliser.

Finally, fuel use data in fisheries was obtained from two types of data sources, namely:

- For the anchovy fisheries, large datasets of fishing trips, including number of sets, distances, landings, and fuel consumed or consumption rates were compiled from IMARPE and from private companies.

- For the hake, Patagonian grenadier, non-South American anchovies, and tuna fisheries, datasets for the sample of vessels were obtained from private companies (landings and fuel consumption or accounting data on fuel expenditures, per year and vessel) and complemented with official data on landings.

2.3 Allocation of impacts among co-products

For all coproduction activities (i.e. production systems generating co-products, such as fisheries with commercial by-catch, or the joint production of fishmeal and fish oil), unallocated inventories were built and delivered to ecoinvent, including all data elements to compute economic allocation keys, as ecoinvent applies economic allocation (Wernet et al. 2016). Nonetheless, particularly in fisheries, modelling by the authors and other practitioners has demonstrated that often mass, economic and gross energy content-based allocation alternatives do not create any significant differences.

The different activities representing coproduction, and the rationale behind its allocation, are presented in Table 1.

Table 1. Coproduction and allocation rationales

Activity	Coproducts	Allocation rationale
Peruvian anchovy	Anchovy	No allocation needed, as there’s no bycatch other than non-commercial species discarded at sea (modelled as discards)
Peruvian hake	Hake Hake by-catch	Economic allocation based on mass-weighted relative prices (5-year averages)
Ecuadorian tuna	Tuna Tuna by-catch	Economic allocation based on mass-weighted relative prices (5-year averages)
Spanish anchovy	Anchovy Anchovy by-catch	Economic allocation based on mass-weighted relative prices (5-year averages)
European and Cape hake	Hake by-catch, mainly demersal in Africa and pelagic species in Europe	Economic allocation based on mass-weighted relative prices
Peruvian fishmeal and fish oil	Fishmeal Fish oil	Economic allocation based on mass-weighted relative prices (10-year averages)
Peruvian trout	Trout	No allocation needed, as no coproduct is produced
Brazilian tilapia	Tilapia	No allocation needed, as no coproduct is produced
Fish processing (canning, freezing, curing)	Fish product	No allocation needed, as no coproduct is produced. Allocation of multi-product transformation processes were avoided by system sub-division
Fish sticks	Patagonian grenadier Hake by-catch Fish sticks Residual fishmeal	Economic allocation based on expert judgement

2.4 Fisheries

2.4.1 Description of systems: processes, products, technologies and production levels

Small and large pelagic fish are captured in South America mainly by means of purse seining, as exemplified by the anchovy fishery in Peru and Chile and the tuna fishery in Ecuador. Demersal fish are captured by means of mid-water or bottom trawling, as exemplified by the hake fishery in Peru and the Patagonian grenadier fishery in Chile. Both technologies are current, and especially steel vessels tend to feature bulbous bows to improve FUE. Other European and African sister fisheries have similar features.

Three fisheries systems were modelled: two pelagic ones (Peruvian anchovy and Ecuadorian tuna) and one demersal (Peruvian hake). These fisheries were modelled as follows (activities/datasets):

- Construction of 1000 kg of a steel or wood purse seiner (lifespan: 35 years) or a steel trawler (lifespan: 30 years), including the recommended inventory items detailed in Fréon et al. (2014), namely the hull, structural elements, electric cabling, motors and engines, and fishing gear. Auxiliary processes were modelled and used as inputs to these construction processes: construction of 1000 kg of a marine engine and construction of 1000 kg of electric motors.
- Maintenance of 1000 kg of a purse seiner or trawler during its lifespan.
- Use of a purse seiner or trawler required to capture and land 1000 kg of fish (including both target species and by-catch, while discards are included in excess of the 1000 kg).
- EOL of 1000 kg of a purse seiner or trawler.

Two of the three fisheries modelled are among the largest in the world, namely the Peruvian anchovy fishery and the Ecuadorian tuna fishery. The Peruvian anchovy fishery features a mean production volume of 5.2 million t/y (2008-2010), representing 95% of landings from the Eastern Pacific Ocean (EPO, the habitat of the Peruvian anchovy). 81% of those landings are made by steel vessels and the difference by wooden ones. The Ecuadorian tuna fleet lands ~233 000 t/y, representing 42% of total EPO captures in 2013. The Peruvian hake fishery, in the other hand, is a relatively minor global fishery (yet important for the country), landing and average of 41 500 t/y, or 48% of Pacific hake landings in the EPO in 2006-2014.

2.4.2 System boundaries: system, geographical and temporal, cut-off criteria

The Peruvian anchovy fisheries were modelled to represent the periods 2008-2010 (steel fleet) and 2005-2011 (wooden fleet). The Peruvian hake fishery was modelled for the years 2006-2010, while the Ecuadorian tuna fishery was modelled for the years 2012-2013. The system boundaries for all fisheries inventories include the complete life cycle of fishing vessels, from construction to EOL, through maintenance and the use phase, but excluding landing infrastructure (Figure 1). In the case of anchovies, landing facilities are considered in the processing activities. Cut-off criteria are explained in detail in Fréon et al. (2014b), and includes all items contributing individually with ≥1% of the overall environmental impacts, for a cumulative contribution of 95.2%. The article proposed a minimal inventory, which was compiled for all fisheries datasets with certain adjustments for wooden vessels.

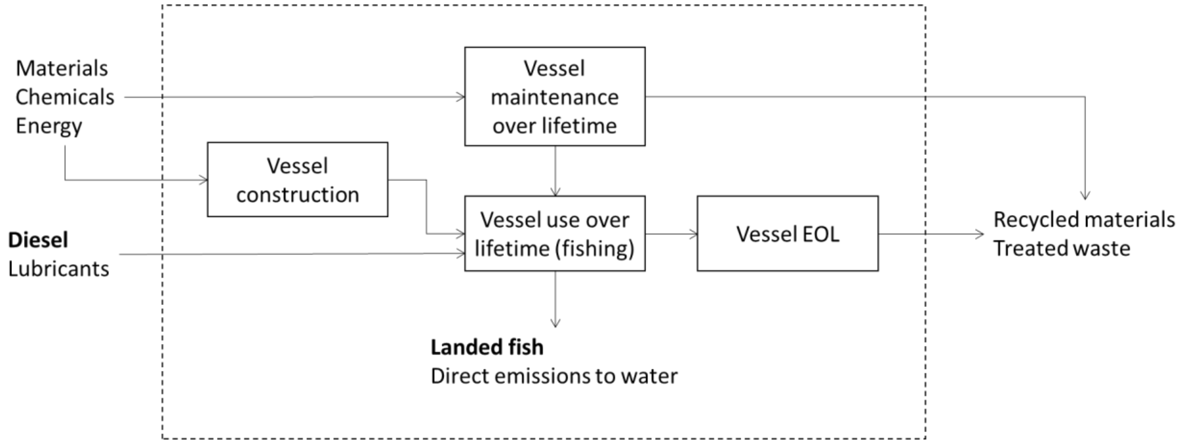

Figure 1. System boundaries for fisheries activities (key inputs and outputs are highlighted)

2.4.3 Inventory creation: calculation models, parameters and properties

Certain key parameters were used to construct the fisheries datasets, namely mean annual landings per vessel and the FUE. These parameters were used to calculate the inclusion of certain inputs from technosphere, namely:

- Proportion of 1000 kg of vessel necessary to capture 1000 kg of fish, calculated as: (mean LSW [kg]/(landings per vessel [kg/y] * lifetime [y]) * 1000).
- Proportion of vessel maintenance associated to the capture of 1000 kg of fish, calculated as: mean LSW [kg]/landings per vessel [kg/y] * 1000.
- Diesel burned in marine engine required to capture 1000 kg of fish, calculated as: FUE [kg/t].

The only calculation model used for fisheries was the computation of antifouling emissions to ocean, which, following repeated use in fisheries LCA literature and a seminal article on the subject (Hospido and Tyedmers 2005), dictates that two thirds of the antifouling paint (solids) applied to vessels is assumed to be released into the ocean.

2.4.4 Datasets created and their fit within ecoinvent

A series of supporting datasets were created, common for all fisheries datasets representing fishing activities (use phase), including the construction of electric motors and marine diesel engines, the treatment of antifouling emissions, and the combustion of diesel in marine engines.

All of these new datasets fit into the existing classification of ecoinvent activities, and complement existing ones. Marine electric motors are simply electric motors, which were lacking from the database. Marine engines are large diesel engines, highly homogeneous around the world for all types of marine applications beyond fisheries. The combustion of diesel in said engines represents global average conditions and emissions, according with (EMEP/EEA 2016). The treatment of antifouling paint emissions represents the direct emissions to water of solids (active substances) contained in antifouling paint used mainly in Peru, but updatable to represent the formulations of other internationally used antifouling paints.

Specific fisheries datasets were created to represent these fishing activities, segregating per target species and type of vessel (steel/wood, purse seiner/trawler). Antifouling emission datasets were segregated per dominating active molecule (Cu or Sn).

These datasets, both supporting and fisheries-specific, inaugurate the seafood sector in ecoinvent. See list of datasets and details in Appendix 4. List of datasets created and some modelling details.

2.5 Other fisheries: Spain, Europe, Namibia

Other "sister" anchovy and hake fisheries, operating in other geographic locations, were modelled in the same fashion as the corresponding South American ones, to profit from similar features and sharing the modelling approach.

2.5.1 Description of systems: processes, products, technologies and production levels

Landed hake in European and African locations

The capture and landing of demersal hake in Europe (*Merluccius merluccius*) and in Namibia is developed by the use of trawling and long liners fishing fleet. Three fisheries systems were modelled: three demersal ones (European hake, Spanish hake and Namibian hake). These fisheries were modelled as the Peruvian hake landings.

Annual hake landings in year 2008 in Galician ports added up to 26 439 tons, whereas in 2017 this value had risen to 32 418 metric tons, although this value can be highly variable due to stock availability, recruitment or fishing bans on an annual basis in the different targeted fisheries. Two of the three fisheries modelled by the use of trawlers (Spain and Namibia) and the use of long liners in the case of Europe. In Spain, hake species have become strategic product in the food market and one of the main sources of marine protein in an average diet. In line with the economic expansion in the 1960s, Spanish vessels started to exploit a new fishery off the coast of Namibia: cape hake (*Merluccius capensis*).

Landed anchovy in Spanish locations

This activity represents the purse seining operations to capture and land European anchovy (*Engraulis encrasicolus*) in the region of Cantabria, in northern Spain. All the anchovy is landed fresh, but then only 50% is consumed fresh. An additional 25% is sent to the local industry to produce canned anchovy-based products, whereas the remaining 25% is used to produce salted anchovy. These purse seiners target European anchovy, but they also capture other species, such as mackerel (*Scomber* spp.), European pilchard (*Sardina pilchardus*) and, to a lesser extent, some types of tunids. Fishing operations occur in the Bay of Biscay within the Spanish EEZ. 41 vessels belonged to this fleet in 2015.

2.5.2 System boundaries: system, geographical and temporal, cut-off criteria

Landed hake in European and African locations

The Spanish, European and Namibian hake were modelled to represents different periods 2008-2009 (Spanish and European) and 2010-2011 (Namibian) hake using a steel fleet. The system boundaries for all the fisheries inventories include the complete life cycle of fishing vessels, from construction to EOL, through maintenance and the use phase, but excluding landing infrastructure. The system boundary due to the similitude to the

Peruvian hake, present the same limits showed in Figure 1. The activities are composed by the vessel use (including landing) and maintenance phases, including all upstream processes. Furthermore, port operations and post-landing processing activities are beyond the system boundary.

Landed anchovy in Spanish locations

The Spanish anchovy was modelled to represent the year 2015 landed anchovy in Spain using a steel fleet. The system boundaries for the anchovy include the complete life cycle of fishing vessels, from construction to EOL, through maintenance and the use phase, but excluding landing infrastructure. The system boundary due to the similitude to the Peruvian and Ecuadorian hake, present the same limits showed in Figure 1.

2.5.3 Inventory creation: calculation models, parameters and properties

Landed hake in European and African locations

The Spanish inventory represent 24 vessels (trawler) out of 101, over two years of operation. Sample belongs to data from 11 different ports along the Galician coast, representative of regional and national operation (Spanish data). Moreover, the European inventory represent 12 vessels (long lining) out of 49, over one full year of operation. Sample belongs to data from three different ports along the European cost.

Certain parameters were used to construct the European and Namibian fisheries datasets, namely mean annual landings per vessel and the FUE. These parameters, similar to the ones used for the Latin American countries, were used to calculate the inclusion of certain inputs from technosphere.

Landed anchovy in Spanish locations

Data were collected for year 2015 for a sample of 32 purse seiners out of 41 belonging to the Cantabrian fishing fleet. These vessels represented 78% of the fleet, guaranteeing the representativeness of the results. The sample size represents also the rate of response of the skippers, since the questionnaires were delivered to all 41 vessels of the fleet. Vessels from the ports of Colindres, Santoña, San Vicente de la Barquera, Comillas, Laredo, Santander and Castro Urdiales were included in the sample.

2.5.4 Datasets created and their fit within ecoinvent

See list of datasets and details in Appendix 4. List of datasets created and some modelling details.

Landed hake in European and African locations

All five datasets fit into the existing classification of ecoinvent activities, as the Peruvian and Ecuadorian datasets, will complement the existing ones. Moreover, the datasets related to Spain, Europe and Namibia, will contribute to support the datasets of food industry.

Specific datasets, both supporting and fisheries-specific, inaugurate the seafood sector in ecoinvent. See list of datasets and details in Appendix 3. Metadata for the primary data used for all datasets constructed.

Landed anchovy in Spanish locations

This dataset fits into the existing classification of ecoinvent activities, as the Peruvian and Ecuadorian datasets, complementing the existing ones. In addition, the data will contribute to support the datasets of food industry.

2.6 Fishmeal and fish oil production

2.6.1 Description of systems: processes, products, technologies and production levels

Peru is the main global fishmeal and fish oil (FMFO) producer. A very detailed description and life cycle assessment of this industry, referred to as the "reduction" industry, is presented in Fréon et al. (2017). From the supplementary material of that publication, we reproduce, *verbatim*, a description of the FMFO production process and product characteristics:

> "[…] 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). 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 consist 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 an 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 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."

[Plant 1 in this description refers to a studied FAQ fishmeal-producing plant.]

A graphical representation of the production process is presented in Figure 2.

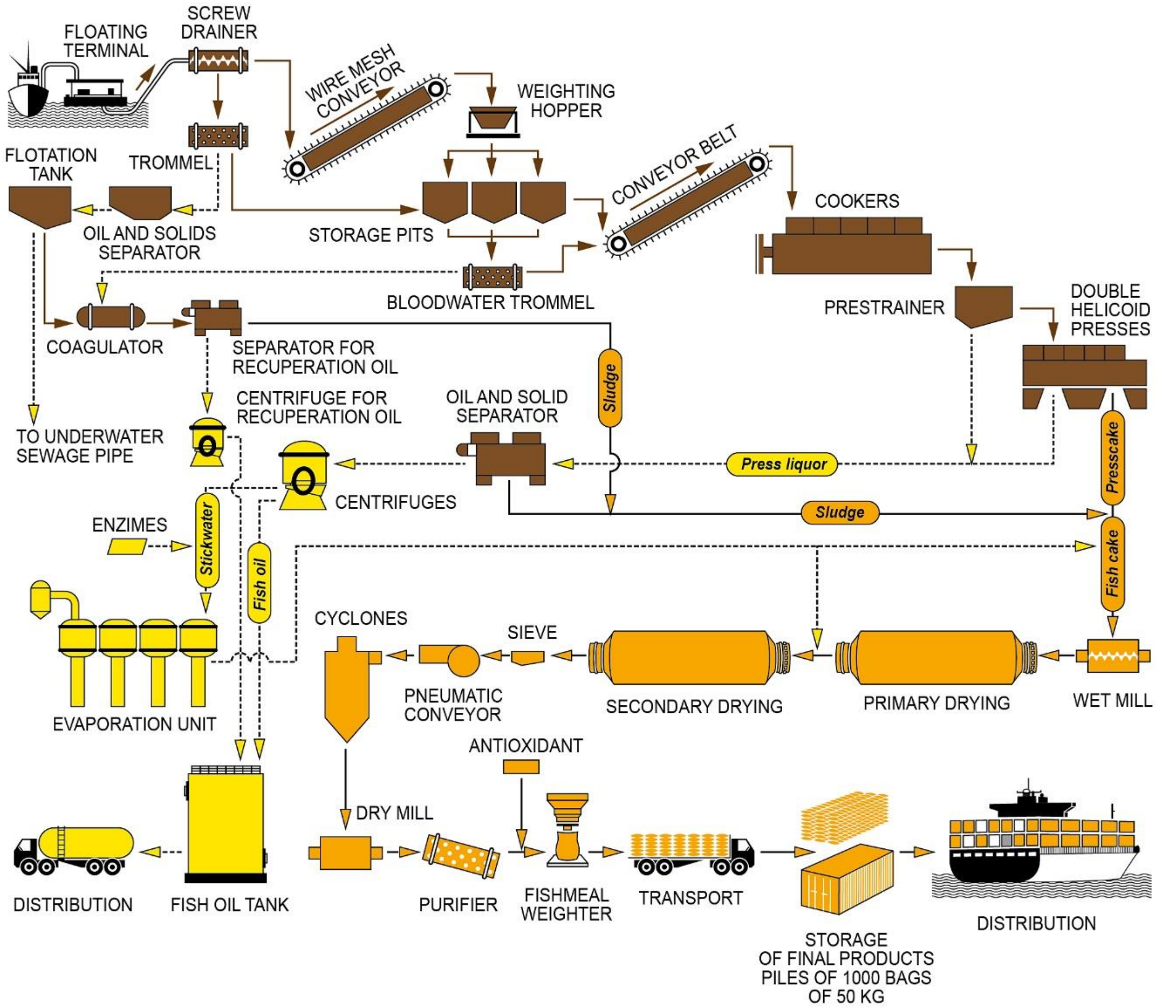

Figure 2. Process tree for a Peruvian fishmeal. Brown flows are common to fishmeal and fish oil production, orange flows are specific to fishmeal and yellow flows are specific to fish oil (Fréon et al. 2017)

Three different categories of fishmeal were produced in Peru during the study period, where quality refers mainly to protein, lipid and salt content, and is determined by the technology used:

- Standard fishmeal (63-65% protein), 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 lower quality, produced from fish residues.
- Prime fishmeal (65-67% protein) and Super Prime fishmeal (67% protein); for the production of which 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.

The production of two types of fishmeal, FAQ and Prime/Super Prime, was modelled as follows (activities/datasets):

- Construction, maintenance and EOL of 1000 kg of processing capacity of a FMFO plant (lifespan: 30 years) including the recommended inventory items detailed in Fréon et al. (2017), namely the infrastructure materials, electric installations, equipment, piping and maintenance consumables (cleaning chemicals and water).
- Use of the processing capacity of a FMFO plant required to produce 1000 kg of fishmeal of a specific quality (63-65% protein or 65-67% protein) plus the mass of fish oil determined by the proportional yields of meal and oil of fresh Peruvian anchovies (0.210±0.08 kg fish oil per kg fishmeal).

The Peruvian FMFO production reached, in average during the period 2006-2015, 1.183 million t of fishmeal and 230 000 t of fish oil per year, representing respectively 24% and 23% of the global production. Roughly 81% of the fresh fish destined for reduction is provided by the steel purse seiner fleet, while the difference is provided by the industrial wooden purse seiner fleet.

2.6.2 System boundaries: system, geographical and temporal, cut-off criteria

The Peruvian FMFO production was modelled to represent the period 2008-2010. The system boundaries for the inventories of both production types include the partial life cycle of FMFO plants, from construction, through maintenance and the use phase (excluding landing infrastructure), but excluding plant EOL, as no data were available (Figure 3). The use phase of FMFO plants includes the provision of Peruvian anchovy as input from technosphere. We ascertain that a skilled ecoinvent user would be easily able to substitute the provision of fish from the Peruvian fishery with another raw material activity.

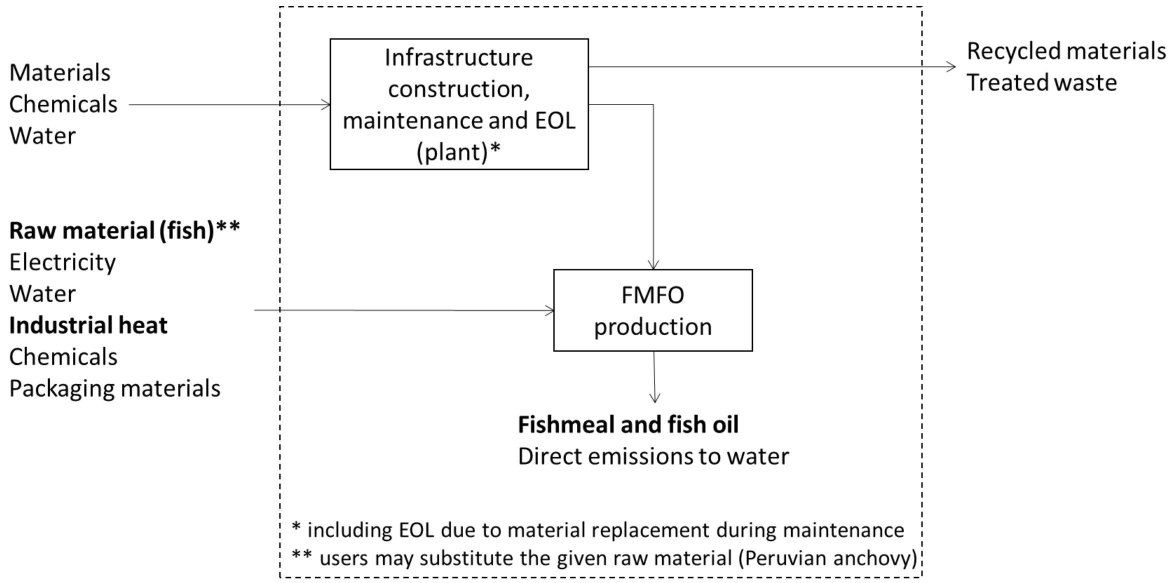

Figure 3. System boundaries for fishmeal and fish oil activities (key inputs and outputs are highlighted)

2.6.3 Inventory creation: calculation models, parameters and properties

Certain key parameters were used to construct the reduction datasets, namely the raw material to fishmeal ratio and all direct emissions and inputs from technosphere. The datasets were modelled this way to facilitate the inclusion of inputs from technosphere, which are different depending on the target fishmeal quality and technology deployed.

The production yield in particular was used to express all inputs as a function of the yield, which would facilitate manipulations of the dataset and the inclusion of uncertainty data.

No additional calculation models were required.

2.6.4 Datasets created and their fit within ecoinvent

Specific reduction datasets were created to represent the two concerned types of production/fishmeal qualities. These datasets contribute to the seafood sector in ecoinvent, namely due to the inclusion of FMFO in most aquafeeds worldwide (the main purchaser of Peruvian fishmeal is China and of fish oil is the European Union). See list of datasets and details in Appendix 4. List of datasets created and some modelling details.

2.7 Aquaculture

2.7.1 Description of systems: processes, products, technologies and production levels

Aquaculture is widespread in South America, yet in global terms, its output is minor. The most prevalent seafood culturing systems are freshwater ones (if the important Ecuadorian shrimp and Chilean salmon aquaculture industries are excluded), either land-based (ponds) or large water bodies-based (cages). Two specific aquaculture systems were modelled: pond-based semi-extensive tilapia and cage-based semi-intensive trout production. These tilapia systems are common in tropical areas of Brazil, Colombia, Peru and Ecuador, while the cage systems are dominant in lake Titicaca and other Andean lakes and water bodies. Technologically speaking, these systems are simple and well established. The pond systems usually consist of earthen ponds without aeration, and featuring manual feeding and fertilisation. Cage systems are anchored relatively close to shore, and are tended to by means of small motor boats. Both types of systems use predominantly commercial aquafeed, including floating pellets in the case of cage systems.

2.7.2 System boundaries: system, geographical and temporal, cut-off criteria

The selected South American aquaculture systems were modelled to represent the period 2012-2013 (trout) and 2010 (tilapia). The system boundaries for the inventories of both production types include the partial life cycle of production means, from construction, through maintenance and the use phase, but excluding plant EOL, as no data were available (Figure 4):

- Construction, maintenance and EOL of a floating cage system, expressed either in terms of its diameter (if floating collar) or side length (if hexagonal cage), with their associated lifetimes. The specific fish holding capacity of each system is expressed as well per m of diameter or side length.
- Production of 1000 kg of commercial fish feed.
- Use of an aquaculture system featuring either cage or pond infrastructure required to produce 1000 kg of fish, and consuming as much feed as determined by the system's FCR. In the case of pond systems, the construction and maintenance of ponds is integrated in the system's use phase.

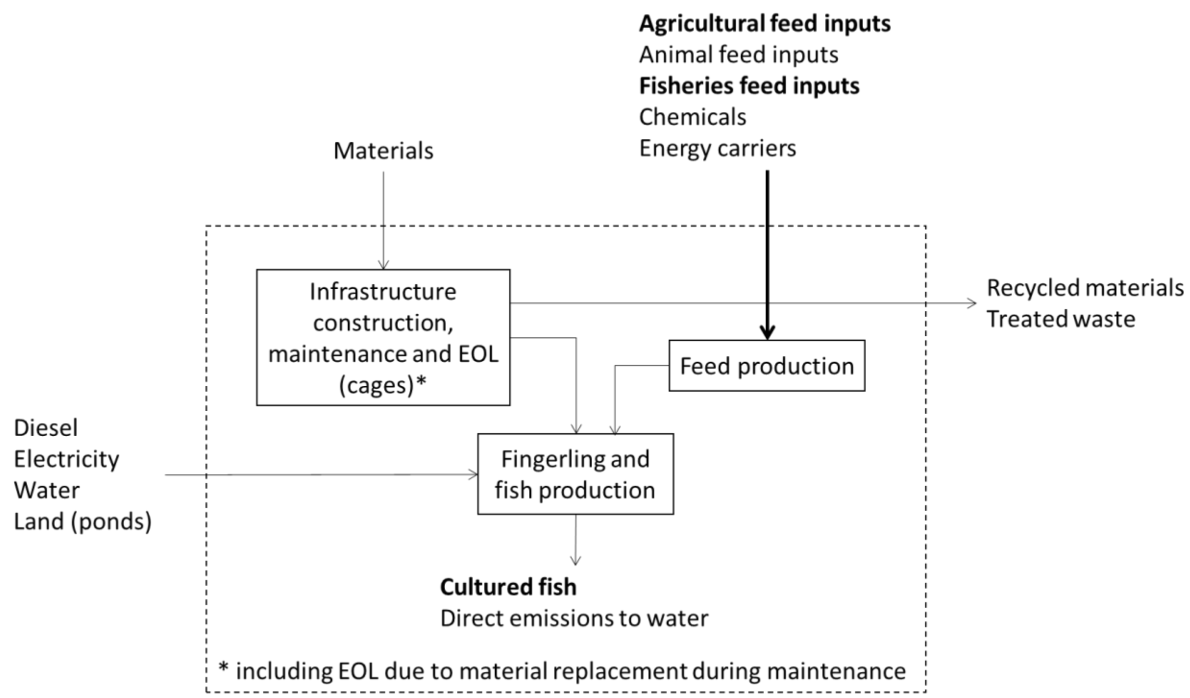

Figure 4. System boundaries for aquaculture activities (key inputs and outputs are highlighted)

Cages were modelled as separate activities, but ponds were integrated into the main pond-based aquaculture dataset, due to low construction and maintenance input requirements.

The provision of fingerlings was not modelled explicitly, for instance as a separate hatchery/nursery activity, but its material and energy requirements included in the main fish production dataset.

Aquafeeds were modelled as separate activities, as the use phase of a feed mill. As feed mills are simple mills with a few refinements (such as high-powered extruders and oil coating machines for producing floating pellets), a generic oil mill from ecoinvent was included as the infrastructure required for aquafeed production. Average aquafeed datasets were constructed for tilapia (~30% protein) and trout (42% protein), by averaging several commercial feeds for the growing phase of each species production cycle. These activities include as inputs all agricultural, animal husbandry and fisheries-derived inputs, as well as the required energy expenditures (electricity, industrial heat). Direct emissions to the aquatic environment were also estimated by means of a calculation model.

2.7.3 Inventory creation: calculation models, parameters and properties

To calculate direct nutrient emissions to water from fish faeces, mortalities and uneaten feed, the well-known and widely used mass-balance model by Cho and Kaushik (1990) was used. This model takes into consideration the composition of the feed, the FCR and the composition of the fish itself to estimate nutrient losses (Papatryphon et al. 2005). Model parameters were obtained from Avadí et al. (2015b).

Additional key parameters were the system's FCR and stocking density, used respectively to input the feed consumption and the infrastructure requirements.

2.7.4 Datasets created and their fit within ecoinvent

Specific datasets were created to represent the two selected aquaculture systems, including infrastructure and feed production, segregated per produced species. These datasets contribute to the seafood sector in ecoinvent, namely due to the local and global relevant of the two species represented. Moreover, the two technologies are widespread throughout the world. The cage infrastructure datasets in particular will be useful for international applications, as floating cages are used worldwide for both marine and fresh/brackish water species. See list of datasets and details in Appendix 4. List of datasets created and some modelling details.

2.8 Canning, freezing and curing

2.8.1 Description of systems: processes, products, technologies and production levels

Fish processing for DHC is an economically important sector in South America, for both national consumption and exports, notably in Ecuador (tuna) and Peru (anchovies). Four types of fish processing were modelled: canning of large pelagic fish in Ecuador, canning and freezing of small pelagic fish and Peru, and curing of anchovies in Peru. Fish processing plants perform either one or more among the three fish processing types, but we modelled each activity separately, including their required infrastructure. Technology used for each activity is standard, yet modern, as most of the equipment is imported from global technology providers. Emissions from industrial heat and refrigeration systems are constrained by legislation. In general, these systems perform similarly to international ones, in terms of energy use and emissions profiles.

2.8.2 System boundaries: system, geographical and temporal, cut-off criteria

The selected South American aquaculture systems were modelled to represent the periods 2012-2013 (Ecuadorian canning), 2010-2012 (Peruvian curing), and 2012 (Peruvian canning and freezing). The system boundaries for the inventories of all production types include the partial life cycle of production means, from construction, through maintenance and the use phase, but excluding plant EOL, as no data were available (Figure 5):

- Construction, maintenance and EOL of 1000 kg of processing capacity of a seafood processing plant (canning plants lifespan: 40 years, other plants: 30 years). Canning of fish was modelled as two different systems, processing small pelagic fish and tuna, respectively, as proxies of small and large fish. There are important differences between the two systems regarding their relative generation of residues and energy demand for cooling/freezing/industrial heat.
- Use of the processing capacity of a seafood processing plant required to process 1000 kg of fish into a product (1000 kg of fish plus the required weight of other ingredients and packaging materials). Additional ingredients such as vegetable oils, water, industrial heat and packaging materials were modelled as inputs from technosphere.

The use phase of processing plants excludes the provision of fish, as the datasets are generic enough to be usable in association with any fishery, provided that the fish as raw material is clearly identified as small (e.g. small pelagics such as sardines, anchovies and herrings) or large (e.g. tunas, cod) fish.

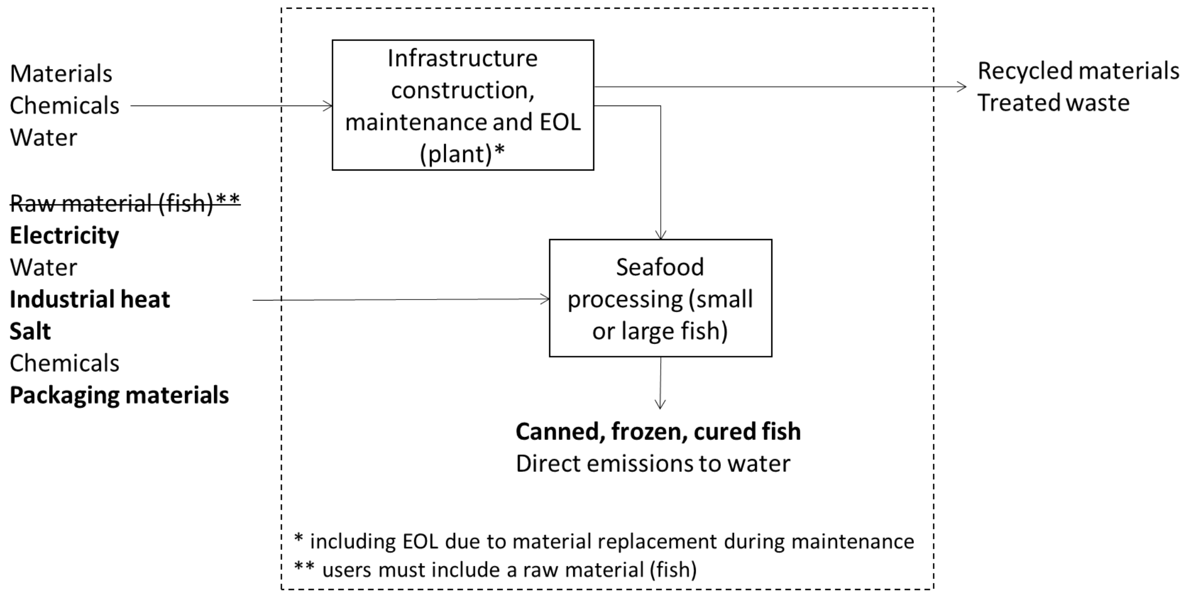

Figure 5. System boundaries for Direct Human Consumption activities (key inputs and outputs are highlighted)

2.8.3 Inventory creation: calculation models, parameters and properties

No additional calculation models or parameters were required.

2.8.4 Datasets created and their fit within ecoinvent

Specific datasets were created to represent the four selected seafood processing systems, segregating per type of process and size of fish (for canning). These datasets contribute to the seafood sector in ecoinvent, by introducing seafood-processing activities with global applicability. See list of datasets and details in Appendix 4. List of datasets created and some modelling details.

2.9 Fish sticks production

2.9.1 Description of systems: processes, products, technologies and production levels

Fish sticks production

This activity represents the processing of a multi-ingredient hake product, referred to as fish sticks or fish fingers, at a fish processing factory. The main product is fish blocks of Patagonian grenadier (*Macrunorus magellanicus*). There fish blocks are marine freighted and once they arrive at the ports' premises, they are delivered in refrigerated trucks to the processing plant. Two other important products are breadcrumbs and a wheat flour mix that are used in the battering of fish sticks. These are produced in a mill near the seafood processing plant and transported by truck. Data were reported by technical staff at the seafood processing industry, extrapolated from RER conditions. Uncertainty was adjusted accordingly.

Breadcrumbs production

This activity represents the production of breadcrumbs in an ingredient and food additive processing plant. The flour used for the breadcrumbs is obtained from conventional wheat production. The wheat is then grinded at a milling plant to produce wheat flour and thereafter it is transported by trucks to an ingredient and food additive processing plant, where the breadcrumbs are produced. Breadcrumbs are made up of 90% wheat flour, and less than 5% content of corn dextrose, sunflower oil, salt, yeast and spices.

Wheat mix production

This activity represents the production of wheat mix for batter to produce fish sticks, also named fish fingers. The wheat is then grinded at a milling plant to produce wheat flour. The flour is then freighted by truck to an ingredient and food additive processing plant. The composition of the final wheat mix produced is: a) 80% wheat flour arriving from the mill, b) less than 10% wheat starch, c) less than 10% salt, d) less than 5% sunflower oil, e) pH regulators, and f) less than 1% vitamins A and C. Furthermore, data are from 2011 and were reported by the company per t of final product.

Patagonian grenadier fishery

This activity represents the capture of Patagonian grenadier (*Macruronus magellanicus*) along the southern Chilean coast by industrial processing vessels (FAO Area 87; Subarea 87.3). Patagonian grenadier is a gadoid from the Merluccidae family. Therefore, this type of hake is sold as hake in many international markets. The hake is processed on board, producing an intermediate fish block product. To produce this block, a set of processing stages on board are performed. In the first place, the fish is headed and passed through a filleting machine. The following stage consists of separating the skin from the flesh using a wheel and a blade. Prior to the formation of the fish blocks, the flesh containing the few remaining bones is removed. Finally, the last processing activity on board implies the packaging and storage in the cooling chamber of the obtained fish blocks. The organic residues derived from the filleting machines are processed to produce fishmeal on board. Fish blocks are landed at a Chilean port (usually Punta Arenas or Chacabuco). Data collected are linked to landings in year 2011.

2.9.2 System boundaries: system, geographical and temporal, cut-off criteria

The production system included the production stages of the different ingredients (raw materials), their arrival to the processing plant and the processing undergone at the plant (Figure 6). Fish blocks arriving from the Patagonian grenadier fishery in Chile (see above) were included as raw material for this product. Additional ingredients such as vegetable oils, water, industrial heat and packaging materials were modelled as inputs from the technosphere. The system boundaries for the fish stick production inventory of both production types include the partial life cycle of production means, through maintenance and the use phase, but excluding the construction and EOL of the plant, as no data were available (Figure 6). The selected functional unit (FU) for the studied product was set as one package of frozen fish sticks. Acquired data for the study refer to year 2011.

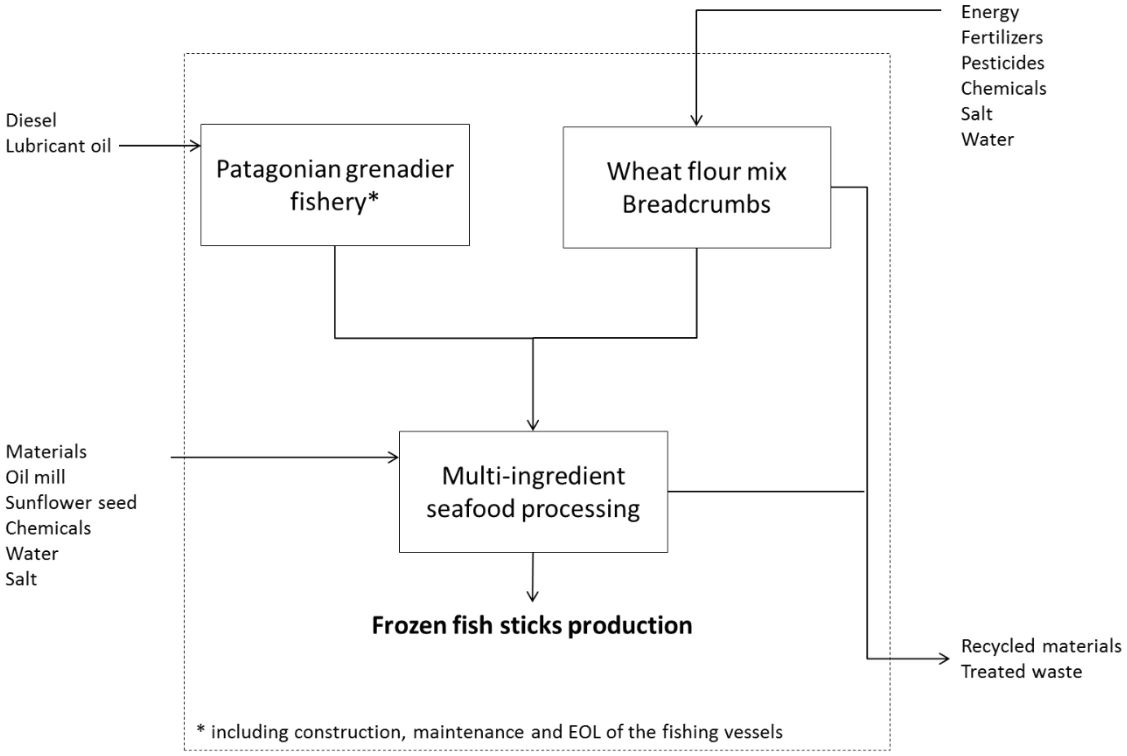

Figure 6. System boundaries for fish sticks production (Vázquez-Rowe et al. 2013)

Fish sticks production

Included activities starts in seafood processing factory located in Southwest Europe. Activities include the reception of hake fish blocks and their processing until they are transformed into fish fingers in a multi-ingredient final product. Finally, the excluded activities were the distribution from factory to wholesalers and packaging. This packaging in this particular product is constituted by 22.98 g of cardboard and 1.17 g of polyethylene.

Breadcrumbs production

Activities include the production of all raw materials to produce the breadcrumbs, the grinding of wheat at a milling plant and the production of the final product. The transport of breadcrumbs beyond the gate of the ingredient and food additive plants were not included in the modelling. The amount of plastic used in packaging, not included in the database, is 1.41 g per kilogram of breadcrumbs production.

Wheat mix production

Activities includes provision of raw materials, transport to mill and activities at the mill, including use of energy. Furthermore, the activities excluded were the transport from the mill to the fish stick processing factory.

Patagonian grenadier fishery

Activities includes the extraction of hake in south Pacific maritime areas and on board processing of hake-based fish blocks and residual fishmeal. Nevertheless, post-landing port activities were excluded from system boundaries.

2.9.3 Inventory creation: calculation models, parameters and properties

Fish sticks production

Data were collected for average conditions in year 2011. 323.47 g of fish sticks is the mass content of the ten (10) fish sticks (i.e. fish fingers) contained in one cardboard package ready for distribution and sale. The package itself weighs 25.97 g. View Annex 3 and 4 for extra information about the datasets modelling.

Breadcrumbs production

The breadcrumbs processing plant is located in NW Spain, but its products are exported throughout Europe. Furthermore, data collection was performed directly with the company that processed the final products. Data from upstream processes were described by plant technicians based on data exchanged with other companies providing materials. This dataset may be used for breadcrumbs production in other geographical contexts, provided that the uncertainty linked to geography, reliability and technology is considered.

Wheat mix production

No sampling was undergone. The data were directly provided by the concerned company. This dataset can be used for battering of a wide range of food products.

Patagonian grenadier fishery

Capture of Patagonian grenadier (*Macruronus magellanicus*) is performed along the southern Chilean coast by industrial processing vessels (FAO Area 87; Subarea 87.3). Fish blocks are landed at a Chilean port (usually Punta Arenas or Chacabuco). Patagonian grenadier is also caught in other areas of the Southern Pacific. Two industrial vessels belonging to a Spanish company were included in the study. Together, they landed 11 000 metric tons of fish blocks in 2011.

2.9.4 Datasets created and their fit within ecoinvent

The dataset fits into the existing classification of ecoinvent activities, as the Peruvian and Ecuadorian datasets, complementing the existing ones. In addition, the data will contribute to support the datasets of food industry. In addition, the data will contribute to support the datasets of food industry.

See list of datasets and details in Appendix 4. List of datasets created and some modelling details.

3 Results

3.1 General description of the results

3.1.1 Fisheries

As mentioned above, the main source of environmental impact in fisheries is linked to the production and consumption of fuel, mainly marine diesel, for the propulsion of the fishing vessels. In addition, fuel use efficiency (FUE) has been a repeatedly used indicator in the scientific literature, beyond Life Cycle Thinking, to report the energy intensity of fishery activities. In this sense, FUE represents the amount of diesel (in litres) that is needed to capture and land one t of fish. Although the computation of FUE does not consider the energy requirements of many fishery operations that rely on other sources of energy (e.g., electricity or net or ice production), it is considered a useful proxy to understand the energy intensity of a given fishery or fishing fleet (Vázquez-Rowe et al. 2014a).

Several studies available in the literature have provided data on these values for a variety of different fisheries worldwide. For instance, a recent study by Parker and Tyedmers (2014) shows that when divided by target species class, with the lowest values recorded for small pelagic fish and finfish, whereas crustaceans and flat fish, which tend to congregate in demersal areas of the ocean column, present the highest values. Similarly, purse seining nets and other surrounding nets show the lowest FUE values, a fact that is not surprising considering that it is with these types of nets that most small pelagic fisheries are targeted. In this sense, Parker and Tyedmers (2014) report an average FUE value of 71 L/t for small pelagics if they are targeted with seiners, a value that rises to 169 L/t if targeted with pelagic trawls. In contrast, some crustacean fisheries have reported FUE values above 10 000 L/t, although on average the value was 2 923 L/t. Another fuel-intensive fishery reported in this study was flatfish bottom trawls, averaging 2 827 L/t.

The results obtained for the fisheries included in the current study show similar trends to those described in Parker and Tyedmers (2014). Firstly, the FUE computed for the anchoveta fishery in Peru showed an average value for steel vessels of 19.95 L/t. This computation was based on a total of 561 data-points between years 2008 and 2013. The wooden fleet that targets the same species along the Peruvian coast reported an average value of 15.87 L/t, a value 20% lower than for steel vessels. This value was based on 25 data-points in the period 2012-2013. These values are, as far as the authors were able to ascertain, the lowest report worldwide for fuel-powered fisheries. Nevertheless, they are in line with results reported by Parker and Tyedmers (2014) for small pelagics, and in a similar range to those reported by Ramos et al. (2011) for the Atlantic mackerel fishery in northern Spain.

Results for the tuna fishery in Ecuador show an average FUE of 831.6 L/t. This value is in a similar range to FUE values reported for purse seining tuna fisheries elsewhere, as well as other large pelagic fisheries (Parker and Tyedmers 2014).

3.1.2 Fishmeal and fish oil production

The production of FMFO was modelled, for the first time in such detail, by Fréon and colleagues. Previous LCIs available (a Peruvian and a Norwegian screening, and the Danish Triplenine plant inventory included in http://www. lcafood.dk/) were less detailed and less representative of the global production. Peru, in the other hand, is the largest producer of FMFO in the world, and its technology is representative of the sector's state of the art (Fréon et al. 2017). Impacts were dominated by fuels use (modulated by quantity and type of energy carriers), as expected from an energy-intensive industry.

The modelled processes, despite including specific raw material sources (Peruvian fisheries and residues from DHC fish processing), are easily modifiable by users to include different raw material sources.

3.1.3 Aquaculture

For all types of aquaculture modelled, feed is the main contributor to impacts, a conclusion aligned with the bulk of previous aquaculture LCA research (Henriksson et al.

2012; Aubin 2013; Bohnes et al. 2018). The composition and origin of inputs of modelled feeds is presented in Table 2.

Table 2. Composition of average feeds modelled, per t of feed

Feed inputs	Unit	Trout feed, 42% protein (PE)	Tilapia feed, 24-28% protein (PE)	Origin
Protein content	%	42	24-28	
Meat and bone meal	kg	200.0	-	RER
Lime (proxy for calcium carbonate)	kg	8.0	42.0	RLA
Fish oil	kg	60.0	10.0	PE, RLA
Fishmeal, 65-67% protein	kg	200.0	110.0	PE, RLA
Maize grain (proxy for maize and maize gluten meal)	kg	100.0	200.0	RLA
Palm oil	kg	10.0	-	RLA
Rice	kg	100.0	350.0	RLA
Soybean oil	kg	10.0	-	RLA
Soybean meal	kg	200.0	280.0	RLA
Sodium chloride (proxy for premix)	kg	5.0	3.0	RER
Wheat grain	kg	100.0	-	RLA
Protein feed, 100% crude (proxy for aminoacids by-products)	kg	7.0	5.0	RER

The feeding efficiency of aquaculture systems is expressed in terms of its FCR. We used FCRs between 1.4 and 1.8 for trout and between 1.4 and 1.7 for tilapia; all values within the ranges reported in the relevant literature (e.g. Aubin et al. 2009; Pelletier and Tyedmers 2010; Boissy et al. 2011; Mungkung et al. 2013). Our estimations of direct nutrient emissions (N, P) are also within the same orders of magnitude previously reported (Table 3).

Table 3. Nitrogen and phosphorus releases to water (per tonne of live-weight fish): comparison of literature values

Emissions (kg/t fish)	Trout				Salmon	Tilapia	
	This study	Grönroos et al. (2006)	Aubin et al. (2009)	Boissy et al. (2011)	Pelletier et al. (2009)	This study	Pelletier and Tyedmers (2010)
Total N	66.1	52.6	65.0	41.6	71.3	34.7	64.0
Total P	9.6	6.6	10.0	4.2	12.6	3.0	4.6

3.1.4 Canning, freezing and curing

Impacts are driven by energy use and packaging strategy, in line with findings discussed in the literature (e.g. Hospido et al. 2006; Iribarren et al. 2010; Almeida et al. 2015; Laso et al. 2017).

DHC fish processing was modelled in terms of the processing activities, excluding specific sources of raw materials. This approach will enable users to model their own fish processing supply chains.

3.1.5 Fish sticks production

Impacts linked to the production of fish sticks are driven by the use of electricity in the premises of the seafood processing plant, as well as the use of additional ingredients, namely wheat-based breadcrumbs, batter and sunflower oil, and the use of packaging material (Vázquez-Rowe et al. 2013).

The modelling approach selected will enable users to change the proportions of raw materials, since they can be highly variable in terms of the fish species used. For instance, in the United Kingdom the main species used for fish fingers is mackerel, and the use of other vegetable oils is probably the case in most countries.

3.1.6 Mandatory properties

The ecoinvent guideline for data providers (Moreno-Ruiz et al. 2017) demands the provision of eight mandatory properties for all elementary and intermediate flows created by data providers. We obtained these data from multiple sources (Table 4).

Table 4. Mandatory and other useful properties (fat, protein and energy content) for newly created elementary and intermediate flows related with the seafood datasets

Properties	Wet mass	Dry mass	Water in wet mass	Water content	Organic C content	Fat (kg)	Protein (kg)	Energy content (MJ/kg)
Tuna	1.000	0.585	0.415	0.708[a]	0.469	0.025[b]	0.252[b]	5.811[b]
Anchovy	1.000	0.262[c]	0.738	2.817	0.482	0.088[c]	0.191[c]	7.900[c]
Hake	1.000	0.549	0.451	0.820[a]	0.457	0.012[c]	0.166[c]	4.300[c]
Tilapia	1.000	0.562	0.438	0.781[d]	0.460	0.019[c]	0.183[c]	4.500[c]
Trout	1.000	0.577	0.423	0.732[a]	0.479	0.076[c]	0.184[c]	7.200[c]
Fishmeal	0.993	0.916[c]	0.077	0.084[c]	0.466	0.082[c]	0.677[c]	17.900[c]
Fish oil	1.000	0[c]	1.000	1.000[c]	0.726	0.990[c]	0[c]	38.600[c]
Frozen fish	1.000	0.523	0.477	0.911[e]	0.436	0.061[e]	0.180[e]	4.010[e]
Fish residues, discards	1.000	0.569	0.431	0.759[e]	0.474	0.061[e]	0.180[e]	4.010[e]
Canned tuna	1.000	0.676	0.324	0.480[f]	0.549	0.277[f]	0.233[f]	14.482[f]
Canned sardine	1.000	0.599	0.401	0.669[d]	0.482	0.105[d]	0.209[d]	7.740[d]
Canned anchovy	1.000	0.667	0.333	0.500[d]	0.478	0.090[c]	0.213[c]	6.900[c]
Canned small fish	1.000	0.633[g]	0.367[g]	0.584[g]	0.480[g]	0.097[g]	0.211[g]	7.320[g]
Cured anchovy	0.900	0.683[h]	0.217	0.317 [h]	0.476	0.040[c]	0.300[c]	6.500[c]
Trout feed	0.990	0.900[i]	0.090	0.100[i]	0.544	0.276[c]	0.425[c]	39.500[c]
Tilapia feed	0.992	0.910[i]	0.082	0.090[i]	0.452	0.080[c]	0.336[c]	26.500[c]
Pelagic fish	1.000	0.570	0.430	0.754[j]	0.477	0.070[j]	0.179[j]	4.049[j]
Demersal fish	1.000	0.564	0.436	0.773[k]	0.467	0.039[k]	0.181[k]	3.914[k]

Sources: [a] http://frida.fooddata.dk/, [b] http://www.fao.org/wairdocs/tan/x5916e/x5916e01.htm, [c] Avadí (2014), [d] https://ndb.nal.usda.gov/, [e] calculated from data for 49 commercial species (http://www.fao.org/wairdocs/tan/x5916e/x5916e01.htm) and assuming 10% glazing for frozen fish, [f] http://www.fao.org/wairdocs/tan/x5916e/x5916e01.htm, [g] averages of sardine and anchovy values, [h] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3791226/, [i] http://www.fao.org/fishery/affris/other-species/en/, [j] calculated from data for 35 commercial species (http://www.fao.org/wairdocs/tan/x5916e/x5916e01.htm), [k] calculated from data for 15 commercial species (http://www.fao.org/wairdocs/tan/x5916e/x5916e01.htm).

Notes:

- All numbers without a specific source are calculated based on the internal relations among the properties, as defined in Moreno-Ruiz et al. (2017).
- Properties without a unit are dimensionless.
- Organic C content, when unknown, was calculated using the following equations (A. Wilfart, INRA, pers. comm.):
  - C content = polysaccharides * 0.444 + protein * 0.535 + lipids * 0.774
  - polysaccharides = 1 - (protein + lipids + ash)
- Ash contents were obtained from source [a]. Ash content of fish is between 1-2% of the edible portion (http://www.fao.org/wairdocs/tan/x5916e/x5916e01.htm)

3.2 Adapting the modelled activities to other circumstances

The new datasets are easily adaptable by ecoinvent users to model similar systems in other geographies or circumstances, including different fisheries providing raw materials for processing (which implies different FUE), different raw materials for processing, different FCR in aquaculture, and different energy efficiencies in processing. The strategies to follow are summarised in Table 5.

Table 5. Strategies to adapt seafood datasets to different circumstances

Type of activity	Variation	Strategy
Fisheries	By-catch	Add a relevant by-catch
	FUE	Modify fuel consumption
	Vessel size	Recalculate the inclusion of vessel according with mean annual landings and LSW
Aquaculture	FCR	Modify feed input
Seafood processing	Packaging	Add/replace the relevant packaging
	Energy	Modify the energy input to processing
	Co-production	Create a new activity combining the individual activities representing the coproduction
	Different source of raw material	If the source is a different fishery, model the fishery separately and modify the concerned processing activities to use the new fishery as source of inputs. If it is a non-fishery activity (e.g. residues from another industry), models the new activity if necessary and modify the concerned processing activities to use the new input raw material-providing activity as source of inputs

3.3 Influence of system model on the results

Specific choices in the system model, such as the allocation strategy to handle coproduction —economic (Wernet et al. 2016)—, have influenced the results (e.g. the impacts estimated from the modelled inventories). For instance, the preferred allocation for the co-production of fishmeal and fish oil was originally energy content, following seafood LCA literature (Ayer et al. 2007; Pelletier et al. 2015). The original allocation keys were as different as 34:66 when using the criterion of gross energy content, 69:31 based on economic value (using average 2008-2012 prices), and 84:16 by mass (Fréon et al. 2017). In contrast, for the anchovy fishery in Spain, the use of mass, energy or economic allocation implied only marginal changes in the results (Laso et al. 2018).

Other assumptions, such as a complete recycling/disposal of EOL means of production, did not greatly influence results, albeit being necessary for respecting mass balances within the ecoinvent database.

3.4 Limitations and data gaps of the datasets

3.4.1 Fisheries

Modelling of diesel emissions was based on the EMEP/EEA air pollutant emission inventory guidebook 2016 (EMEP/EEA 2016). While this modelling perspective has been repeatedly used for the calculation of emissions from internal combustion in marine engines from fishing vessels in the LCA literature for fisheries, it should be noted that it is considered a proxy for emissions from diesel combusted for inland, coastal and deep-sea fishing. The main pollutants considered in the model are CO, VOC, NO_x and PM derived from soot which mainly have to do with engine technology, and CO_2, SO_x, heavy metals and further PM (mainly sulphate-derived) which originate from fuel speciation (EMEP/EEA 2016). In contrast, ammonia, benzo(a)pyrene, benzo(b)fluoranthene, benzo(k)fluoranthene or indeno(1,2,3-cd)pyrene were excluded from the computation of emissions. A Tier 1 approach was selected, assuming an average technology for each inventoried fleet.

In terms of vessel infrastructure, the main materials of the hull were considered in all the fleets considered in this report. However, other activities linked to vessels were omitted from the modelling. These omissions included electronic material used on the vessels for spotting and navigation, detergents used on board, as well as daily activities of the crew (e.g. cooking, cabin life, etc.). In the specific case of electronic materials, Laso et al. (2018) have acknowledged the existence of this data gap, not only in terms of production, but also in terms of EOL of e-waste (i.e. “waste of electrical and electronic equipment”—WEEE).

As can be observed in Appendix 3. Metadata for the primary data used for all datasets constructed, the representativeness for the anchoveta fleets in terms of landings and fuel use was close to 100% of existing vessels. However, representativeness was lower for the use of lubricant oil and antifouling emissions, since only a few vessels were inventoried for the steel and wooden fleets. Similar trends were also identified for the remaining fleets assessed in this report, where FUE is the most documented inventory and performance parameter.

Modelling of the construction of marine diesel engines and electric motors was based on linear regressions relating the mass of these engines and motors to the proportion of materials used in their construction (Supplementary Material in Fréon et al. 2014b). This approach is more accurate for interpolations than for extrapolations (i.e. engines and motors smaller or larger than those considered in the regressions).

3.4.2 Fishmeal and fish oil production

The main limitation of the datasets for fishmeal and fish oil, as clearly stated in Fréon et al. (2017) is linked to the small number of plants that were inventoried, three. However, it should be also noted that two of these plants constitute some of the biggest by production volume not only in Peru, but also in the world. The third plant, producing residual fishmeal, is representative of the Peruvian residual fishmeal industry, in terms of technology and production volumes. Moreover, the lack of characterisation of the impacts of the production of certain pollutants, as well as their subsequent release to the environmental compartments (e.g., oils, some antifouling substances, biological oxygen demand (BOD)), was excluded from dataset modelling. This also included the omission of odour impacts, which have not been fully integrated into life-cycle modelling.

3.4.3 Aquaculture

Modelled trout systems are representative of the various aquaculture systems operating in the Andean lakes and other South American water bodies. Feed formulations are representative of common commercial formulations for salmonids used in South America. The modelling of tilapia is also representative of tropical aquaculture in South America, mainly based on primary data from Peru and secondary data from Brazil. Modelled feeds represent mean commercial feeds used for tilapia production in the continent, with a predominance of Peruvian companies reporting their products. Overall, simplifications and central values were necessary to be able to represent, in terms of a few processes, the actual complexity of trout and tilapia aquaculture systems (differences among systems for the same fish regarding FCRs, feed formulations and feeding strategies, water management, fertilisation management, etc.). The resulting datasets, nonetheless, are constructed in such a way that could be modified to represent other cage and pond based systems. Moreover, the recommended direct emissions model used is common in aquaculture LCA research.

3.4.4 Canning, freezing and curing

Similarly to that of FMFO production, modelling of fish processing was based on a reduced sample of plants, yet considered as representative of Peruvian production in terms of technologies and production volumes (Avadí et al. 2014a). One of the plants, engaging in canning among other processing activities, is a government-run research-oriented plant (https://www.itp.gob.pe/) whose main purpose is to develop new products on behalf of the private sector. Nonetheless, the scale, specific technologies, and performances are representative of the industry, as confirmed by anonymous industry representatives.

3.4.5 Fish sticks production

The modelling of fish sticks production was based on the data reported by a well-known multinational in the seafood sector. However, these data still constitute one single data point in a varied and fragmented sector. These type of factories usually have a modular disposition, in which different days different types of products can be produced, such as squid rings, fish fingers or other types of battered or frozen, ready-to-fry fish products. Nevertheless, considering the quality of the data provided by the company, with highly detailed energy and raw material inputs, we consider that the data is a solid benchmark for the seafood battering sector.

3.5 Considerations on the sector’s future

We believe the aquaculture sector will continue growing, worldwide and in South America. The reasons have been widely discussed in the literature (e.g. FAO 2018), and could be reduced to a key combination of factors: depletion of wild stocks combined with growing populations with improving purchasing power (which contribute to an increasing demand for fish). Aquafeeds are expected to increment their proportion of alternative protein sources to FMFO, due to economic reasons. Moreover, and perhaps being guilty of wishful thinking, we expect that new business models, better adapted to smallholder fish producers, will be popularised in South America and other areas of the world with predominantly emerging economies.

Fisheries, on the other hand, are expected to be better managed both globally and in South America, as historical experiences of stock degradation or even collapse are taken seriously by both governments and the fishing private sector. However, the displacement of fish schools due to climate change, in many situations drifting away from tropical waters, will alter trophic dynamics and will affect local fishing communities.

The new datasets represent some of the most important (in terms of volume and value) seafood supply chains in Latin America. Key missing systems include Ecuadorian shrimp, Titicaca lake fisheries, Chilean salmon, and other large commercial fisheries in the Pacific (such as the small pelagics fisheries from Peru and Chile).

We expect that more seafood-related datasets will be included in ecoinvent, representing for instance Chinese and other Asian aquaculture systems (which represent the bulk of global fish production, by volume), as well as integrated aquaculture systems which are common in the world (e.g. rice-fish, livestock-fish, integrated multi-trophic aquaculture - IMTA). Additional seafood DHC processing should also be included, representing some widely consumed products, such as surimi and other fish cakes and fish sauces.

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Appendix 1. Maps of seafood production centres in Latin America

Figure 7. The 35 main fishery poles in Latin America (60% of production in 2003)

Source: http://www.fao.org/docrep/006/y4961e/y4961e0e.htm

Appendix 2. Statistics of seafood production in Latin America

Figure 8. South American wild fisheries (marine and inland), top 9 producing countries. Source: (FAO 2017)

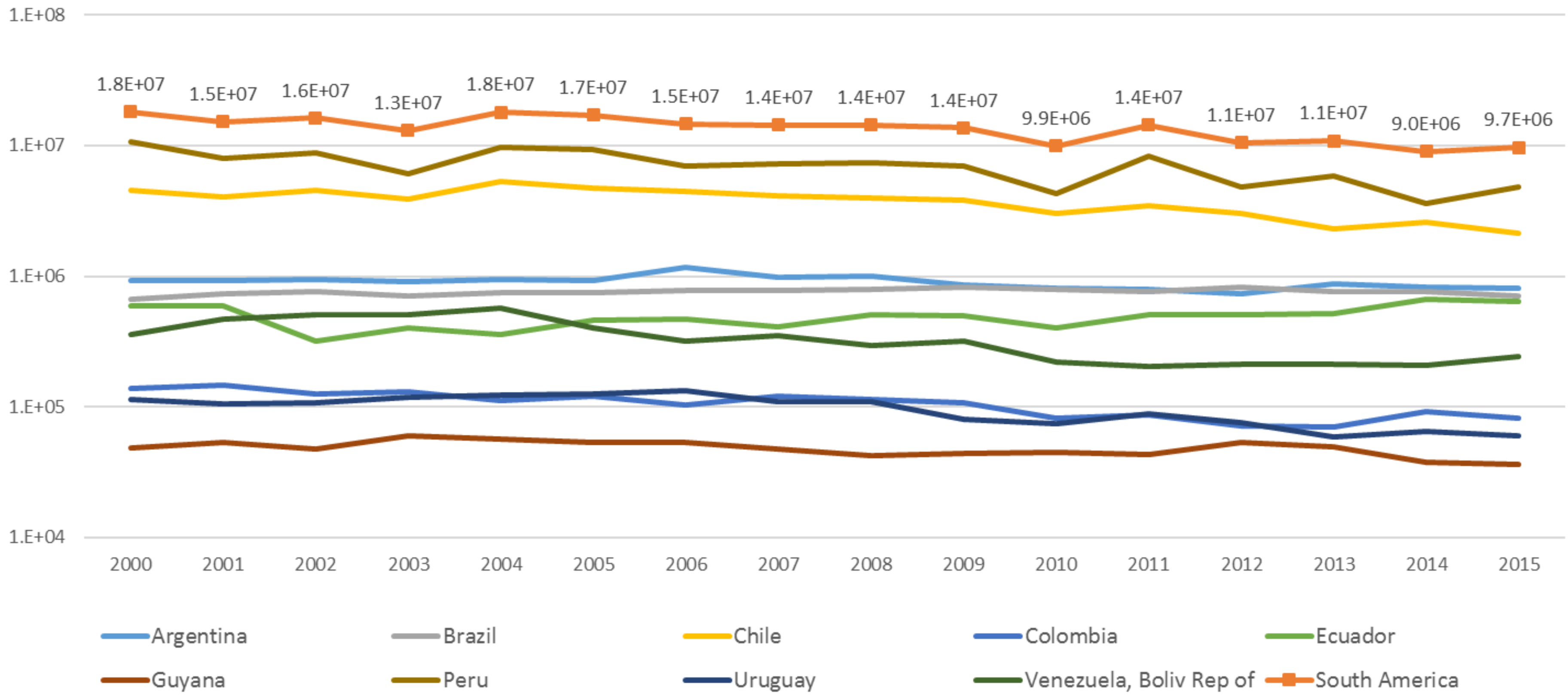
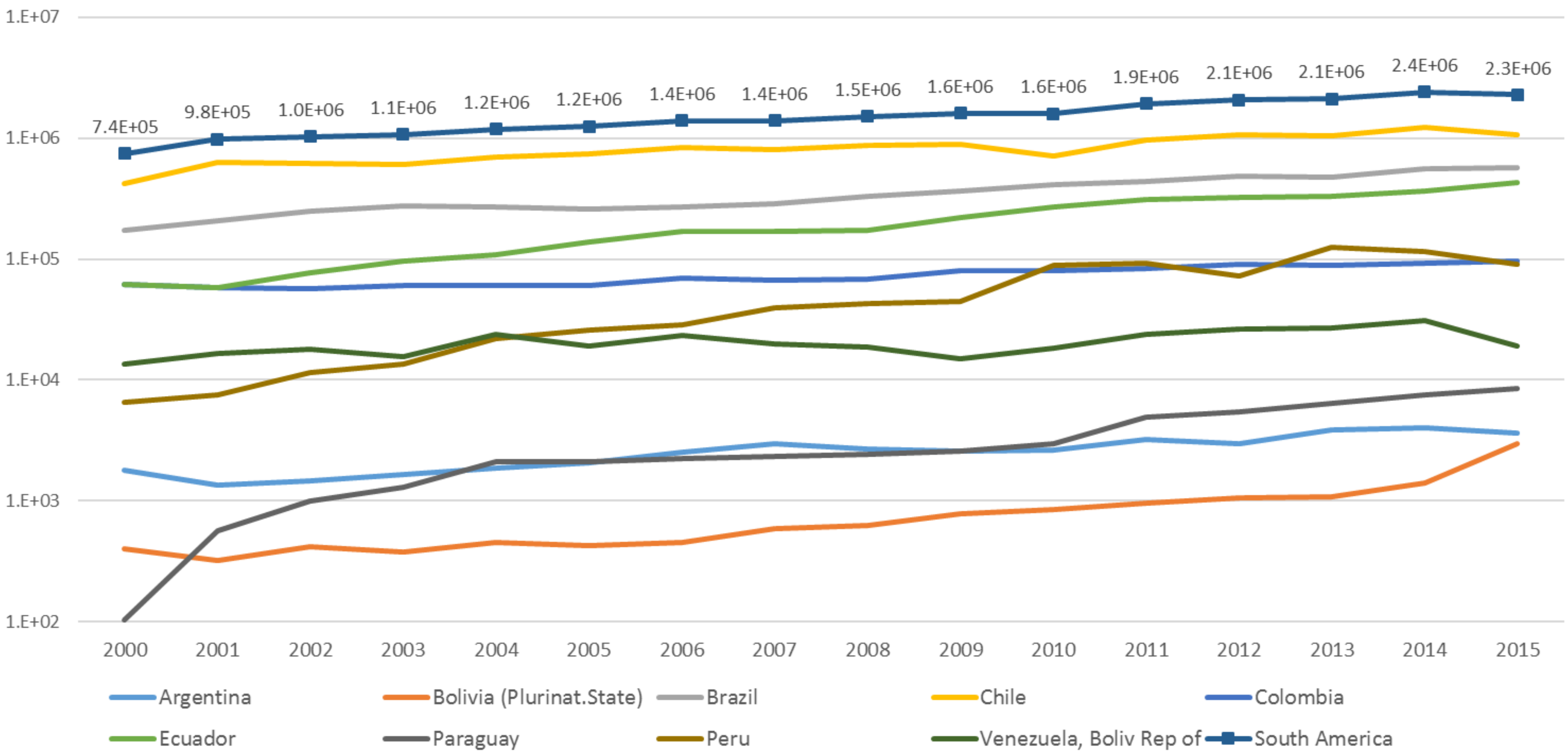


Figure 9. South American aquaculture (marine and inland), top 9 producing countries. Source: (FAO 2017)



Appendix 3. Metadata for the primary data used for all datasets constructed

Datasets	Items	Sampling remarks	Sources
FISHERIES			
Anchovy landed by steel vessels (PE)	Landings/sets Fuel use/trips	561 data points on annual landings and fuel consumption from 316 vessels in 2008-2010	(Fréon et al. 2014b) (FAO 2017)
	Antifouling emissions	Sample: 22 vessels Calculated: 10.4 g per t fish	(Fréon et al. 2014b) (FAO 2017)
	Lubricating oil	Sample: 24 vessels	(Fréon et al. 2014b)
Anchovy landed by wood vessels (PE)	Landings/sets Fuel use/trips	6 915 data points on landings per trip from 1248 vessels in 2005-2011, fuel consumption rates (kg/h) based on secondary data	(Fréon et al. 2014a) (FAO 2017) (Universidad de Piura 2008)
	Antifouling emissions	Sample: 10 vessels Calculated: 10.4 g per t fish	(Fréon et al. 2014b) (FAO 2017)
	Lubricating oil	Sample: 10 vessels	(Fréon et al. 2014a)
Hake landed by steel vessels (PE)	Landings/sets	32 data points from 9 vessels in 2006-2010	(Avadí et al. 2017) (FAO 2017)
	Fuel use/trips	25 data points from 13 vessels in 2012-2013	(Avadí et al. 2017)
	By-catch	Calculated: 6% of hake landings	(Avadí et al. 2017) (FAO 2017)
	Antifouling emissions	Data for 9 vessels	(Avadí et al. 2017)
	Lubricating oil	Monthly data for 9 vessels over 2006-2010	(Avadí et al. 2017)
Tuna landed by steel purse seiners (EC)	Landings/sets Fuel use/trips	25 data points from 13 vessels in 2012-2013	(Avadí et al. 2015a) (FAO 2017)
	By-catch	Calculated: 4% of tuna landings	(Avadí et al. 2015a) (FAO 2017)
	Lubricating oil	Monthly data for 12 vessels over 2012-2013	(Avadí et al. 2015a)
	Refrigerants	Monthly data for 3 vessels over 2012-2013	(Avadí et al. 2015a)
Construction of marine engine (GLO)	Materials	Data from 143 vessels	(Avadí 2014)
Construction of electric motor (GLO)	Materials	Data from 24 motors	(Avadí 2014)
Diesel burned in marine engine (GLO)	Emissions	Emission data from guidelines	(EMEP/EEA 2013) (Tyedmers et al. 2005)

Datasets	**Items**	**Sampling remarks**	**Sources**
Treatment of antifouling paint emissions (PE)	Emissions	Composition from lab analyses of 3 Peruvian antifouling paints; emission rates from scientific publication	(Avadí 2014) (Hospido and Tyedmers 2005)
Construction of steel purse seiner (RLA)	Steel Fishing gear Equipment Engine, motors	Data from 22 to 143 vessels	(Fréon et al. 2014b)
	Electric wiring	Based on 8 different estimations based on reports, shipyard work orders, invoices, etc.	(Fréon et al. 2014b)
Maintenance of steel purse seiner (RLA)	Materials	Data from 143 vessels, some assumptions on replacement rates	(Fréon et al. 2014b)
EOL of steel purse seiner (RLA)	Materials	Assumptions on recycling rates	(Fréon et al. 2014b)
Construction of wood purse seiner (PE)	Steel Wood Fishing gear Equipment Engine, motors	Data from 10 to 600 vessels	(Avadí 2014)
	Electric wiring	Based on 8 different estimations based on reports, shipyard work orders, invoices, etc.	(Fréon et al. 2014b)
Maintenance of wood purse seiner (PE)	Materials	Data from 10 vessels, some assumptions on replacement rates	(Avadí 2014)
EOL of wood purse seiner (PE)	Materials	Assumptions on recycling rates	(Avadí 2014)
Construction of steel trawler (PE)	Steel Fishing gear Equipment Engine, motors	Data from 9 vessels	(Avadí et al. 2017)
	Electric wiring	Based on 8 different estimations based on reports, shipyard work orders, invoices, etc.	(Fréon et al. 2014b) (Avadí et al. 2017)
Maintenance of steel trawler (PE)	Materials	Data from 9 vessels, some assumptions on replacement rates	(Avadí et al. 2017)
EOL of steel trawler (PE)	Materials	Assumptions on recycling rates	(Avadí et al. 2017)
Hake landed by steel vessels- capture by trawler and landing whole (SPAIN)	Landings/sets	The Spanish inventory represent 24 vessels (trawler) out of 101, over two years of operation (2008-2009).	(Vázquez-Rowe et al. 2011)

Datasets	Items	Sampling remarks	Sources
		Sample belongs to data from 11 different ports along the Galician coast, representative of regional and national operation (Spanish data)	
	Fuel use/trips	Amount of marine fuel consumed per landed unit of fish, 495.6 kg per t of landed hake.	(Vázquez-Rowe et al. 2011)
	By-catch	Landed by-catch demersal fish and other crustaceous, 4649.7 kg per t of landed hake	(Vázquez-Rowe et al. 2011)
	Antifouling emissions	Data: Sample 24 vessels. Calculated: 425.8 g per t of landed hake	(Vázquez-Rowe et al. 2011)
	Lubricating oil	Sample 24 vessels. 2.15 kg per t of landed hake	(Vázquez-Rowe et al. 2011)
Diesel burned in marine engine (SPAIN)	Emissions	Emissions data from guidelines	(Vázquez-Rowe et al. 2011)
Treatment of antifouling paint emissions (SPAIN)	Emissions	Composition from lab analyses of 3 antifouling paints; emission rates from scientific publication.	(Vázquez-Rowe et al. 2011)
Construction of steel trawler (SPAIN)	Steel	Data from 24 vessels	(Avadí et al. 2017)
Hake landed by steel vessels - capture by Long lining (RER)	Landings/sets	The European data represent 12 vessels (long lining) out of 49, over one full year of operation (2009). Sample belongs to data from 3 different ports along the European cost.	(Vázquez-Rowe et al. 2011)
	Fuel use/trips	Amount of marine fuel consumed per landed unit of fish, 1305.5 kg per t of landed hake.	(Vázquez-Rowe et al. 2011)
	By-catch	Landed by-catch demersal fish and other crustaceous, 647.98 kg per t of landed hake	(Vázquez-Rowe et al. 2011)
	Antifouling emissions	Data: Sample 12 vessels. Calculated: 1.25 kg per t of landed hake	(Vázquez-Rowe et al. 2011)
	Lubricating oil	Sample 12 vessels. 14.76 kg per t of landed hake	(Vázquez-Rowe et al. 2011)
Diesel burned in marine engine (RER)	Emissions	Emissions data from guidelines	(Vázquez-Rowe et al. 2011)
Treatment of antifouling paint emissions (RER)	Emissions	Composition from lab analyses of 3 antifouling paints; emission rates from scientific publication.	(Vázquez-Rowe et al. 2011)
Construction of steel long lining (RER)	Steel	12 vessels out of 49, over one full year of operation. Sample belongs to data from 3 different ports along the Galician coast, representative of regional and national operations. Spanish data.	(Vázquez-Rowe et al. 2011)

Datasets	Items	Sampling remarks	Sources
	Fishing gear Equipment Engine, motors		(Fréon et al. 2014b)
	Electric wiring	Based on different estimations based on reports, shipyard work orders, invoices, etc.	(Fréon et al. 2014b)
EOL of steel long lining (RER)	Materials	Assumptions on recycling rates	(Vázquez-Rowe et al. 2011)
Operation freezing long lining (RER)	Energy	Data from 12 vessels, freezing and cooling operation during the transport of the fish. 411.53 kg per day	(Vázquez-Rowe et al. 2011)
Hake landed by steel vessels - capture by trawler and landing whole (NA)	Landings/sets	The Namibian data represent 4 vessels in 2011 (capture by trawler and landing whole) over one full year of operation. No feasible data on the size of the fleet.	(Vázquez-Rowe et al. 2014b)
	Fuel use/trips	Amount of marine fuel consumed per landed unit of fish, 370 kg per t of landed hake	(Vázquez-Rowe et al. 2014b)
	By-catch	Landed by-catch demersal fish and other crustaceous, 1244 kg per t of landed hake	(Vázquez-Rowe et al. 2014b)
	Antifouling emissions	Data: sample 4 vessels. Calculated: 0.12 kg per t of landed hake	(Vázquez-Rowe et al. 2014b)
	Lubricating oil	Sample 4 vessels. 0.8 kg per t of landed hake	(Vázquez-Rowe et al. 2014b)
Diesel burned in marine engine (NA)	Emissions	Emissions data from guidelines	(Vázquez-Rowe et al. 2014b)
Treatment of antifouling paint emissions (NA)	Emissions	Composition from lab analyses of 3 antifouling paints; emission rates from scientific publication	(Vázquez-Rowe et al. 2014b)
Construction of steel trawler (NA)	Steel	4 vessels in 2011. No feasible data on the size of the fleet. Namibian data.	(Vázquez-Rowe et al. 2014b)
	Fishing gear Equipment Engine, motors Electric wiring		(Vázquez-Rowe et al. 2014b)
EOL of steel trawler (NA)	Materials	Assumptions on recycling rates	(Vázquez-Rowe et al. 2014b)
Hake landed by steel vessels - capture by trawler and landing whole (GLO)	Landings/sets	13 vessels out of 107, over two years of operations (2006 and 2010). Sample belongs to a single company, representative of national operations. Extrapolated from Peruvian data, uncertainty adjusted accordingly.	(Avadí et al. 2017)

Datasets	Items	Sampling remarks	Sources
	Fuel use/trips	Amount of marine fuel consumed per landed unit of fish, 120 kg per t of landed hake	(Avadí et al. 2017)
	By-catch	Landed by-catch demersal fish and other crustaceous. 1150 kg per t of landed hake	(Avadí et al. 2017)
	Antifouling emissions	Data: sample 13 vessels. Calculated: 0.76 kg per t of landed hake	(Fréon et al. 2014b)
	Lubricating oil	Sample 13 vessels. 0.11 kg per t of landed hake	(Avadí et al. 2017)
Diesel burned in marine engine (GLO)	Emissions	Emissions data from guidelines	(Avadí et al. 2017)
Treatment of antifouling paint emissions (GLO)	Emissions	Composition from lab analyses of 3 antifouling paints; emission rates from scientific publication	(Avadí et al. 2017)
Construction of trawler (GLO)	Steel	13 vessels out of 107, over two years of operations.	(Avadí et al. 2017)
	Fishing gear Equipment Engine, motors Electric wiring		(Avadí et al. 2017)
EOL of steel trawler(GLO)	Materials	Assumption on recycling rates	(Avadí et al. 2017)
Operation freezing trawler (GLO)	Energy	Data from 13 vessels, freezing and cooling operation during the transport of the fish. 600 kg per day	(Avadí et al. 2017)
Hake landed by steel vessels - capture by long liner (GLO)	Landings/sets	12 vessels out of 49, over one full year of operation. Sample belongs to data from 3 different ports along the Galician coast, representative of regional and national operations. Spanish data.	(Vázquez-Rowe et al. 2011)
	Fuel use/trips	Amount of marine fuel consumed per landed unit of fish, 1305.5 kg per t of landed hake	(Vázquez-Rowe et al. 2011)
	By-catch	Landed by-catch demersal fish and other crustaceous. 1664.7 kg per t of landed hake, resource extracted by fisheries	(Vázquez-Rowe et al. 2011)
	Antifouling emissions	Data: sample 12 vessels. Calculated: 1.25 per t of landed hake	(Vázquez-Rowe et al. 2011)
	Lubricating oil	Sample 12 vessels. 14.766 kg per t of landed hake	(Vázquez-Rowe et al. 2011)
Diesel burned in marine engine (GLO)	Emissions	Emissions data from guidelines	(Vázquez-Rowe et al. 2011)

Datasets	Items	Sampling remarks	Sources
Treatment of antifouling paint emissions (GLO)	Emissions	Composition from lab analyses of 3 antifouling paints; emission rates from scientific publication	(Vázquez-Rowe et al. 2011)
Construction of long liner (GLO)	Steel	12 vessels out of 49, over one year of operation. Sample belongs to data from 3 different ports along the Galician coast, representative of regional and national operations. Spanish data.	(Vázquez-Rowe et al. 2011)
	Fishing gear Equipment Engine, motors Electric wiring		(Fréon et al. 2014b)
EOL of long liner (GLO)	Materials	Assumption on recycling rates	(Vázquez-Rowe et al. 2011)
Operation freezing long lining (GLO)	Energy	Data from 12 vessels, freezing and cooling operation during the transport of the fish. 600 kg per day	(Vázquez-Rowe et al. 2011)
Anchovy landed by seining vessels (SPAIN)	Landings/sets	Fresh whole European anchovy (*Engraulis encrasicolus*) captured in the Cantabrian Sea within the Spanish EEZ and landed for fresh consumption and canning. Data were collected for year 2015 for a sample of 32 purse seining vessels out of a total of 41 belonging to the Cantabrian fishing fleet.	(Laso et al. 2018)
	Fuel use/trips	Amount of marine fuel consumed per landed unit of fish, 340 kg per t of landed anchovy	(Laso et al. 2018)
	By-catch	Landed by-catch pelagic fish and discards, 2473.2 kg of fish by-catch per t of landed anchovy	(Laso et al. 2018)
	Antifouling emissions	Data: Sample 32 seining vessels. 1.65 kg per t of landed anchovy	(Laso et al. 2018)
	Lubricating oil	Data: Sample 32 seining vessels. 2.23 kg per t of landed anchovy	(Laso et al. 2018)
Diesel burned in marine engine (RER)	Emissions	Emissions data from guidelines	(Laso et al. 2018)
Treatment of antifouling paint emissions (SPAIN)	Emissions	Composition from lab analyses of 3 antifouling paints; emission rates from scientific publication.	(Laso et al. 2018)

Datasets	Items	Sampling remarks	Sources
Construction of steel seining vessels (SPAIN)	Steel Fishing gear Equipment Engine, motors Electric wiring		(Fréon et al. 2014b)
EOL of steel seining vessel (SPAIN)	Materials	Assumptions on recycling rates	(Laso et al. 2018)
Operation freezing seining vessel (SPAIN)	Energy	Data from 32 purse seining vessels, freezing and cooling operation during the transport of the fish. 10.564 kg per t of landed anchovy	(Laso et al. 2018)
Anchovy landed by seining vessels (GLO)	Landings/sets	Data for a large sample of vessels from various large companies (anonymous) and institutions monitoring landings and operations was collected. Data were collected for a year 2011 for a sample from 20 to 135 vessels.	(Fréon et al. 2014b)
	Fuel use/trips	Amount of marine fuel consumed per landed unit of fish, 16.6 kg per t of landed anchovy	(Fréon et al. 2014b)
	By-catch	Pelagic fish landed as by-catch with anchovy. 0.95 kg of pelagic fish per t of landed anchovy	(Fréon et al. 2014b)
	Antifouling emissions	Data: Sample 20-135 seining vessels. 0.0104 kg per t of landed anchovy	(Fréon et al. 2014b)
	Lubricating oil	Data: Sample 20-135 seining vessels. 0.0806 kg per t of landed anchovy	(Fréon et al. 2014b)
Diesel burned in marine engine (GLO)	Emissions	Emissions data from guidelines	(Fréon et al. 2014b)
Treatment of antifouling paint emissions (GLO)	Emissions	Composition from lab analyses of 3 antifouling paints; emission rates from scientific publication.	(Fréon et al. 2014b)
Construction of steel seining vessels (GLO)	Steel Fishing gear Equipment Engine, motors Electric wiring		(Fréon et al. 2014b)
EOL of steel seining vessel (GLO)	Materials	Assumptions on recycling rates	(Fréon et al. 2014b)

Datasets	Items	Sampling remarks	Sources
Patagonian grenadier, capture by trawler and landing in fish blocks, frozen. RLA	Production	This activity represents the capture of Patagonian grenadier (*Macruronus magellanicus*) along the southern Chilean coast by industrial processing vessels (FAO Area 87; Subarea 87.3). Patagonian grenadier is a gadoid from the Merluccidae family. Two industrial vessels belonging to a Spanish company were included in the study. Together, they landed 11.000 metric tons of fish blocks in 2011. Data is from year 2011	(Vázquez-Rowe et al. 2013)
	boundary	Post landing, port activities were excluded from system boundaries.	
	Fishmeal, 63-65% protein, from anchovy	Fishmeal from the coproduction of fishmeal and fish oil from anchoveta. 164.78 kg per t of fish block hake.	(Vázquez-Rowe et al. 2013)
	Methane, chlorodifluoro, HCFC-22	Cooling agent emissions of R22. 0.78302 kg per 1 t of fish block, hake	(Vázquez-Rowe et al. 2013)
	Ethane, 1,1,1-trifluoro- HCH-1343a	R134a represents 4% of the composition of the cooling agent R404A. 0.0004 kg per 1 t of fish block, hake	(Vázquez-Rowe et al. 2013)
	Trawler, steel	Construction of a trawler, per 1000 kg of light ship weight (LSW). Regressions based on mainly primary data were created to relate the weight of each inventory item to a trawler's LSW. The list of inventory items (granularity) contribute >95% of environmental impacts, as described in the reference publication. 5.3493 kg per 1 t of fish block, hake	(Vázquez-Rowe et al. 2014b)
Patagonian grenadier, capture by trawler and landing in fish blocks, frozen. GLO	Geography	Capture of Patagonian grenadier (*Macruronus magellanicus*) is performed along the southern Chilean coast by industrial processing vessels (FAO Area 87; Subarea 87.3). Fish blocks are landed at a Chilean port (usually Punta Arenas or Chacabuco). Patagonian grenadier is also caught in other areas of the Southern Pacific.	
	Production	This activity represents the capture of Patagonian grenadier (*Macruronus magellanicus*) along the southern Chilean coast by industrial processing vessels	(Vázquez-Rowe et al. 2013)

Datasets	Items	Sampling remarks	Sources
		(FAO Area 87; Subarea 87.3). Patagonian grenadier is a gadoid from the Merluccidae family. Two industrial vessels belonging to a Spanish company were included in the study. Together, they landed 11.000 metric tons of fish blocks in 2011. Data is from year 2011	
	boundary	Post landing, port activities were excluded from system boundaries.	
	Fishmeal, 63-65% protein, from anchovy	Fishmeal from the coproduction of fishmeal and fish oil from Anchoveta. 164.78 kg per t of fish block hake.	(Vázquez-Rowe et al. 2013)
	Methane, chlorodifluoro, HCFC-22	Cooling agent emissions of R22. 0.78302 kg per 1 t of fish block, hake	(Vázquez-Rowe et al. 2013)
	Ethane, 1,1,1-trifluoro- HCH-1343a	R134a represents 4% of the composition of the cooling agent R404A. 0.0004 kg per 1 t of fish block, hake	(Vázquez-Rowe et al. 2013)
	Trawler, steel	Construction of a trawler, per 1000 kg of light ship weight (LSW). Regressions based on mainly primary data were created to relate the weight of each inventory item to a trawler's LSW. The list of inventory items (granularity) contribute >95% of environmental impacts, as described in the reference publication. 5.3493 kg per 1 t of fish block, hake	(Vázquez-Rowe et al. 2014b)
PROCESSING FOR INDIRECT HUMAN CONSUMPTION			
Construction and maintenance of fishmeal plant (PE)	Materials Chemicals Water	Data from 3 plants	(Fréon et al. 2017)
FMFO production (PE), 2 fishmeal qualities	Production Fuel consumption Chemicals Emissions to water	Operative data from 3 plants; statistical data for determining fish:fishmeal and fishmeal:fish oil (PRODUCE annual production figures for the period 2001-2011)	(Fréon et al. 2017)
AQUACULTURE			
Construction and maintenance of a floating collar cage (GLO)	Materials	Data from literature	(Vázques-Olivares 2003)

Datasets	Items	Sampling remarks	Sources
Construction and maintenance of a floating hexagonal metal cage (GLO)	Materials	Data from 6 aquaculture farms	(Avadí et al. 2015b)
Trout feed, 42% protein (RLA)	Ingredients Energy	Data from various literature sources and primary data from feed producers	(Avadí et al. 2015b)
Trout production, semi-intensive, in lake (PE)	Diesel Electricity Feed Infrastructure Transportation of eggs/fingerlings Fingerling provision Emissions to water	FCR based on literature on trout production and primary data from 6 aquaculture farms; input data from primary data from the same farms	(Avadí et al. 2015b)
Tilapia feed, 30% protein (RLA)	Ingredients Energy	Data from various literature sources and primary data from feed producers	(Avadí et al. 2015b)
Tilapia production, semi-extensive, in pond (RLA)	Diesel Electricity Feed Infrastructure Fingerling provision Emissions to water	FCR and input data based on literature on tilapia production	(Avadí et al. 2015b)
PROCESSING FOR DIRECT HUMAN CONSUMPTION			
Construction and maintenance of fish canning plant (RLA)	Infrastructure Equipment (industrial heat) Piping Cleaning agents and other chemicals	Based on a sample of one small-scale Peruvian plant (processing small pelagic fish, capacity: 461 t/y), one Ecuadorian plant (processing tuna, 61 000 t/y) and data from other industry representatives.	(Avadí et al. 2014a) (Avadí et al. 2015a)
Fish canning, small pelagic fish (PE)	Electricity Industrial heat Packaging materials Residues Emissions to water Water	Data from one plant and data from other industry representatives (2011-2012)	(Avadí et al. 2014a)

Datasets	Items	Sampling remarks	Sources
	Salt Infrastructure		
Fish canning, large pelagic fish (EC)	Electricity Industrial heat Packaging materials Residues Emissions to water Water Salt Infrastructure	Data from one plant and data from other industry representatives (2012-2013)	(Avadí et al. 2015a)
Construction and maintenance of fish freezing plant (PE)	Infrastructure Equipment (cooling/freezing) Piping Cleaning agents and other chemicals	Based on a sample of one Peruvian plant (processing small pelagic fish, capacity: 16 200 t/y) and data from other industry representatives.	(Avadí et al. 2014a)
Fish freezing (PE)	Electricity Industrial cooling Packaging materials Residues Emissions to water Water Salt Infrastructure	Data from one plant and data from other industry representatives (2011-2012)	(Avadí et al. 2014a)
Construction and maintenance of fish curing plant (PE)	Infrastructure Equipment (cooling/freezing and industrial heat) Piping Cleaning agents and other chemicals	Based on a sample of one Peruvian plant (processing small pelagic fish, capacity: 2 700 t/y) and data from other industry representatives.	(Avadí et al. 2014a)
Fish curing, small pelagic fish (PE)	Electricity Industrial heat Packaging materials Residues	Data from one plant and data from other industry representatives (2011-2012)	(Avadí et al. 2014a)

Datasets	Items	Sampling remarks	Sources
	Emissions to water Water Salt Infrastructure		
Batter Wheat mix production (RER)	What flour mix Kraft paper, bleached Water Sodium chloride, powder Vegetable oil, refined	This activity represents the production of wheat mix for batter to produce fish sticks, also named fish fingers. The wheat is then grinded at a milling plant in to produce wheat flour. The flour is then freighted by truck to an ingredient and food additive processing plant. No sampling was undergone. The data were directly provided by company technical staff.	(Vázquez-Rowe et al. 2013)
Batter Wheat mix production (GLO)	What flour mix Kraft paper, bleached Water Sodium chloride, powder Vegetable oil, refined	This activity represents the production of wheat mix for batter to produce fish sticks, also named fish fingers. The wheat is then grinded at a milling plant in to produce wheat flour. The flour is then freighted by truck to an ingredient and food additive processing plant. The data were directly provided by company technical staff.	(Vázquez-Rowe et al. 2013)
Breadcrumbs production (RER)	Process plant	Data collection was performed directly with the company that processed the final products. Data from upstream processes were described by plant technicians based on data exchanged with other companies providing materials. Data were collected for a year 2011 as a reference for breadcrumb production in Europe. The breadcrumbs processing plant is located in NW Spain but its products are exported throughout Europe.	
	Production	0.078 Breadcrumbs produced at a grain mill factory in a year	Based on GDP production of Spain.
	Wheat flour	Wheat flour used as main raw material to produce the breadcrumbs. 0.0702 kg per 0.078 kg of breadcrumb produced.	(Vázquez-Rowe et al. 2013)
	Electricity	Electricity used at the plant for breadcrumb processing. 0.00554 kWh per 0.078 kg of breadcrumb produced.	(Vázquez-Rowe et al. 2013)

Datasets	Items	Sampling remarks	Sources
	Heat, central or small-scale, natural gas	Heat from natural gas used for energy at the plant. 0.05971	(Vázquez-Rowe et al. 2013)
	Vegetable oil, refined	Amount of sunflower oil added to produce the breadcrumbs. 0.00234 kg per 0.078 kg of breadcrumb produced.	(Vázquez-Rowe et al. 2013)
	Tap water	Water used in the ingredient and additive food plant. 0.03767 kg per 0.078 kg of breadcrumb produced.	(Vázquez-Rowe et al. 2013)
Breadcrumbs production (GLO)	Process plant	Data collection was performed directly with the company that processed the final products. Data from upstream processes were described by plant technicians based on data exchanged with other companies providing materials. Data were collected for a year 2011 as a reference for breadcrumb production in the world. The breadcrumbs processing plant is located in NW Spain but its products are exported throughout Europe.	
	Production	0.078 Breadcrumbs produced at a grain mill factory in a year	GDP value at a worldwide level.
	Wheat flour	Wheat flour used as main raw material to produce the breadcrumbs. 0.0702 kg per 0.078 kg of breadcrumb produced.	(Vázquez-Rowe et al. 2013)
	Electricity	Electricity used at the plant for breadcrumb processing. 0.00554 kWh per 0.078 kg of breadcrumb produced.	(Vázquez-Rowe et al. 2013)
	Heat, central or small-scale, natural gas	Heat from natural gas used for energy at the plant. 0.05971	(Vázquez-Rowe et al. 2013)
	Vegetable oil, refined	Amount of sunflower oil added to produce the breadcrumbs. 0.00234 kg per 0.078 kg of breadcrumb produced.	(Vázquez-Rowe et al. 2013)
	Tap water	Water used in the ingredient and additive food plant. 0.03767 kg per 0.078 kg of breadcrumb produced.	(Vázquez-Rowe et al. 2013)
Frozen fish sticks production (GLO)	Process plant	Data were reported by technical staff at the seafood processing industry. Extrapolated from RER conditions. Uncertainty was adjusted accordingly. Seafood processing factory in SouthWest Europe activities	(Vázquez-Rowe et al. 2013)

Datasets	Items	Sampling remarks	Sources
		include the reception of hake fish blocks and their processing until they are transformed into fish fingers in a multi-ingredient final product. Data were collected for a year 2011 as a reference for fish sticks production in the world.	
	Production	323.47 grams of fish sticks is the mass content of the ten (10) fish sticks (i.e., fish fingers) contained in one cardboard package ready for distribution and sale. The package itself weighs 25.97 grams. Functional unit of 0.32347 kg of frozen fish sticks, hake.	Global GDP value
	Fish block, hake	Amount of fish block necessary to produce 1 standard package of fish sticks (i.e, 323.47 grams of final product). 0.18 kg of fish block per 0.32347 kg of frozen fish stick	(Vázquez-Rowe et al. 2013)
	Breadcrumbs	Breadcrumbs produced at a grain mill factory. 0.078 kg of breadcrumb per 0.32347 kg of frozen fish stick	(Vázquez-Rowe et al. 2013)
	Sodium hydroxide	Detergents for cleaning purposes. 4.911E-05 kg of sodium hydroxide per 0.32347 kg of frozen fish stick	(Vázquez-Rowe et al. 2013)
	Electricity	Electricity is used in the following activities at the fish stick producing plant: air conditioning, illumination, cold chambers, hydraulic consumption, unwrapping, cutting, battering, breadcrumb addition, frying, freezing, packaging and wastewater treatment. 0.22224 kWh of electricity per 0.32347 kg of frozen fish stick	(Vázquez-Rowe et al. 2013)
	Lubricating oil	Lubricating oil used in the machinery at the plant. 3.11E-06 kg of lubricating oil per 0.32347 kg of frozen fish stick	(Vázquez-Rowe et al. 2013)
	Sunflower seed	Amount of sunflower seeds needed for sunflower oil in the cooking of the fish sticks. 0.028 kg of sunflower seed per 0.32347 kg of frozen fish stick	(Vázquez-Rowe et al. 2013)
	Oil mill	Oil mill used to refine sunflower seeds for the production of sunflower oil added in the process. 2.8025E-09 unis of oil mill kg per 0.32347 kg of frozen fish stick	(Vázquez-Rowe et al. 2013)

Datasets	Items	Sampling remarks	Sources
	Wastewater from vegetable oil refinery	Wastewater from excess of batter. 3.16E-06 m3 of wastewater per 0.32347 kg of frozen fish stick.	Global GDP value
Frozen fish sticks production (RER)	Process plant	Data were reported by technical staff at the seafood processing industry. Extrapolated from RER conditions. Uncertainty was adjusted accordingly. Seafood processing factory in South West Europe activities include the reception of hake fish blocks and their processing until they are transformed into fish fingers in a multi-ingredient final product. Data were collected for a year 2011 as a reference for fish sticks production in Europe.	Production volume calculated on the basis of the European GDP as a proportion of global GDP (i.e., world GDP= 1).
	Production	323.47 grams of fish sticks is the mass content of the ten (10) fish sticks (i.e., fish fingers) contained in one cardboard package ready for distribution and sale. The package itself weighs 25.97 grams. Functional unit of 0.32347 kg of frozen fish sticks, hake.	(Vázquez-Rowe et al. 2013)
	Fish block, hake	Amount of fish block necessary to produce 1 standard package of fish sticks (i.e., 323.47 grams of final product). 0.18 kg of fish block per 0.32347 kg of frozen fish stick	(Vázquez-Rowe et al. 2013)
	Breadcrumbs	Breadcrumbs produced at a grain mill factory. 0.078 kg of breadcrumb per 0.32347 kg of frozen fish stick	(Vázquez-Rowe et al. 2013)
	Sodium hydroxide	Detergents for cleaning purposes. 4.911E-05 kg of sodium hydroxide per 0.32347 kg of frozen fish stick.	(Vázquez-Rowe et al. 2013)
	Electricity	Electricity is used in the following activities at the fish stick producing plant: air conditioning, illumination, cold chambers, hydraulic consumption, unwrapping, cutting, battering, breadcrumb addition, frying, freezing, packaging and wastewater treatment. 0.22224 kWh of electricity per 0.32347 kg of frozen fish stick.	(Vázquez-Rowe et al. 2013)
	Lubricating oil	Lubricating oil used in the machinery at the plant. 3.11E-06 kg of lubricating oil per 0.32347 kg of frozen fish stick.	(Vázquez-Rowe et al. 2013)

Datasets	Items	Sampling remarks	Sources
	Sunflower seed	Amount of sunflower seeds needed for sunflower oil in the cooking of the fish sticks. 0.028 kg of sunflower seed per 0.32347 kg of frozen fish stick.	(Vázquez-Rowe et al. 2013)
	Oil mill	Oil mill used to refine sunflower seeds for the production of sunflower oil added in the process. 2.8025E-09 unis of oil mill kg per 0.32347 kg of frozen fish stick.	(Vázquez-Rowe et al. 2013)
	Wastewater from vegetable oil refinery	Wastewater from excess of batter. 3.16E-06 m3 of wastewater per 0.32347 kg of frozen fish stick.	Production volume calculated on the basis of the European GDP as a proportion of global GDP (i.e., world GDP= 1).

Appendix 4. List of datasets created and some modelling details (as published in v3.5 & v3.6)

Activity name	Geography	Functional unit	Reference product	By-products, waste, direct emissions	Inputs
FISHERIES					
marine electric motor construction	GLO	1000 kg of motor	marine electric motor	• copper scrap, sorted, pressed • aluminium scrap, post-consumer • waste plastic, mixture • scrap steel	• metal working, average for steel product manufacturing • steel, chromium steel 18/8 • aluminium alloy, metal matrix composite • copper • wire drawing, copper • polyethylene, high density, granulate • extrusion, plastic pipes
marine engine construction	GLO	1000 kg of diesel engine	marine engine	• scrap steel • iron scrap, unsorted • aluminium scrap, post-consumer	• metal working, average for steel product manufacturing • steel, chromium steel 18/8 • cast iron • aluminium alloy, metal matrix composite
diesel, burned in fishing vessel	GLO	1 kg of diesel	diesel, burned in fishing vessel	• Sulfur dioxide • Nitrogen oxides • Carbon monoxide, fossil • NMVOC, non-methane volatile organic compounds, unspecified origin • Sulfur oxides • Particulates, < 2.5 um • Lead • Cadmium • Mercury • Arsenic • Chromium • Copper	• diesel

				• Nickel • Selenium • Zinc • Polychlorinated biphenyls • Benzene, hexachloro- • Carbon dioxide, fossil • Particulates, > 2.5 um, and < 10um	
treatment of antifouling paint emissions (2 datasets: one Cu-based and one Sn-based)	PE, GLO	1 kg of antifouling paint solids emitted	antifouling paint emissions	• Arsenic, ion • Copper, ion • Nickel, ion • Lead • Tin, ion • Zinc, ion • Tributyltin compounds • Monobutyltin • Dibutyltin • Monophenyltin • Diphenyltin • Triphenyltin • Trioctyltin • Oils, unspecified	
purse seiner construction, steel	RLA, GLO	1000 kg of light ship weight (LSW)	purse seiner, steel	• used purse seiner, steel	• steel, low-alloyed, hot rolled • steel, low-alloyed • wire drawing, copper • nylon 6-6 • polyethylene, low density, granulate • lead • marine engine • marine electric motor • copper • copper scrap, sorted, pressed

					• metal working, average for steel product manufacturing • alkyd paint, white, without solvent, in 60% solution state
purse seiner maintenance, steel	RLA, GLO	1000 kg of LSW	purse seiner maintenance, steel	• lead in car shredder residue • waste paint on metal • waste plastic, mixture • copper scrap, sorted, pressed • iron scrap, unsorted	• steel, low-alloyed, hot rolled • copper • wire drawing, copper wire drawing, copper • nylon 6-6 • lead • marine engine • alkyd paint, white, without solvent, in 60% solution state
treatment of used steel purse seiner	RLA, GLO	1000 kg of LSW	used purse seiner, steel	• waste polyethylene • waste paint on metal • copper scrap, sorted, pressed • iron scrap, unsorted • waste plastic, mixture • lead in car shredder residue	
purse seiner construction, wood	RLA, GLO	1000 kg of LSW	purse seiner, wooden	• used purse seiner, wooden	• steel, low-alloyed • wire drawing, copper • nylon 6-6 • polyethylene, low density, granulate • lead • marine engine • copper • metal working, average for steel product manufacturing metal working, average for steel product manufacturing • sawn wood, board, hardwood, dried (u=20%), planed • zinc • marine electric motor • cast iron

					• cotton fibre • epoxy resin insulator, SiO2 • bronze • alkyd paint, white, without water, in 60% solution state
purse seiner maintenance, wood	RLA, GLO	1000 kg of LSW	purse seiner maintenance, wooden	• lead in car shredder residue • copper scrap, sorted, pressed • waste paint on wood • waste wood, post-consumer • waste plastic, mixture • iron scrap, unsorted • Solids, inorganic	• steel, low-alloyed, hot rolled • wire drawing, copper • nylon 6-6 • lead • marine engine • alkyd paint, white, without solvent, in 60% solution state • sawnwood, board, hardwood, dried (u=20%), planed • copper • copper scrap, sorted, pressed
treatment of used wooden purse seiner	RLA, GLO	1000 kg of LSW	used purse seiner, wooden	• waste polyethylene • bronze • waste textile, soiled • zinc in car shredder residue • waste paint on wood • copper scrap, sorted, pressed • lead in car shredder residue • iron scrap, unsorted • waste wood, untreated • waste plastic, mixture	
trawler construction, steel	PE, GLO	1000 kg of LSW	trawler, steel	• used trawler, steel	• steel, low-alloyed, hot rolled • steel, low-alloyed • wire drawing, copper • alkyd paint, white, without solvent, in 60% solution state nylon 6-6 • marine engine • marine electric motor

					• copper • reinforcing steel • metal working, average for steel product manufacturing • synthetic rubber
trawler maintenance, steel	PE, GLO	1000 kg of LSW	trawler maintenance, steel	• waste rubber, unspecified • waste paint on metal • waste plastic, mixture • iron scrap, unsorted • copper scrap, sorted, pressed • Solids, inorganic	• steel, low-alloyed, hot rolled • wire drawing, copper • nylon 6-6 • marine engine • alkyd paint, white, without solvent, in 60% solution state • copper • steel, low-alloyed • synthetic rubber
treatment of used steel trawler	PE, GLO	1000 of LSW	used trawler, steel	• waste rubber, unspecified • waste plastic, mixture • waste paint on metal • iron scrap, unsorted • copper scrap, sorted, pressed	
long liner construction, steel	RER, GLO	1000 kg of LSW	long liner, steel		• steel, low-alloyed, hot rolled • steel, low-alloyed • wire drawing, copper • alkyd paint, white, without solvent, in 60% solution state nylon 6-6 • marine engine • marine electric motor • copper • reinforcing steel • metal working, average for steel product manufacturing synthetic rubber
long liner maintenance, steel	RER, GLO	1000 kg of LSW	long liner maintenance, steel	• waste rubber, unspecified • waste paint on metal	• steel, low-alloyed, hot rolled • wire drawing, copper

				• waste plastic, mixture • iron scrap, unsorted • copper scrap, sorted, pressed Solids, inorganic	• nylon 6-6 • marine engine • alkyd paint, white, without solvent, in 60% solution state • copper • steel, low-alloyed • synthetic rubber
anchovy, capture by steel purse seiner and landing whole, fresh	ES, PE, GLO	1000 kg of landed fish	landed anchovy, fresh, EPO	• landed anchovy by-catch, fresh • antifouling paint emissions • waste mineral oil • Discarded fish, pelagic, to ocean	• Fish, pelagic, in ocean • lubricating oil • purse seiner, steel • purse seiner maintenance, steel • diesel, burned in fishing vessel • operation, reefer, freezing
anchovy, capture by wooden purse seiner and landing whole, fresh	PE, GLO	1000 kg of landed fish	landed anchovy, fresh, EPO	• antifouling paint emissions • waste mineral oil • Discarded fish, pelagic, to ocean	• Fish, pelagic, in ocean • lubricating oil • diesel, burned in fishing vessel • purse seiner, wooden • purse seiner maintenance, wooden
hake, capture by trawler and landing whole, fresh	ES, NA, PE, GLO	1000 kg of landed fish (hake and by-catch)	landed hake, fresh	• waste mineral oil • antifouling paint emissions • demersal fish, fresh	• Discarded fish, pelagic, to ocean • Discarded fish, demersal, to ocean • Fish, pelagic, in ocean • Fish, demersal, in ocean • trawler maintenance, steel • trawler, steel • operation, reefer, freezing • lubricating oil • diesel, burned in fishing vessel
hake, capture by long liner and landing whole, fresh	RER, GLO		landed hake, fresh	• antifouling paint emissions • demersal fish, fresh • waste mineral oil • Methane, chlorodifluoro-, HCFC-22	• Fish, demersal, in ocean • diesel, burned in fishing vessel • lubricating oil • long liner maintenance, steel • long liner, steel • operation, reefer, freezing

				• Discarded fish, demersal, to ocean	• landed anchovy, fresh
tuna, capture by purse seiner and landing whole, frozen	EC, GLO	1000 kg of landed fish (tuna and by-catch)	landed tuna, frozen, EPO	• waste mineral oil • small pelagic fish, fresh • antifouling paint emissions	• Fish, pelagic, in ocean • lubricating oil • carbon dioxide, liquid • chlorodifluoromethane • purse seiner, steel • purse seiner maintenance, steel • diesel, burned in fishing vessel • operation, reefer, freezing
PROCESSING FOR INDIRECT HUMAN CONSUMPTION					
fishmeal and fish oil plant construction and maintenance	PE, GLO	1000 kg of processing capacity	fishmeal plant	• scrap steel • iron scrap, unsorted • copper scrap, sorted, pressed • waste concrete • Water	• concrete, normal • sodium hydroxide, without water, in 50% solution state • sodium chloride, powder • metal working, average for metal product manufacturing • copper • wire drawing, copper • steel, low-alloyed • steel, chromium steel 18/8 • tap water
fishmeal and fish oil production, 63-65% protein	PE, GLO	1000 kg of fishmeal	fishmeal, 63-65% protein	• fish oil, from anchovy • Suspended solids, unspecified • BOD5, Biological Oxygen Demand • Oils, non-fossil • TOC, Total Organic Carbon • COD, Chemical Oxygen Demand • DOC, Dissolved Organic Carbon • waste plastic, mixture • Water	• heat, district or industrial, other than natural gas • landed anchovy, fresh • electricity, medium voltage • cyclohexane • polypropylene, granulate • extrusion, plastic film • weaving, bast fibre (ecoinvent v3.5 naming, to be updated in v3.6) • fishmeal plant • fish residues

fishmeal and fish oil production, 65-67% protein	PE, GLO	1000 kg of fishmeal	fishmeal, 65-67% protein	• fish oil, from anchovy • Suspended solids, unspecified • BOD5, Biological Oxygen Demand • Oils, non-fossil • TOC, Total Organic Carbon • COD, Chemical Oxygen Demand • DOC, Dissolved Organic Carbon • waste plastic, mixture • Water	• heat, district or industrial, natural gas • landed anchovy, fresh • electricity, medium voltage • cyclohexane • polypropylene, granulate • extrusion, plastic film • weaving, bast fibre • fishmeal plant
AQUACULTURE					
floating collar net cage for aquaculture 25 m construction and maintenance	GLO	1 unit (70 000 kg fish)	floating collar cage	• waste expanded polystyrene • waste polyethylene • scrap steel	• nylon 6-6 • polyethylene, high density, granulate • steel, low-alloyed • wire drawing, steel • sheet rolling, steel • metal working, average for steel product manufacturing • extrusion, plastic pipes • extrusion, plastic film • weaving, bast fibre • polystyrene, expandable
floating hexagonal metal cage for aquaculture 6 m construction and maintenance	GLO	1 unit (1000 kg fish)	floating hexagonal metal cage	• scrap steel • waste plastic, mixture • waste polyethylene • waste polyurethane foam	• chromium steel pipe • polyurethane, rigid foam • polyethylene, high density, granulate • nylon 6-6 • extrusion, plastic film • weaving, bast fibre • thermoforming of plastic sheets
trout feed production, commercial	RLA, GLO	1000 kg of feed	trout feed, 42% protein	-	• electricity, medium voltage • heat, district or industrial, natural gas

					• heat, district or industrial, other than natural gas • meat and bone meal • quicklime, milled, loose • fish oil, from EPO anchovy • fishmeal, 65-67% protein, from EPO anchovy • maize grain, feed • vegetable oil, refinedrice • soybean meal • sodium chloride, powder • wheat grain, feed • protein feed, 100% crude • oil mill
trout, production in semi-intensive system, in lake	RLA, GLO	1000 kg of whole fish	trout, from aquaculture	• Phosphorus • Nitrogen • Water, unspecified natural origin	• trout feed, 42% protein • floating hexagonal metal cage • diesel, burned in fishing vessel • electricity, medium voltage • oxygen, liquid • transport, freight, aircraft with reefer, freezing • transport, freight, lorry with refrigeration machine, 3.5-7.5 ton, EURO3, R134a refrigerant, freezing • transport, freight, lorry 16-32 metric ton, EURO3
tilapia feed, commercial	RLA, GLO	1000 kg of feed	• trout, from aquaculture	• Phosphorus • Water • Nitrogen	• Water, unspecified natural origin • floating hexagonal metal cage • electricity, medium voltage • trout feed, 42% protein • oxygen, liquid • diesel, burned in fishing vessel

tilapia production, extensive aquaculture, in pond	RLA, GLO	1000 kg of whole fish	• tilapia	• waste concrete • Nitrogen • Water • Water • Phosphorus	• Water, unspecified natural origin • tilapia feed, 24-28% protein • potassium fertiliser, as K2O • poultry manure, dried • electricity, medium voltage • quicklime, milled, packed • concrete, normal • ammonium sulfate, as N
PROCESSING FOR DIRECT HUMAN CONSUMPTION					
fish canning plant construction and maintenance	RLA, GLO	1000 kg of processing capacity	fish canning plant	• waste mineral oil • spent solvent mixture • wastewater from vegetable oil refinery • copper scrap, sorted, pressed • scrap steel	• chromium steel pipe • lubricating oil • industrial furnace, natural gas • soap • polymer foaming • industrial furnace, 1MW, oil • chlorine, liquid • solvent, organic • tap water • propane, burned in building machine • copper • building, hall, steel construction • drawing of pipe, steel • wire drawing, copper • air compressor, screw-type compressor, 300kW
fish canning, large fish	EC, GLO	1000 kg of fish processed into a product	fish canning, large fish	• fish residues • waste polyethylene, for recycling, unsorted • wastewater from vegetable oil refinery • scrap tin sheet • DOC, Dissolved Organic Carbon • TOC, Total Organic Carbon	• extrusion of plastic sheets and thermoforming, inline • fish canning plant • polyethylene, low density, granulate • extrusion, plastic film • carton board box production, with offset printing • electricity, medium voltage

				• BOD5, Biological Oxygen Demand • COD, Chemical Oxygen Demand	• polyethylene, high density, granulate • water, completely softened, from decarbonised water, at user • vegetable oil, refined • heat, district or industrial, other than natural gas • sodium chloride, powder • metal working, average for chromium steel product manufacturing • tin plated chromium steel sheet, 2 mm
fish canning, small fish	PE, GLO	1000 kg of fish processed into a product	fish canning, small fish	• fish residues • scrap tin sheet • wastewater from vegetable oil refinery • Nitrogen • Phosphorus	• fish canning plant • electricity, medium voltage • operation, reefer, freezing • heat, district or industrial, other than natural gas • water, completely softened, from decarbonised water, at user • metal working, average for chromium steel product manufacturing • sodium chloride, powder • vegetable oil, refined • tin plated chromium steel sheet, 2 mm
fish curing plant construction and maintenance	PE, GLO	1000 kg of processing capacity	fish curing plant	• scrap steel • iron scrap, unsorted • waste concrete • copper scrap, sorted, pressed • waste mineral oil • waste aluminium • wastewater from vegetable oil refinery • waste paint on wall • spent solvent mixture	• air compressor, screw-type compressor, 300kW • wire drawing, copper • generator, 200kW electrical • building, hall, steel construction • copper • steel, chromium steel 18/8 • metal working, average for chromium steel product manufacturing • concrete, normal • aluminium, primary, ingot

					• sheet rolling, aluminium • air compressor, screw-type compressor, 4kW • soap • steel, low-alloyed • gas boiler • sodium hydroxide, without water, in 50% solution state • lubricating oil • methyl ethyl ketone • chlorine, liquid • alkyd paint, white, without solvent, in 60% solution state • tap water
fish curing	PE, GLO	1000 kg of fish processed into a product	fish curing, small fish	• fish residues • waste polyethylene, for recycling, unsorted • waste packaging glass, unsorted • scrap aluminium • wastewater from vegetable oil refinery • scrap tin sheet • Nitrogen • Phosphorus	• electricity, medium voltage • vegetable oil, refined • water, completely softened, from decarbonised water, at user • tin plated chromium steel sheet, 2 mm • sodium chloride, powder • metal working, average for chromium steel product manufacturing • fish curing plant • polyethylene terephthalate, granulate, amorphous • thermoforming of plastic sheets • extrusion, plastic film • packaging film, low density polyethylene • nitrogen, liquid • polyethylene, high density, granulate • heat, district or industrial, natural gas • packaging glass, white • sheet rolling, aluminium • aluminium, cast alloy

fish freezing plant construction and maintenance	PE, GLO	1000 kg of processing capacity	fish freezing plant	• scrap steel • used insulation spiral-seam duct rockwool, DN 400 • waste plastic, mixture • wastewater from vegetable oil refinery • copper scrap, sorted, pressed	• tap water • glass wool mat • air compressor, screw-type compressor, 300kW • wire drawing, copper • building, hall, steel construction • copper • steel, chromium steel 18/8 • pump, 40W • metal working, average for chromium steel product manufacturing • generator, 200kW electrical • glass fibre reinforced plastic, polyamide, injection moulded
fish freezing, small fish	PE, GLO	1000 kg of fish processed into a product	fish freezing, small fish	• fish residues • waste polyethylene, for recycling, unsorted • wastewater from vegetable oil refinery • Oils, non-fossil • Phosphorus • Nitrogen	• water, completely softened, from decarbonised water, at user • sodium chloride, powder • extrusion, plastic film • polyethylene, low density, granulate • fish freezing plant • electricity, medium voltage
batter wheat mix production	RER, GLO	22.42 g of batter	wheat flour mix	• wastewater from vegetable oil	• electricity, medium voltage • heat • maize starch • sodium chloride, powder • tap water • vegetable oil, refined • wheat flour
breadcrumbs production	RER, GLO	78 g of breadcrumbs	breadcrumbs	• wastewater from vegetable oil	• electricity, medium voltage • heat • sugar, from sugar beet • sodium chloride, powder

					• tap water • vegetable oil, refined 1. wheat flour
frozen fish sticks production, hake	RER, GLO	323.47 g of fish sticks (1 pack)	frozen fish sticks, hake	• protein feed, 100% crude • waste mineral oil • wastewater from vegetable oil	• fish block, hake • electricity, medium voltage • sunflower seed • wheat flour mix • breadcrumbs • ammonia, liquid • oil mill 2. lubricating oil

Appendix 5. Best practice in seafood LCA

State of the Art of seafood LCA

A documentary review was performed, targeting recent reviews (Henriksson et al. 2012; Vázquez-Rowe et al. 2012; Avadí and Fréon 2013; Avadí et al. 2018; Bohnes et al. 2018), methodological papers (Ayer et al. 2007; Vázquez-Rowe et al. 2010; Avadí and Fréon 2014; Henriksson et al. 2015b; Ziegler et al. 2015), case studies (Henriksson et al. 2014; Almeida et al. 2015; Avadí et al. 2015a) and guidelines (BSI 2012; EPD 2014; Hognes 2014; Cloâtre 2018; Hognes et al. 2018) on LCA applied to seafood-based supply chains. From these, suggestions are given for best practices and more homogenised methods for LCA of seafood systems. Best practices were identified based on criteria such as a) their capacity to complete, complement and support the interpretation of life cycle inventory analysis and life cycle impact assessment results; b) their demonstration in literature beyond methodological proposal; and c) our expert judgement based on an extensive contribution to the field by the co-authors. For instance, preferred fisheries-specific indicators complement conventional LCA by addressing ecological impacts and are easy to calculate (e.g. they rely on easily obtainable data), while preferred uncertainty management approaches have been demonstrated in fisheries and aquaculture case studies, and contribute to more robust interpretation of results.

In seafood LCA literature, there is until today a strong focus on salmonids aquaculture in Europe and North America. Most studies that evaluated Asian aquaculture looked at Pangasius in Vietnam, a commodity mainly exported to the EU and the US. Carp farming in China, however, has been sparsely explored despite being the largest source of farmed fish (FAO 2016). As for supporting data, many studies relied upon generic processes for feed resources from LCI databases. This was deemed concerning in some cases, since until recently, ecoinvent mainly covered European agricultural production. Especially concerning was the use of fishmeal from the consequential LCAFood database (http://www.lcafood.dk/), since this process is incompatible with attributional LCA data and only describes fishmeal from sandeel in Denmark, a marginal source of fishmeal on global markets. LCA studies on fisheries have largely focused on industrial fleets targeting small and large pelagics, cephalopods and demersal fish.

Additional challenges identified, the following are of great relevance to improve the utility of LCA in the management of this industry: a) inclusion of fisheries management concerns and related impact categories (e.g. discards, by-catch, seafloor damage, biotic resource use, biomass removal impacts on the ecosystem and species); b) general LCA challenges in the specific context of seafood supply chains, such as the selection of functional units, the delimitation of system boundaries (e.g. inclusion of capital goods, end-of-life scenarios), cut-off criteria, allocation strategy, and selection of impact categories; c) data availability and data management; and d) the relation between LCA and seafood certifications. Seafood LCA guidelines, including the abandoned Product Environmental Footprint seafood pilot (Hognes 2014), were found to have either failed to include all relevant concerns or to be widely applied by the industry, as noticeable from the documentary review. A consolidated set of practices is thus not widely applied by practitioners. To respond to such situation, best practices were identified to address each challenge (Table 6).

Table 6. Challenges and identified best practices for seafood LCAs

Challenges		Best practices
Inclusion of fisheries management concerns	Capture data	Account for landings, discards, by-catch and on-board process losses (Vázquez-Rowe et al. 2012)
	Seafloor damage	Account for at least distance trawled per functional unit (Nilsson and Ziegler 2007)
	Biomass removal impacts	Prefer less data-intensive indicators (e.g. Hélias et al. 2014; Helias et al. 2018)
	Biotic resource use (BRU) [a]	Calculate BRU per functional unit, including all wild caught and agriculture-derived inputs to processes assessed (applies also to aquaculture and seafood processing)
	Management-related indicators	Include indicators derived from and informing fisheries management (e.g. Shin et al. 2010)
Methodological LCA challenges in the seafood context	Selection of functional units [a]	• Fisheries: 1 mass unit of whole landed fish • Aquaculture: 1 mass unit of whole produced fish at farm gate, 1 mass unit of edible portion at farm gate • Seafood processing: 1 mass unit of final product, including packaging; 1 mass unit of whole fish equivalent in product
	Delimitation of system boundaries [a]	• Include capital goods (infrastructure, fishing vessels) • Include end-of-life in terms of material recycling and land use change • Model fate of by-products (e.g. fish processing residues, process water, excess heat) considering any raw materials they substitute in their receiving treatment/valorisation process (e.g. fish residues may partially substitute fresh whole fish in the fishmeal industry)
	Cut-off criteria	Include ad-minima inventories (Henriksson et al. 2012; Vázquez-Rowe et al. 2012; Fréon et al. 2014b)
	Allocation strategy	Contrast mass-, economic- and gross energy content-based allocation; alternatively, treat it as choice uncertainty (Mendoza Beltran et al. 2016)
	Selection of impact categories	• Select ad-minima lists of impact categories (Henriksson et al. 2012; Vázquez-Rowe et al. 2012; Avadí and Fréon 2013; EC 2013) • Include seafood-specific impact categories (BRU, biomass removal, etc.)
	Direct emissions	Aquaculture: nutrient budget modelling by means of mass balances (including weight gain, feed, faeces and not consumed feed, mortalities) to estimate direct emissions (e.g. Cho and Kaushik 1990; Papatryphon et al. 2005)
Data availability and data management	Data gaps	• Reconstruction of missing data (e.g. fuel use) data from economic data (Fréon et al. 2014b) • Approximate missing values within a dataset by multiple linear regression (Fréon et al. 2014b) • Use models to calculate fuel use or seafloor area trawled from fishing effort
	Uncertainty management	• Data variability: create a typology of systems (fishing vessels, aquaculture farms) on the base of size or

	another defining criterion (Fréon et al. 2014b), or even better by means of statistical methods such as principal component analysis (Abdou et al. 2017). • Data uncertainty: Horizontal averaging of unit process data including estimates for uncertainty (Henriksson et al. 2013). For comparative purposes, perform dependent sampling and pair-wise comparisons (Henriksson et al. 2015b, a) • Data and choice uncertainty: Statistical or pseudo-statistical methods for joint treatment (Andrianandraina et al. 2015; Mendoza Beltran et al. 2016)
Relation between LCA and seafood certifications	Use full-fledged LCAs to provide environmental indicators for and complement seafood certifications (Jonell et al. 2013)

[a] Anchoveta Supply Chains project (http://anchoveta-sc.wikispaces.com)

These proposed best practices aim at improving the quality of seafood LCAs, including the construction of seafood LCI datasets and databases.

Current opportunities, challenges and threats in seafood LCA

Much inventory data relevant to seafood LCAs has been produced. However, a great deal of it has unfortunately gone unreported and there is an overrepresentation in the literature of intensive systems in Western countries. Future efforts should therefore aim at collecting data on a more diverse set of countries and systems, and report these properly.

A large variety of indicators have been proposed by different research groups to cover seafood specific environmental impacts. The most relevant ones, useful to comparatively assess the status of exploited marine ecosystems, were compiled by the IndiSeas project (Shin and Shannon 2009). These type of indicators may complement the environmental impact indicators informed by LCA. Moreover, additional key indicators pertinent to exploited marine ecosystems and fisheries have been proposed and used by environmental assessment practitioners, including those presented in Table 6. Alternatives to these indicators, such as the fish-in fish-out ratio (Jackson 2009; Tacon et al. 2011) as an alternative to BRU or the Lost Potential Yield (Emanuelsson et al. 2014) as an alternative to the impacts on the Biotic Natural Resource (Langlois et al. 2014), were not retained in our list due to additional complexity, refinement specific to certain supply chains but in our view not general enough, and reliance on not easily accessible data (especially for less studies stocks). Other indicators were excluded because they are indices based on more common indicators, such as the energy return on investment, which is the ratio of the energy contained in a seafood product and the industrial energy required for its production (e.g. gross energy or protein energy content per cumulative energy demand) (Tyedmers 2000; Vázquez-Rowe et al. 2014a).

Key methodological, choice and study design challenges in LCA include the selection of functional units, delimitation of system boundaries, cut-off criteria, allocation strategies, selection of impact categories and estimation of direct emissions. Our retained best practices are mainly based on our own experience applying LCA to fisheries, marine and freshwater aquaculture, and seafood processing. We believe the suggested approaches allow delivering more robust and objective results. In the case of allocation, for instance, the use of contrasting allocation keys prevents criticism of the results based on contrasting opinions and preferences by the research community (given that the ISO 14040 standard is subject of dissimilar and even contradictory interpretations (Weidema 2014)).

Data and specially uncertainty management address critical elements determining the results of LCA studies. The quality of the life cycle inventories and an adequate propagation and incorporation of uncertainty into impact assessment results contribute to the robustness of the latter, and facilitate their interpretation. The approaches retained are relatively easy to implement and, in the case of the highlighted uncertainty management methods, they successfully address two of the main sources of uncertainty in LCA, namely data and choices. Addressing the uncertainty due to missing, inaccurate or imprecise characterisation factors is beyond the scope of these recommendations, yet we recommend using the latest and more complete impact assessment methods, models and characterisation sets available, and to clearly identified uncharacterised substances (e.g. antifouling molecules).

Impact assessment results from different studies should not be compared, because they may rely on very different assumptions and methodological choices (at least until a Product Environmental Footprint Category Rules – PEFCR is available). Key inventory items such as fuel, water and chemicals use, in the other hand, can and should be contrasted per equivalent functional units for different studies, because the life cycle inventories analysis phase of LCA also contributes with results and elements of interpretation on the studied system.