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Comparative environmental performance of artisanal and commercial feed use in Peruvian freshwater aquaculture

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ABSTRACT

We used Life Cycle Assessment (LCA) to evaluate some of the environmental implications of using commercial versus artisanal feeds in Peruvian freshwater aquaculture of trout (*Oncorhynchus mykiss*), tilapia (*Oreochromis* spp.) and black pacu (*Colossoma macropomum*). Several scenarios believed to be representative of current Peruvian aquaculture practices were modelled, namely: production of trout in Andean lake cages; and culture of black pacu and tilapia in Amazonian and coastal lowland ponds, respectively. In general, Peruvian aquaculture is characterised by low technological intensity practices. Use of commercial aquafeeds is widespread, but artisanal feeds are frequently used in certain small-scale farms.

We found that trout feeds feature higher environmental burdens than do black pacu and tilapia feeds. A similar trend is observed for production of these species. Across species, the substitution of artisanal with commercial feeds, despite improving feed conversion ratios in all cases, does not always reduce overall environmental impacts. This is due to the additional energy use and transportation requirements associated with commercial feed inputs. The substitution of artisanal feeds with commercial ones generally increases environmental impacts of the fish farming systems for the specific feeds considered, despite enhanced FCRs and economies of scale. This is due to the higher environmental impacts associated to certain feed inputs used in commercial feeds, in particular highly refined feed inputs. Consequently, in light of the importance of feeds to overall life cycle impacts of aquaculture production, the Peruvian aquafeed industry should preferentially source less refined and, in general, less environmentally burdened feed inputs (e.g. Bolivian soybean products over Brazilian, high quality over lower quality fishmeal, avoiding protein concentrates, etc.), to the extent that fish farming performance (i.e. feed conversion efficiency and cost structure) is not strongly affected. Among species, black pacu aquaculture shows the best environmental performance.

1. Introduction

Aquaculture is a globally important food production sector. Worldwide, 59.9 million tonnes of cultured fish, crustaceans, molluscs and other aquatic animals for human consumption, representing USD 119 billion in economic value, were produced in 2010 (SOFIA, 2012). In contrast to stagnation in fisheries landings, aquaculture production has grown, on average, 8.8% per year since the 1980s (SOFIA, 2010, 2012). Freshwater species, largely carps, account for close to 60% of production (SOFIA, 2010).

Feed provision is often considered to be a critical constraint in further expansion of the aquaculture sector (New and Wijkström, 2002) although this issue is highly debated (Asche and Tveterås, 2004; Tacon and Metian, 2008a; Tacon et al., 2011). Only 30% of cultured seafood is currently produced without feed (bivalves) or with limited feed inputs (extensive aquaculture of herbivorous fish species like cyprinids), compared to 50% in 1980 (Chiu et al., 2013; SOFIA, 2012). Moreover, the proportion of fed aquaculture continues to increase as a result of both consumer preference for higher trophic level species and producer preference for the higher growth rates achieved in fed aquaculture systems (SOFIA, 2012).

Availability of fishmeal and oil (FMFO) is of particular concern with respect to ongoing global expansion of fed aquaculture. Despite that inclusion rates of FMFO have declined over time for salmonids and

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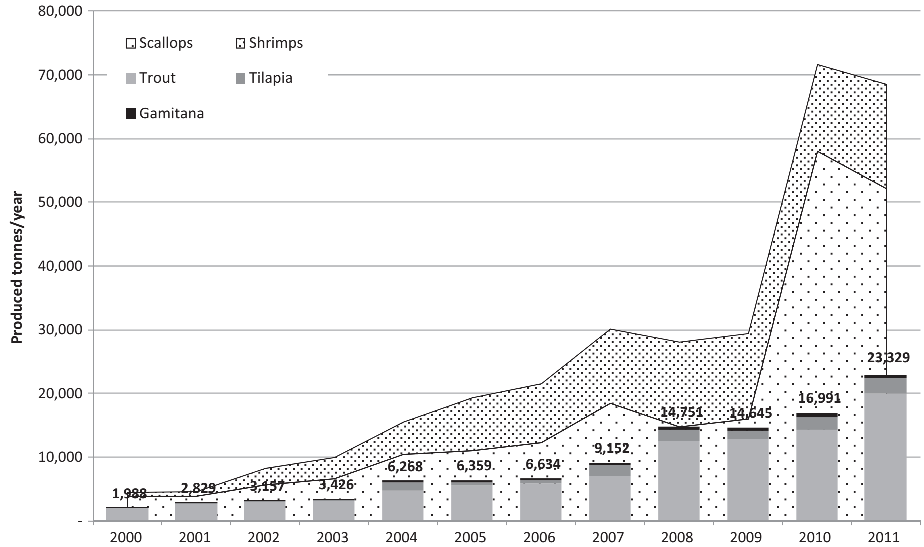

Fig. 1. Production level of the main aquaculture species in Peru (2000–2011).
Source: (PRODUCE, 2012).

shrimps due to increasing use of alternative protein sources (Welch et al., 2010), overall demand has remained relatively constant due to increased use in the production of omnivorous and herbivorous species (Chiu et al., 2013; Naylor et al., 2009; SOFIA, 2012).

Previous research has shown that feed provision accounts for a large fraction of many of the environmental impacts associated with aquaculture supply chains (Henriksson et al., 2012). For instance, several publications highlight the contribution of feeds to overall impacts and specific environmental impact categories (Aubin et al., 2009; Boissy et al., 2011; Cao et al., 2011; Ellingsen and Aanondsen, 2006; Mungkung et al., 2013; Pelletier et al., 2009).

Peruvian aquaculture has grown at an average rate of 30% over the past 20 years. As shown in Fig. 1, production is dominated by marine species (scallops and shrimps, accounting respectively for 50% and 23% of all production), as well as freshwater species such as trout (*Oncorhynchus mykiss*; 22%), red tilapia (*Oreochromis* spp.; 3%) and, more recently, black pacu[1] (*Colossoma macropomum*; 1%) (Mendoza, 2013; PRODUCE, 2009). Other than scallops, production of these species is reliant on exogenous feed inputs. Both artisanal and commercial feeds are used, but the use of commercial feeds is preferred when economically viable for cultured fish producers, especially in the case of trout, mainly because of improved feed conversion ratios (technical feed conversion ratio — FCR, defined as the total feed distributed divided by biomass weight gain). In other words, Peruvian fish farmers usually apply either one or a combination of the following two feeding strategies: one is based on low cost (low value) artisanal feed with limited rearing performance, and the other is based on higher value industrial (commercial) feed with expected better rearing performances. These two strategies and the degree of overlap between them are dependent on the available operational budget of the farmer and the level of technical control over the production cycle.

This paper focuses on the environmental performance of aquaculture, with specific attention to the role of feed provision, for rainbow trout, tilapia and black pacu production in Peru. We developed full Life Cycle Assessment (LCA; ILCD, 2010) models for trout and black pacu production systems. In order to complete an overview of the three main cultured species in the Peruvian freshwater aquaculture sector, tilapia production was also modelled using a screening-level LCA (Wenzel, 1998). We assessed the environmental performance of various types of aquaculture systems of the three above-mentioned species, at farm gate, in order to compare their environmental performance. This was achieved by taking into account the use of either commercial or artisanal feeds and feed formulations. Feeds were also compared directly, at mill gate, in order to gauge their relative environmental performance without considering feed conversion ratios.

The results of this analysis are intended to inform both aquafeed and cultured fish producers as to the relative environmental performance of feed and fish production for alterative species and feeds. A presupposition of this study was that simpler feeds would perform better than more complex ones, when compared in isolation, on a per tonne basis. An a priori supporting argument was that certain feed inputs, especially those featuring more energy-intensive processing stages would feature higher environmental impacts than less processed crop-derived feed inputs. Typical feed inputs of the former type are wet-milling or higher levels of animal- and fish-derived inputs such as fishmeal, fish oil and animal meat.

2. Methods

2.1. Goal and scope definition

This study follows the ISO-standardised framework for Life Cycle Assessment (LCA) studies: 1) goal and scope definition, 2) life cycle inventories, 3) life cycle impact assessment and 4) interpretation (ISO, 2006a).

We constructed LCA models of scenarios for Peruvian fish aquaculture production systems that represent common practices in terms of choice of species (trout, black pacu, tilapia), rearing techniques (intensive and semi-intensive), feed origin (artisanal and commercial) and associated FCRs. In the case of trout and black pacu, only semi-intensive operations were considered because they represent 98% and 97% of national production, respectively (Mendoza, 2011a, 2013). In the case of tilapia, two different methods/operational scales common in Peru were modelled: semi-intensive and super-intensive. These represent 11% and 88% of total national production, respectively (Baltazar, 2009). For the three species considered, the rest of Peruvian production is characterised by small-scale subsistence operations, not included in the current analysis (Mendoza, 2013). Both artisanal and commercial feeds were modelled. We define artisanal feeds as those produced with very simple technology (e.g. extruded cold-pressed and air-dried pellets), at

[1] *Colossoma macropomum* is known as *gamitana* in Peru, *tambaqui* in Brazil, *paco*/*pacu* in Ecuador and Bolivia, *cachama* in Venezuela and Colombia, and internationally as *pacu* or *black pacu*.

small scale, and relying on rather simple formulations that employ mostly local inputs. It is a common practice among Peruvian fish farmers, even small-scale producers, to use commercial feeds when feasible. However, artisanal feed is often used for part of, or over, the whole production cycles due to cost factors (Peruvian fish farmers, anonymous pers. comms.).

Overall, eight different scenarios were analysed in order to determine the influence of these different factors on environmental performance. Table 1 summarises the scenarios that were evaluated, including FCR and feeds used (commercial vs. artisanal). In most tables throughout the paper, abbreviated names are concatenations of three identifiers: the species name (two first letters of their name; "Ga" stands for "gamitana" — black pacu), the type of feed used (three first letters) and the numbering of the scenario (S1 to S3) or the type of feed (F1 to F3).

Full LCAs were performed for trout and black pacu production. Due to lack of access to primary data, a life cycle screening (LCS) – a lighter version of LCA (Wenzel, 1998) – based on secondary data was applied to tilapia production. The functional unit (FU) for this study was one metric tonne (t) of live weight, fresh farmed fish at farm gate; consistent for all species studied. A secondary FU, consisting of 1 t of fresh farmed fish, edible yield, was also used. Both types of FU have been used in aquaculture LCAs (Henriksson et al., 2012). Assessment results using both FUs were compared to isolate the effect of edible yields. Farm-level capital goods, transportation of key production inputs (e.g. fertilised eggs, fishmeal), provision of fry and land transformation activities were included in the analysis. Fig. 2 depicts the system boundaries for the analysis.

The environmental performances of each scenario were compared within and between species. Since no previous LCA studies of black pacu systems were available, our results were benchmarked against tilapia results (similar nutritional requirements and rearing practices at the semi-intensive level), as well as previous demonstrations that, under culture conditions, farming of black pacu and tilapia are similar in terms of yield (Peralta and Teichert-Coddington, 1989).

2.2. Life Cycle Inventory (LCI)

Data collection was carried out during 2012, in cooperation with civil servants of the following institutions: Ministerio de la Producción — Peruvian Ministry of Production, PRODUCE, Instituto del Mar del Perú — Peruvian Institute of the Sea, IMARPE (2012), Instituto de Investigaciones de la Amazonía Peruana — Research Institute of the Peruvian Amazonia, IIAP (2012), and a trout development project of the regional Puno government (PETT, 2012). Five aquaculture farms, three hatcheries and three artisanal aquafeed plants were visited in Puno and Iquitos, and primary operational data collected for the purpose of building life cycle inventories.

General data on Peruvian aquaculture were compiled from official statistics and reports (Mendoza, 2011b, 2013; PRODUCE, 2009, 2010, 2012; Ruiz, 2013). Data for the Life Cycle Screening of Peruvian tilapia farming, including composition of artisanal feeds, were acquired from published sources, reports, theses and other informal literature (Baltazar, 2009; Baltazar and Palomino, 2004; Furuya et al., 2004; Gupta and Acosta, 2004; Handal, 2006; Hurtado, 2005a, 2005b; Lochmann et al., 2009; Luna, 2008; Maradiague et al., 2005; Mendoza, 2011b, 2013; Pelletier and Tyedmers, 2010; UNALM, 2012). Infrastructure and basic maintenance activities were assumed to be similar to black pacu systems, with minor adjustments when necessary. For the purpose of quantifying inputs of capital goods, life spans of black pacu and tilapia production systems (infrastructure, ponds) were estimated at 20 years, while trout cage systems were expected to operate for 10 years (with net replacement every two years) before major infrastructure recapitalisation. The national Peruvian grid energy mix and the local Iquitos grid energy mix were modelled based on recent, official energy reports (MINEM, 2009, 2012).

Table 1
Peruvian aquaculture scenarios defined for this study. See Table 3 for a key of feeds.

	Artisanal feeds	Commercial feeds	
Trout systems	**TrArtS1**	TrComS2	TrComS3
Rearing system	**Cages, semi-intensive**	Cages, semi-intensive	Cages, semi-intensive
Feed	TrArtF1	TrComF2	TrComF3
FCR (average)	**1.8**	1.4	1.4
Black pacu systems	**GaArtS1**	GaComS2	
Rearing system	**Ponds, semi-intensive**	Ponds, semi-intensive	
Feed	GaArtF1	GaComF3	
FCR (average)	**1.7**	1.4	
Tilapia systems	TiArtS1	TiArtS2	TiComS3
Rearing system	Ponds, semi-intensive	Ponds, super-intensive	Ponds, super-intensive
Feed	TiArtF1	TiArtF1	TiComF2
FCR (average)	1.7	1.7	1.4

Primary LCI data were collected for scenarios in bold.
Scenarios represent variations of the base scenario for each species/feed (TrArtS1, GaArtS1, TiArtS1) by replacing artisanal feeds with commercial feeds (expert-provided Peruvian commercial formulations TrComF2, GaComF3 and TiComF2, as detailed in Table 3). Peruvian FCRs are based on Peru-specific experience by the fifth author, and represent national averages.

Due to the importance of feed provision with respect to potential environmental impacts, we used country/product-specific inventory data for key fish (ANCHOVETA-SC project,[2] unpublished data) and agriculture-derived (Pelletier et al., 2009) feed input supply chains, as well as feed manufacturing subsystems. Filleting and other post-farm processing were not considered.

2.2.1. Rearing systems

Fig. 3 depicts the geographical distribution of main aquaculture production areas in Peru.

Most trout culturing operations are artisanal, yet semi-intensive, especially those in the Puno area (Lake Titicaca and nearby water bodies) where the bulk of the national production takes place. Trout farming in the Puno region water bodies consist of artisanal wood- or metal–nylon floating cages (800 kg to 2 000 kg carrying capacity according to size and fish density) and larger scale metal–nylon floating cages (up to 6 t carrying capacity). The production cycle starts at hatcheries with fertilised eggs imported from the USA and Denmark.[3] Fingerlings (fry) are directly transferred into water body-based systems. The total local cycle takes seven to nine months and consumes almost exclusively commercial feeds. Trout is mainly destined for export, despite increasing consumption in the producing areas and large Peruvian cities, particularly in the capital, Lima. Reference literature for the trout LCA, in complement to directly collected data, were derived from Aubin et al. (2009), Boissy et al. (2011), Grönroos et al. (2006) and Roque d'Orbcastel et al. (2009). Water management (i.e. pumping and aeration) is not required here.

Black pacu farming is carried out mainly in large, semi-intensive artificial pond systems, yielding ~10 $t \cdot ha^{-1} \cdot y^{-1}$. The production cycle takes 12 months and consumes mostly commercial feeds. Water replenishment is estimated at 200% per cycle; hence associated energy inputs were included in the model. Fry are provided predominantly by IIAP (2012). This species is cultured almost exclusively in the Amazon basin (Loreto and San Martin areas). Black pacu is mostly consumed locally for three main reasons: the physical isolation of Amazonian

[2] Anchoveta Supply Chains project (ANCHOVETA-SC), http://anchoveta-sc.wikispaces.com.
[3] Fertilised trout eggs, except for a minimum amount, are imported to avoid genetic defects common in the Peruvian broodstock, as well as to improve quality and to decrease mortality (MAXIMIXE, 2010; PETT, 2011).

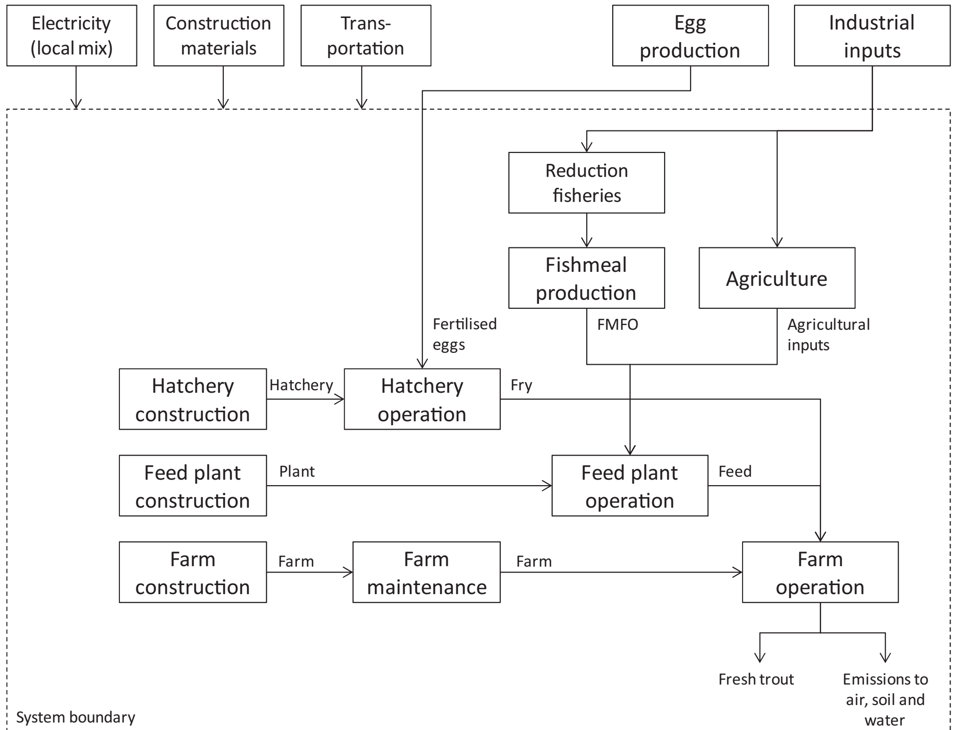

Fig. 2. System boundaries for the trout system model. For black pacu, egg production would be inside the perimeter. Processes outside the perimeter are modelled by modifying ecoinvent processes, except for "egg production", which was not included.

breeders, the growing local demand that resulted in overexploitation of wild stock (Anderson et al., 2011) and the lack of a cold transportation/storage chain for national distribution. No previously published LCA studies of black pacu production are available, thus only directly collected data were used to model production-level activities.

Tilapia is produced using a variety of methods and operational scales, mostly intensive. Most of the farms are located in northern Peru, in the Piura (>88% of production) and San Martín regions (>10% of production). They rely either on semi-intensive pond systems with an annual yield of 15 $t \cdot ha^{-1}$ or on intensive/super-intensive pond systems yielding 200 to 500 $t \cdot ha^{-1}$. Super-intensive production takes place in geomembrane-filled ponds or in concrete ponds with water replenishment rates of up to 700% over the production cycle, and pond aeration (80 $HP \cdot ha^{-1}$, 3 h of use per day). Semi-intensive production usually takes place in semi-natural pond systems, with a water replenishment rate of ~200%, by stream derivation. In Peru, most tilapia fry produced are mono-sex males, obtained by hormone-induced sex reversal (Baltazar, 2009). The whole local production cycle of tilapia takes seven months, and consumes mostly commercial feeds. Tilapia was historically destined to the national market, but over the last decade increasing shares of production have been exported. In complement to directly collected data, reference data for the LCS of tilapia production were derived from a study of lake- and pond-based tilapia farming in Indonesia (Pelletier and Tyedmers, 2010).

Estimated technical FCRs represent Peruvian averages encompassing small and large producers, using artisanal and commercial feeds (see Table 1). Transportation activities (i.e. for commercial feeds and feed inputs transported from Lima to farm areas, and fertilised trout eggs imported mainly from North America) were modelled based on available *ecoinvent* (Ecoinvent, 2012) data, surveys and estimations of distances and routes. The use of fertilisers is very limited in the studied systems. However, the use of quicklime and organic fertiliser (poultry manure) in black pacu ponds and in semi-intensive tilapia farms was included in the models as free inputs, that is to say, without accounting for substitution of chemical fertilisers. Edible yields were obtained by averaging various reference values from literature.

Table 2 describes key features of the modelled systems.

2.2.2. Artisanal and commercial feeds

For commercial feed production, composition data were provided by industrial aquafeed producers (anonymous pers. comms.). A commercial salmonids feed used in Chilean salmon farming (Pelletier et al., 2009), which is sometimes used by Peruvian trout producers, was also modelled. Data for energy inputs to feed milling were derived from published sources (Pelletier and Tyedmers, 2010; Pelletier et al., 2009). Commercial aquafeeds were assumed to be transported from Lima (where most of aquafeed production in Peru takes place) to the farm location by truck.

Fisheries inputs to feeds were modelled using unpublished primary data (ANCHOVETA-SC project) that were collected in the period 2010–2013 and encompass three different fishmeal plants, as detailed in the Supplementary Material (SM), Table B.3. According to this research, fishmeal and fish oil yield rates were 21.3% and 4.3% respectively based on average data for the period 2002–2011. These figures are lower than other values recently reported for Peruvian and foreign FMFO industries (Péron et al., 2010; Samuel-fitwi et al., 2013). Agricultural and animal husbandry inputs to feeds were based on the aquaculture feed supply chain models reported in Pelletier et al. (2009). Additional models were developed (for instance, for Peruvian rice production) where necessary, using equivalent modelling protocols (SM, Appendix A). Geographical origins of feed inputs were assumed based on market share. Minor feed inputs such as micronutrients (vitamin and mineral premixes) were not considered.

For artisanal feed production, composition and operational data were collected via survey. Transportation of all non-local inputs was included in the analysis. Input data for local agricultural feed crops were assumed to be equivalent to national average inputs except

Fig. 3. Department map of Peru, showing main aquaculture-producing regions and main species (PRODUCE data). Labels in bold represent the leading producing region for each species.

when specific data was available (e.g. for seasonal Amazonian rice). Table 3 presents detailed feed formulations, plus additional composition and performance data. Table 4 compares the retained FCRs with other values presented in literature.

It is worth noticing that fishmeal and oil used in Peru are 100% sourced in the country. The bulk of reduction produce is exported, but small amounts are sold for national use (INEI, 2012).

2.2.3. Nutrient emissions

Nitrogen and phosphorus emissions to water from fish farm operations were modelled using the mass balance approach described in Cho and Kaushik (1990) and Kaushik and Cowey (1991). The method was complemented with an emissions fate analysis, based on literature addressing nutrient flows in ponds (Gross et al., 2000; Jiménez-Montealegre et al., 2005). Modelling of emissions to water was based on specific feed and FCR values for each Peruvian scenario modelled.

2.2.4. Allocation

Allocation of impacts among agricultural (crop and animal husbandry) and fisheries inputs and their co-products was based on mass-weighted gross energy content (GEC) (Ayer et al., 2007). Following Pelletier and Tyedmers (2011) we understand LCA as a bio-physical accounting framework, and therefore consider that it should rely on biophysically-driven relationships, not market ones that fail to account for the value of ecosystem services. In the case of fisheries products, for instance, economic allocation (Aubin et al., 2009; Boissy et al., 2011) was deemed less preferable than GEC based allocation, given fluctuating relative prices for FM and FO[4] (Fréon et al., 2013). Relative energy content of FM and FO is, despite natural fluctuations in oil content of fresh *anchoveta* (*Engraulis ringens*, the main species used for reduction in Peru), historically stable, as is the yield of FM and FO per tonne of fish. For methodological consistency, and in compliance

[4] The use of 5-year price averages may help overcome such divergence in relative prices for FM and FO, as done by Aubin et al. (2009) and Boissy et al. (2011).

Table 2
Main features of studied Peruvian aquaculture systems (PRODUCE data, field data and informal literature: Baltazar, 2009; Luna, 2008; Mendoza, 2013; Rebaza et al., 2008; UNIDO, 2005).

Features	Trout (LCA)	Black pacu (LCA)	Tilapia (LCS)
Species	*Oncorhynchus mykiss*	*Colossoma macropomum*	*Oreochromis* spp.
Edible yield (raw fillets)[a]	61%	45%	35%
Location	Titicaca lake, Puno	Iquitos, Loreto	Lancones, Piura and San Martín
Scale	Semi-intensive (artisanal)	Semi-intensive	Intensive
Production	**10 t·cage system^{-1}·y^{-1}**	**10 t·ha^{-1}·y^{-1}**	**Semi-intensive: 15 t·ha^{-1}·y^{-1}** Intensive: 200 t·ha^{-1}·y^{-1} Super-intensive: 500 t·ha^{-1}·y^{-1} **Average intensive: 350 t·ha^{-1}·y^{-1}**
Fry origin	**Imported fertilised eggs, fry produced in Chichillapi, Puno**	**Fry produced and distributed by IIAP**	**Fry produced locally by private companies**
Fry weight	**1.4 g**	**2.0 g**	**5.0 g**
Harvest weight	**350 g**	**1200 g**	**850 g**
Production cycle	**9 months**	**12 months**	**7 months**
Technology	**Lake floating cages**	**Artificial ponds (soil walls), with fertilisation**	**Artificial ponds (geomembrane insulation), fertilisation when semi-intensive**
Mortality	10%	20%	15%
Final density	30 u·m^{-3}	0.5 u·m^{-3}	Semi-intensive: 2–10 u·m^{-3} Average intensive: 15–20 u·m^{-3}
Representativeness[b]	98%	97%	Semi-intensive: 11% Average intensive: 88%
Number of farms[c]	1581	38	56

Note. Figures used for the life cycle modelling are highlighted in bold.
[a] Edible yields are averages of various sources, namely Celik et al. (2008) and Bugeon et al. (2010) for trout; Torry Research Station (1989) and Bocanegra and Bucchi (2001) for black pacu; and Torry Research Station (1989), Mendieta and Medina (1993) and Garduño-Lugo et al. (2003) for tilapia.
[b] Percentage of the national production represented by the modelled system
[c] Only small-scale farms, in 2012 (in Peru, those producing less than 50 t per year).

with the International Organization for Standardization 14044 standard for LCA (ISO, 2006a,2006b), a consistent allocation criterion was used for all feed inputs. System expansion, as strictly defined in ISO 14044, was not appropriate for our analysis since quantification of impacts at the level of individual co-products was of interest.

2.3. Life Cycle Impact Assessment (LCIA)

This study includes some of the impact categories most commonly used in aquaculture LCAs (Aubin, 2013; Parker, 2012), as listed in Table 5. Most of these impact categories are categorised in several Life Cycle Impact Assessment methods, such as CML 2 baseline 2000 v2.05 (Guinée et al., 2001a) and ReCiPe v1.07 (Goedkoop et al., 2012) and are available in the LCA software SimaPro v7.3 (PRé, 2012), which was used in the current analysis. The aggregated ReCiPe single score was also used for comparison purposes. It is computed by applying an additional set of characterisation factors to transform midpoints into endpoints, and then a weighting set to calculate a single score (Goedkoop et al., 2012). The egalitarian perspective was retained for the weighting set because it considers a precautionary (i.e. conservative) principle that assumes a set of high and mid risk scenarios for damage assessment (Goedkoop et al., 2012). Nonetheless, it is worth noting that marine eutrophication and water depletion are excluded from this conversion (Goedkoop et al., 2012), which may constitute a limitation in some aquaculture study cases (thus our conclusions and recommendations are based on both individual impact categories and the single score; see the Results and discussion section). The use of a single score (index) entails both advantages, such as overcoming trade-offs among individual impact categories by facilitating communication through a single figure; but also disadvantages, particularly the loss of information and weighting (which is arbitrary by nature) associated to its computation (Carvalho et al., 2014).

The CML methods were used for most individual mid-point impact categories. However, we also included a mid-point land use impact category that has been recommended for use in aquaculture studies (Henriksson et al., 2012) and a mid-point water depletion impact category (total water inputs to ponds, irrigation to crops) from ReCiPe. In addition, cumulative energy demand (CED), which accounts for all of the primary energy inputs associated with the provision of a product over its life cycle (Hischier et al., 2009; VDI, 1997), was quantified, as was biotic resource use (BRU). BRU represents the primary productivity that underpins production of the fish, and is a function of the specific FCR and the primary productivity appropriated by the feed consumed (Papatryphon et al., 2004). The BRU of crop inputs to feeds is estimated from its carbon content and dry mater content (Papatryphon et al., 2004). The BRU of wild caught fish is calculated using $\text{BRU} = \text{catch}\cdot 9^{-(\text{Trophic level - 1})}$, a general equation assuming a 9:1 ratio of fish wet weight to carbon and a 10% transfer efficiency between trophic levels (Pauly and Christensen, 1995). BRU has been included in many LCAs of fisheries and aquaculture systems (reviews in Avadí and Fréon, 2013; Henriksson et al., 2012; Parker, 2012). Finally, end-point, aggregated scores were also calculated using ReCiPe.

Human, soil and freshwater ecotoxicity were included as characterised in CML 2 (Guinée et al., 2001a,2001b), but with reservations due to the high uncertainty associated with these impact assessment methods (Vázquez-Rowe et al., 2010; Ziegler and Valentinsson, 2008).

Finally, interpretation of LCA results was two-fold. First we compared aquafeeds within and among species, and then aquaculture scenarios within and among species.

3. Results and discussion

3.1. Life cycle inventories

Key LCI data for the modelled systems are summarised in Table 6.

Nutrient emissions to water for each culture system are depicted in Table 7. Nitrogen and phosphorus budgets (SM, Table B.4) show that trout systems release more nutrients, in terms of kg of nitrogen and phosphorus per t of fish produced, than do black pacu and tilapia systems. These values are not always consistent with previously published values (Aubin et al., 2009; Boissy et al., 2011; Grönroos et al., 2006; Jiménez-Montealegre et al., 2005; Pelletier and Tyedmers, 2010). For trout, nutrient emissions for our scenario using commercial feed are close to those described in literature. For black pacu, the observed difference may reflect that the estimates from Jiménez-Montealegre et al. (2005) are based on data obtained from a laboratory experiment (working with juveniles) rather than a real, full production cycle. For tilapia, the difference relates to the differences in FCR assumed

Table 3
Composition of studied aquafeeds.

	Trout						Black pacu				Tilapia			
Data source	Survey		Expert[b]		Pelletier et al. (2009)		Survey A		Expert[b]		UNALM (2012)[c]		Expert[b]	
Feed production scale	Artisanal		Commercial		Commercial		Artisanal		Commercial		Generic		Commercial	
Country and year of use	PE 2012		PE 2012		CL 2007		PE 2012		PE 2012		PE 2012		PE 2012	
Abbreviation	TrArtF1		TrComF2		TrComF3		GaArtF1		GaComF3		TiArtF1		TiComF2	
Ingredients														
Amino acids by-products			0.7%	US					0.5%	US			0.5%	US
Blood meal (poultry)			5.0%	PE									5.0%	PE
Calcium carbonate, salt, etc.			0.8%	PE					1.5%	PE	0.5%	PE	2.0%	PE
Fish oil	5.0%	PE	6.0%	PE	17.2%	PE CL					0.3%	PE	1.0%	PE
Fishmeal	40.0%	PE	20.0%	PE	25.1%	PE CL PY	6.0%	PE			10.0%	PE	4.0%	PE
Lupin seed					0.8%	CL								
Maize	15.0%	BO	5.0%	BO			49.0%	PE	15.0%	BO	8.9%	PE	24.0%	BO
Maize gluten meal			5.0%	US	7.3%	US								
Meat meal (poultry)			15.0%	PE	15.1%	CL BR FR			10.0%	PE			10.0%	PE
Molasses	5.0%	PE												
Palm oil			1.0%	MY										
Monocalcium phosphate									2.5%	PE			1.5%	PE
Rapeseed meal					2.3%	FR								
Rapeseed oil					1.0%	FR								
Rice (broken grains, powder)			10.0%	PE			7.0%	PE					10.0%	PE
Rice bran									35.0%	PE			20.0%	PE
Soy oil			1.0%	BO	4.8%	AR							0.5%	BO
Soybean meal	15.0%	BO	20.0%	BO	9.7%	AR	34.0%	BO	25.0%	BO	32.2%	US	11.0%	BO
Sunflower meal					10.4%	AR								
Vitamins, minerals (premix)			0.5%	PE			4.0%	PE	0.5%	PE	0.9%	PE	0.5%	PE
Wheat	20.0%	PE	10.0%	PE	5.8%	CL					36.0%	PE		
Wheat bran									10.0%	US	11.3%	PE	10.0%	US
Wheat gluten meal					0.6%	UK								
Number and refinement of main inputs [e]	6 (4)		11 (8)		12 (10)		5 (2)		6 (4)		6 (4)		10 (8)	
Nutritional values and FCRs														
Protein	37.6%		42.0%		42.5%		24.5%		24.0%		30.0%		24–28%	
Lipid	8.7%		12.0%		27.2%		3.0%		6.0%		5.3%		6.0%	
Phosphorus	1.0%[a]		1.0%		1.0%[a]		0.8%[a]		0.8%		0.9%		0.8%	
Humidity	15%		11%		12%		15%		11%		15%		11%	
Digestible energy (kcal/kg)	3100		3800		4600		2750		2550		2700		2700	
FCR declared (fish and feed producers)	1.3		1.2–1.3		1.5		1.5		1.5		1.3–1.8[d]		1.3	
FCR retained (averages)	1.8		1.4		1.4		1.7		1.4		1.7		1.4	

ISO country codes. AR: Argentina, BO: Bolivia, BR: Brazil, CL: Chile, FR: France, MY: Malaysia, PE: Peru, US: United States of America, UK: United Kingdom.
[a] Value adopted from commercial feeds.
[b] Peruvian commercial formulations and retained FCRs were provided by an expert in aquafeeds and fish nutrition, based on Peru-specific experience and interactions with manufacturers (fifth author). The sourcing of inputs was based on national trade data and anecdotal accounts.
[c] Based on unpublished data by the National Agricultural University La Molina (UNALM). UNALM produces aquaculture feeds commercially. 10% inclusion of fishmeal in commercial tilapia feeds is confirmed in Furuya et al. (2004).
[d] A feed conversion ratio of 2.2 for super-intensive tilapia farming in Peru has been reported (Baltazar, 2009), but this rate is based on data from the 1990s. Recent data suggests 1.7 for intensive production in Latin America (third author), while IFFO suggests a range of 1.6–1.8 and UNALM suggests 1.3 for Peruvian production.
[e] Only fish, animal and crop-derived inputs. Numbers in parenthesis represent inputs featuring more than 4 refining (i.e. energy-consuming) processes.

Table 4
Comparison of average Peruvian FCRs and literature FCRs for the studied species.

Farming systems	Retained FCRs	Literature FCRs		
		Country	FCR	Source
Trout, cage	1.4–1.8	Australia	1.5	Glencross et al. (2002)
		Finland	1.3	Grönroos et al. (2006)
		Chile	1.4	Tacon and Metian (2008a)
		Peru	1.1–1.4	Tacon and Metian (2008a)
Trout, flow-through	N/A	France	1.1–1.2	Aubin et al. (2009), Boissy et al. (2011)
Tilapia, pond	1.4–1.7	China	1.4–1.9	Chiu et al. (2013)
		Indonesia	1.7–2.1	Mungkung et al. (2013)
		Indonesia	1.7	Pelletier and Tyedmers (2010)
		Jamaica	1.9–2.0	Watanabe et al. (2002)
Black pacu, pond	1.4–1.7	Argentina	1.4–1.7	Bechara et al. (2005)
		Brazil	1.7–1.9	Carvalho and Rodrigues (2009)
		Brazil	1.7–1.9	Nwannaa et al. (2008)

Table 5
Impact categories and aggregated scores used in this study.

Impact category	Method	Typical unit
Acidification potential	CML	kg SO_2-e
Agricultural land occupation	ReCiPe	$m^2 \cdot yr$
Biotic resource use	–	kg C
Cumulative energy demand	CMD	MJ
Eutrophication potential	CML	kg PO_4-e
Global warming potential	CML	kg CO_2-e
Water depletion	ReCiPe	m^3
Toxicity		**kg 1,4-DB-e**
Freshwater aquatic ecotoxicity	CML	kg 1,4-DB-e
Human toxicity	CML	kg 1,4-DB-e
Terrestrial ecotoxicity	CML	kg 1,4-DB-e
ReCiPe single score	**ReCiPe**	**Pt**

in this study compared to those reported in Pelletier and Tyedmers (2010), which are closer to the Peruvian tilapia scenarios using artisanal feeds (UNALM, 2012). Mortalities considered by the authors, another possible source of the differences in calculations, were not reported in Pelletier and Tyedmers (2010). Pond tilapia is able to fix P from sources other than feeds, for instance, from inlet water, from dissolved P emitted by mud, through plankton production, etc. (Schroeder, 1983). For all species, systems using artisanal feeds release more nutrients per unit production than those using commercial feeds.

3.2. Life Cycle Impact Assessment

3.2.1. Relative performance of aquafeeds: artisanal vs. commercial

In an attempt to generalise the initial hypothesis that more refined (and thus generally more energy-intensive) feed inputs are more environmentally burdened than less refined inputs, environmental impacts of various common feed inputs used in Peru were plotted against their associated CED. CED was considered as an expression of feed input level of refinement, although CED also includes the energy demand of fertilisers, etc. Results weakly support the initial hypothesis, i.e. the trend is indeed positive yet with a very low value of the slope a ($p < 0.05$, $a = 0.0036$), as shown in Fig. 4. Additionally, the relation between overall environmental impact of feeds and their digestible energy (Table 3) was tested, and no statistical trend was found for all studied feeds ($p = 0.121$) nor for the subset of artisanal feeds ($p = 0.163$), as shown in the SM (Fig. B.1).

It should be noted that artisanal feed producers usually use residual FM (access to high quality FM is limited for small producers, due to export pressure) while commercial producers have access to high quality FM (anonymous pers. comms.). Taking into account such disparity in access to high quality FM is relevant, because an almost two-fold difference (higher for residual FM) in associated impacts is observed (ANCHOVETA-SC project, unpublished data; Fig. 4). The main reasons for such difference between fishmeal qualities are twofold. First, the difference in the raw material to fishmeal ratio: 4.2 for high quality FM vs 5.5 for residual FM. This difference is explained by difference in raw material: fresh anchoveta vs fish residues, respectively. Second, the difference in drying technology mostly used: indirect steam drying (gas powered vs. direct flame drying by burning heavy fuel, as is common for residual fishmeal production).

Impacts were also compared per tonne of each feed modelled, taking into account only the upstream impacts of the raw material supply chains (i.e. transportation and feed milling were excluded) (Fig. 5). This analysis further supports the hypothesis that feeds composed of less refined inputs will, in general, be less impactful per tonne of feed produced.

A contribution analysis of the studied feeds, at mill gate, is presented in Fig. 6. Trout feeds had the highest overall impacts per tonne of feed milled. This is largely explained by the higher inclusion rates of FMFO (26–45% in trout feeds vs. 0–12% in black pacu and tilapia feeds). The overall impact[5] associated with FMFO is higher than that of most agricultural ingredients (as illustrated in Fig. 4). Feed formulations are driven fundamentally by requirements of protein, energy and Omega-3 fatty acid by the cultured fish. This also strongly influences their environmental performance due to the generally higher environmental impacts associated with the production of fish and animal protein inputs to feeds (Pelletier and Tyedmers, 2007). For instance, the GaComF3 feed features 10% inclusion of animal meat meal in substitute for FMFO. As expected, the contribution of FMFO to total impacts is very large in the trout feed, and less contributing than agricultural inputs in the black pacu and tilapia feeds (where inclusion levels are lower). In the black pacu feed, feed mill infrastructure contributes an atypically large share of impacts, due to the unusual isolation of the communities located in the Loreto province. Indeed most construction materials and equipment need to be transported at least 500 km by boat from the next Peruvian city served by the national road system (Pucallpa), or flown in from elsewhere (usually Lima). Transportation of feed ingredients is relevant in all cases, due to international road, river and sea freight (e.g. road-transported soybean products from Bolivia). Black pacu and tilapia feeds generally feature similar environmental performance, given similar nutritional requirements.

All feeds were also compared per fed species (Fig. 7a, b, c). Among trout feeds (Fig. 7a), TrComF3 features higher associated BRU and toxicity due to greater inclusion of animal inputs, particularly >17% FO (the input with the highest BRU and worse overall environmental performance, Fig. 4). TrComF2 shows the best overall performance among trout feeds, because of reduced inclusion of some heavily environmentally burdened agricultural products such as certain refined maize, soybean and wheat products such as gluten and concentrates (Fig. 4). TrArtF1, despite a simpler formulation and lower impacts in various impact categories (eutrophication potential, global warming potential and BRU), is the worst environmentally performing feed as a result of greater embodied energy requirements of inputs and transportation stages. Among black pacu feeds, the artisanal Amazonian GaArtF1 features better performance in most impact categories than GaComF3 and in total (Fig. 7b), despite the inclusion of FO, which GaComF3 excludes (but it includes an important share of animal meal, rice and wheat products, which have relatively high associated environmental impacts) (Fig. 4). Among the tilapia feeds (Fig. 7c), the artisanal TiArtF1

Table 6
Main inputs to studied aquaculture systems, per tonne of live-weight fish at farm gate.

Inputs	Unit	Trout[c]	Black pacu[d]	Tilapia 1[e]	Tilapia 2[f]
Fry provision	Unit	3143	875	1235	1235
Feed provision (artisanal, commercial)	t	1.8, 1.4	1.7, 1.4	1.7, 1.4	1.7, 1.4
Energy use (electricity, fuels) per t feed					
For artisanal feed production[a]	MJ	1333	1333	1333	1333
For commercial feed production[b]	MJ	1119	682	682	682
On-farm fuel use (water pumping, aeration)	kg	14.0	8.9	–	378
Land occupation (ponds)	ha	N/A	0.10	0.07	0.003
Water use (ponds)	m^3	N/A	29,000	3429	514

[a] Estimated from two Black pacu feed plants and generalised for trout and tilapia due to similar equipment, processes and scale.
[b] Based on commercial feed manufacturing figures in Pelletier et al. (2009) and Pelletier and Tyedmers (2010).
[c] Artisanal/semi-intensive in Puno.
[d] Semi-intensive in Iquitos.
[e] Semi-intensive in Piura.
[f] Super-intensive in Piura.

[5] From a sustainability perspective, beyond environmental impact categories used in LCA, many authors consider the sustainability of carnivorous fish aquaculture could be improved by replacing FMFO with inputs of vegetable origin (Bendiksen et al., 2011; Hasan and Halwart, 2009; Naylor et al., 2009; Tacon and Metian, 2008b), although more detailed quantitative analysis are still required.

Table 7
Nitrogen and phosphorus releases to water (per tonne of live-weight fish): comparison with other values in literature.

Emissions (kg/t fish)	Trout					Salmon	Black pacu			Tilapia		
	This study (artisanal feed)	This study (commercial feed)	Grönroos et al. (2006)	Aubin et al. (2009)	Boissy et al. (2011)	Pelletier et al. (2009)	This study (artisanal feed)	This study (commercial feed)	Jiménez-Montealegre et al. (2005)	This study (artisanal feed)	This study (commercial feed)	Pelletier and Tyedmers (2010)
Total N	80.3	66.1	52.6	65.0	41.6	71.3	38.7	25.8	12.5	53.6	34.7	64.0
Total P	13.6	9.6	6.6	10.0	4.2	12.6	12.1	9.7	N/A	6.8	3.0	4.6

Feed conversion ratios used are shown in Table 1.

performs better than the commercial TiComF2, due to lower levels of fish inputs and highly burdened agricultural inputs.

Despite the fact that commercial feeds feature a better nutrient balance for all species, as shown in Table 7, they also feature worse eutrophication potential. Such performance is due to the composition of both types of feeds. For instance, for Peru-made artisanal and commercial trout feeds, the main contributors to eutrophication are residual fishmeal and transportation for the former, and poultry by-products for the latter (which represents a larger contribution, both in absolute and relative terms).

3.2.2. Relative performance of alternative aquaculture scenarios

The following highlights were identified when comparing scenarios featuring different feed inputs (detailed LCIA results for all modelled scenarios and feeds are presented in SM, Tables B.1 and B.2):

- When using the live weight based FU and artisanal feed, black pacu and tilapia perform better than trout in the most relevant impact categories, except for agricultural land occupation (Fig. 8a). This result is largely due to higher inclusion of FMFO and heavily burdened agricultural inputs in trout feeds, despite much simpler infrastructure and lower land transformation for infrastructure in the cultivation of this species. The same applies when using different feed scenarios and a single score environmental impact (Fig. 9a). The relatively poor performance of the super-intensive tilapia systems (TiArtS2 and TiComS3), comparable to the performance of the best trout scenario (TrComS2) despite less impacting feeds, is due to a high energy consumption for water pumping and aeration in tilapia rearing. Another reason for poor performance in the tilapia scenarios is the difference in the scale and intensity of farming practices (semi-intensive vs. intensive, artisanal vs. larger scale). For instance, the semi-intensive tilapia scenario features an overall performance comparable to that of the black pacu scenarios, which represent semi-intensive systems as well. The large contribution of the maintenance phase to the performance of TiArtS1 is due to the replacement of the geomembrane in ponds. Across scenarios considered, feed contributed between 54 and 82% of impacts (on an aggregated, single-score basis). Black pacu and tilapia scenarios show very similar performance, due to similar rearing techniques (at semi-intensive scale) and feed features – composition and chemical values (Table 3 and Fig. 8a). The poorer performance of the tilapia scenario in certain categories (CED, BRU, and land use) is due to increased on-farm energy use and higher inclusion of fish inputs in the tilapia feed.
- When using the edible yield based FU, the same general pattern of midpoint impact categories is observed as above, but a dramatic deterioration in the performance of tilapia and black pacu systems is observed for several impact categories: global warming potential, eutrophication potential and CED (Fig. 8b). This is due to lower edible yield of these two species (35% and 45% respectively), compared to trout (61%). In contrast, the single score pattern of the three species are altered when compared to those of live weight based FU, trout aquaculture results becoming better than tilapia ones (Fig. 9b). This is not only due to the above-mentioned differences in edible yield between species, but also to the fact that the single score does not consider water depletion and eutrophication (and not directly CED) which are higher for trout than for tilapia cultivation.

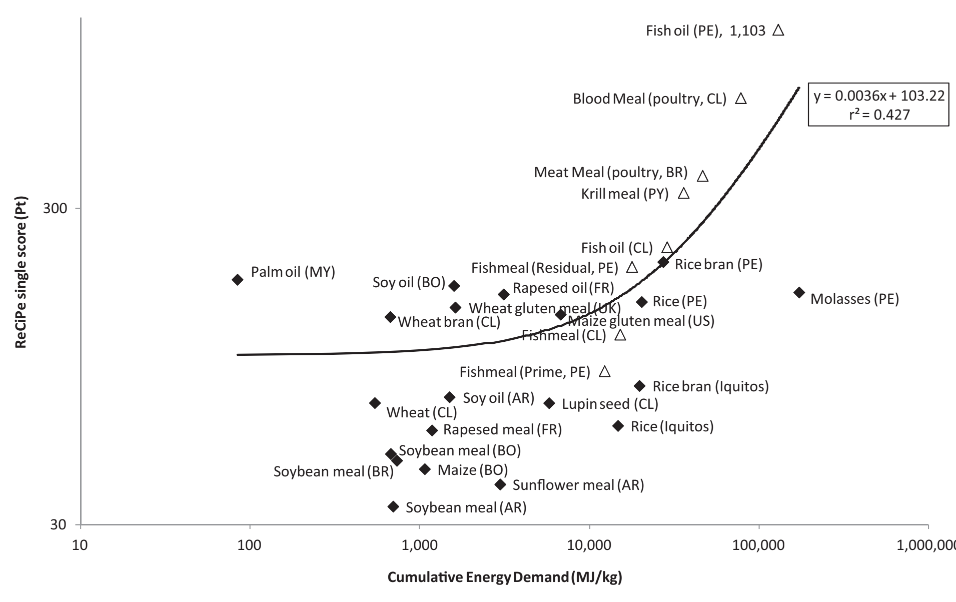

Fig. 4. Environmental performance (ReCiPe single score) of common aquafeed inputs used in Peru in relation to their embodied energy inputs per tonne of product. Triangles represent fish and animal inputs, while diamonds represent agricultural inputs.

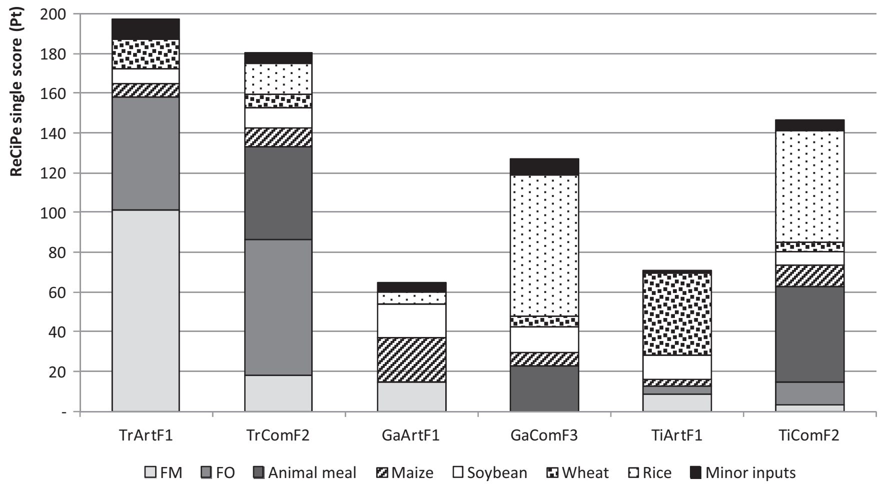

Fig. 5. Contribution analysis of aquafeeds excluding infrastructure, energy and transportation requirements of the milling process to the ReCiPe single score.

- A comparison of all trout scenarios was performed, per impact category and using the live weight based FU, highlighting the contribution of feed (SM, Fig. B.2). As expected (Aubin et al., 2009; Boissy et al., 2011; Pelletier et al., 2009), feed provision contributed with over 50% of the total for most impact categories with the exception of eutrophication potential. For BRU, feed provision contributes 100%. The contribution of feeds to CED represents a larger share in the artisanal Peruvian scenarios because the direct, on-farm energy inputs are low in those systems: in Peru it is common for fish farms to either generate their own electricity with diesel generators and/or use fuel-powered pumping and aeration systems. Trout farming in cages has minimal energy requirements, limited to powering a small storage hall and outboard motor boats.

Performance changes in aquaculture systems occur when replacing artisanal by commercial feeds. In general terms, such a replacement improves fish farming performance, mostly because of improved FCRs. Nonetheless, environmental performance of the aquaculture systems tends to deteriorate, despite improved FCRs and benefits of scale regarding energy use for feed manufacturing. This is due to the large contribution of feeds to overall environmental performance, and to the higher inclusion of more refined (and thus more impacting) inputs in commercial feeds. A clear exception is the trout scenario TrComS2, where the overall performance of both the feed and the aquaculture system is determined by a lower inclusion of FMFO, which compensates for a more complex feed formulation featuring more refined inputs. Transportation of feed plays a minor role in the lower environmental performance, because in artisanal feeds most of the inputs are local (except for fish inputs and non-locally available agricultural inputs, such as soybeans).

3.3. Sensitivity and uncertainty

In LCA studies, there is uncertainty associated to input data, to normative choices and to the underlying mathematical models, or model uncertainty; as discussed in literature (Heijungs and Huijbregts, 2004; Henriksson et al., 2014; Lloyd and Ries, 2007). Methodological

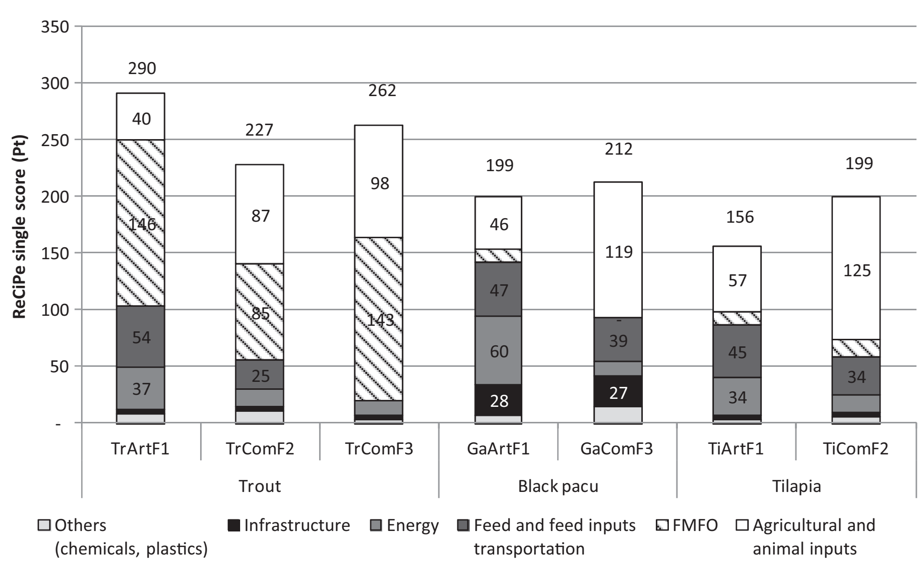

Fig. 6. Contribution analysis of aquafeeds used in Peru (ReCiPe single score). Due to differences in the Pelletier et al. (2009) model and this study's, the value for "Agricultural land and animal inputs" in TrComF3 aggregates the contribution of feed input transportation. Contributions of <20 Pt are not labelled.

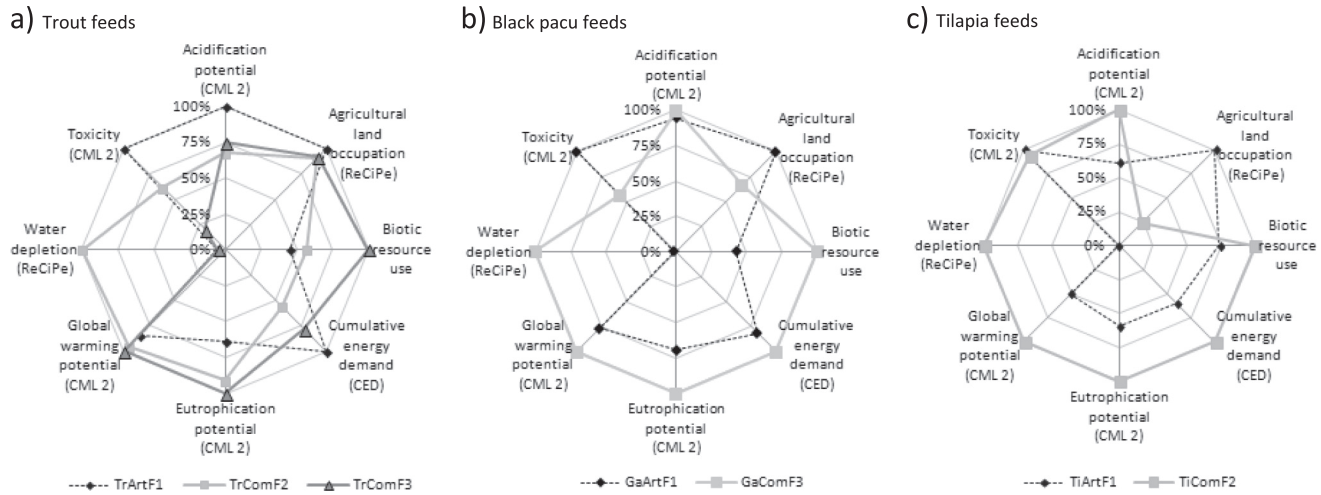

Fig. 7. Relative environmental performance of aquafeeds used in Peru, per tonne of feed, per species.

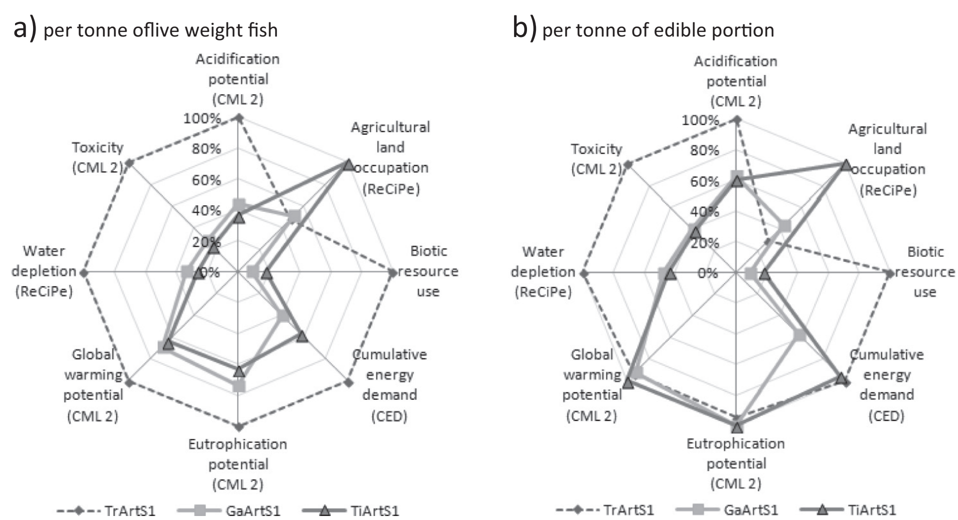

Fig. 8. Relative environmental performance of reference Peruvian aquaculture scenarios, per impact category.

uncertainty is associated to characterisation factors, weighting and normalisation factors, and other elements of the LCA model, also discussed in literature (e.g. Hauschild et al., 2012). In this paper we focused on data uncertainty, mostly associated with assumptions regarding FCRs, feed compositions and modelling of agricultural feed input supply chains, including geographical origin. Some of these attributes were subject to sensitivity and uncertainty analyses, as follows. The protocol for horizontal averaging of unit process data, including estimates for uncertainty (Henriksson et al., 2014) was published after the initial submission of this paper and therefore not used.

Water content of feeds is a source of variation regarding FCRs. When FCRs are recalculated based on dry matter (DM) contents of both fish and feed, in order to compensate for differences in humidity between artisanal (~15%) and commercial (11–12%) feeds, the results suggest that Peruvian commercial black pacu and trout feeds yield more fish DM per unit of feed DM (SM, Table C.1). This is not surprising given that commercial feeds are professionally formulated to match the nutritional needs and promote rapid growth of the cultured organism.

The sensitivity of the aggregate ReCiPe single score results to changes in FCR (±20%) was also analysed. Trout scenarios show higher sensitivity to FCRs (SM, Fig. C1) due to the larger contribution of feeds to overall impacts compared with the tilapia and black pacu scenarios. Regarding emissions to water, results for all species show high sensitivity to changes in assumed FCRs (SM, Table C.2).

Soybean meal and oil are key components in aquafeeds worldwide (SOFIA, 2012). Peruvian feeds use soybean products mainly sourced in Bolivia, but also from Argentina, Brazil and the US. We replaced Bolivian soybean meal in the Peruvian reference trout feed TrArtF1 used in the reference trout scenario TrArtS1 with US and Brazilian soybean meals, to test the influence on the environmental performance of the resulting aquafeed (SM, Fig. C.2). It appears that Bolivian and US products contribute comparably to overall impacts, while Brazilian soybean meal produces a 14% worsening in environmental performance.[6] This difference is mainly due to changes in transportation required and land use demands (i.e. differences in yields). However,

[6] If the comparison would have been done using original *ecoinvent* processes, the contrast would have been even larger. *Ecoinvent* models the provision of stubbed land as a very destructive and impacting process, because transformation of Amazonian rain forest takes place. In the other hand, an *ecoinvent*-based Bolivian soybean model would adapt the original *ecoinvent* Brazilian soybean by identifying the expansion frontier with other biomes less sensitive to natural land transformation, namely bush savannah (Dros, 2004; Kaimowitz and Smith, 2001).

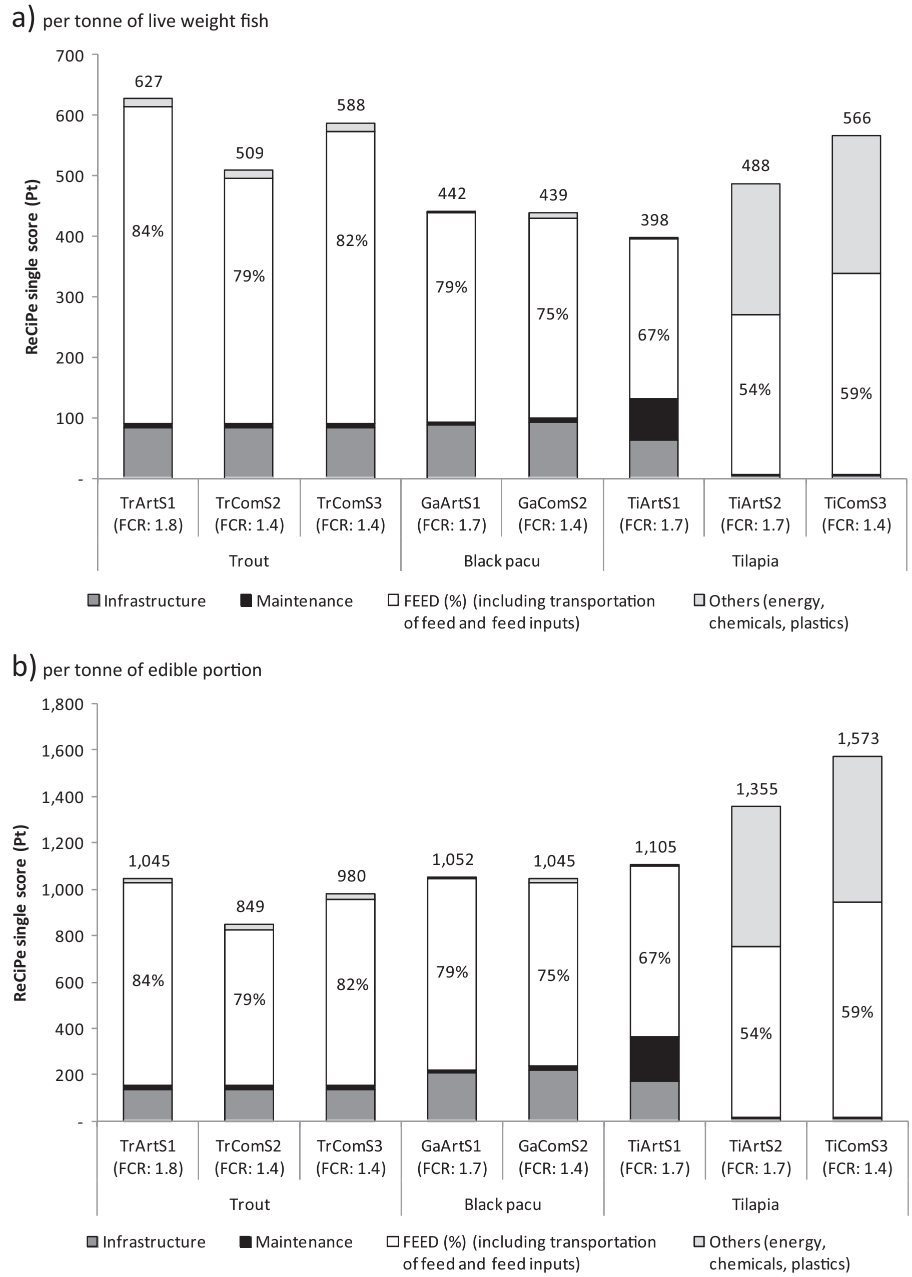

Fig. 9. Relative environmental performance of Peruvian aquaculture scenarios and relative contribution of aquafeed (ReCiPe single score).

land use change and indirect land use change emissions were not considered.

4. Conclusions and recommendations

Peruvian aquaculture is characterised by low levels of technological intensity at farm level (except for super-intensive systems) and the use of both simple artisanal as well as more complex commercial aquafeeds. The substitution of artisanal feeds with commercial ones generally increases environmental impacts of the fish farming systems for the specific feeds considered, despite enhanced FCRs and economies of scale (which decrease, for instance, energy use for feed milling). This reflects the higher environmental impacts attributable to certain feed inputs that are used in commercial feeds — in particular, highly refined feed inputs subject to energy-intensive processing, as well as higher levels of inclusion of animal-derived products. A selection of feed inputs that simultaneously meets the required nutritional profile for the cultured organisms, minimises costs for feed manufacturers,[7] and lowers environmental burdens is therefore desirable. This can be achieved by the use of different feeds according to developmental stages, as shown by ongoing aquaculture, fish nutrition and environmental assessment research (e.g. Amaya et al., 2007; Bendiksen et al., 2011; Hardy, 2006; Li, 2004; Machado and Sgarbieri, 1991; Nguyen et al., 2009; Pelletier and Tyedmers, 2007; Rana et al., 2009; Rust et al., 2011; Samuel-fitwi et al., 2013).

Given the favourable environmental performance of cultured black pacu compared to trout and even more tilapia, when considering the edible yield in the FU, we recommend that further development of black pacu aquaculture (and trout, to a lower extent) be supported in order to increase its supply to both national and export markets. Black pacu aquaculture could be supported, for instance, by diversifying

[7] Prices of feed inputs, especially of FMFO, are key factors in the aquafeed industry, driving innovation and feed formulation decisions (Rana et al., 2009; Tacon et al., 2009).

farming areas to regions with better transportation and cold storage infrastructure. Trout aquaculture would benefit from the national production of high quality fertilised eggs which should overcome existing genetic deficiencies of Peruvian broodstock.

We conclude that, faced with the pressure of increasing the utilisation of cheaper and more efficient commercial aquafeeds, Peruvian aquafeed vendors and aquaculture producers should prefer less environmentally burdened agricultural inputs and low inclusion of highly refined inputs, to the extent that FCR is not compromised. For instance, local maize and rice, Bolivian soybean meal should be preferred to Brazilian soybean meal, whereas gluten meals, protein extracts, vegetable oils with high natural land transformation burdens should be avoided or limited. Peruvian agriculture has not previously been studied by means of life cycle methods, with the exception of a few crops used for bio-fuels (PUCP, 2010). It is advisable that Peruvian agricultural inputs to feeds are analysed using LCA, in order to determine with greater certainty whether local production is environmentally preferable to imported agricultural inputs. Prime instead of residual fishmeal should be used for artisanal feeds when possible because of lower associated environmental impacts.

Finally, best management practices should be developed and applied to Peruvian aquaculture, especially by artisanal/small-scale producers, in order to optimise FCRs by means of enhanced feeding management (e.g. calculation of daily rations; varied feed according to developmental stages). A global approach combining best farming management and good quality feeds (which balance nutritional features and environmental performance) is desirable.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.aquaculture.2014.08.001.

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Supplementary Material

Appendix A. Additional life cycle inventory details and assumptions

Certain assumptions and data treatments were made to construct the life cycle inventories, namely:

- LCIs were collected for the operational phases of aquaculture farming, namely construction, use (including fry and feed provision) and maintenance. No end-of-life or site remediation was considered.
- It was assumed that no chemicals were used during the farm phase of fish production.
- Farm maintenance included water replenishment (when relevant), pond fertilisation only in the cases of black pacu and semi-intensive tilapia farming, and materials replacement in the cases of trout and tilapia (nylon nets and geomembrane, respectively).
- The fuel consumption associated with aeration in super-intensive tilapia farming was calculated based on HP of air pumps and daily operation times.
- Commercial aquafeeds were assumed to be always transported from Lima, where most aquafeed production takes place in Peru, to the farm location. In the case of artisanal feeds produced in the vicinity of the farms, FMFO were assumed to be transported from Lima, while transportation of other non-local inputs (e.g. imported soybean meal and wheat, maize from other regions, etc) is calculated based on the most likely origin and known transportation strategies (e.g. Bolivian soybean meal transported by road, US products transported by freight ship, Chilean products transported by freight ship from Puerto Montt to Ilo, Peru, and then by road; etc).
- All agricultural and animal husbandry inputs were modelled with gross energy content allocation, following (Pelletier et al., 2009). System processes for all major inputs were created or adapted from existing models used in Pelletier et al. (2009). A main difference with the system process modelling described in Pelletier et al. (2009) and its Supplementary Material is that land use (impact category Agricultural land occupation) was considered in the LCIs. Background system data and minor inputs were taken from *ecoinvent* and adapted when necessary (i.e. molasses, monocalcium phosphate, calcium carbonate, and salt) to better approximate regional conditions. Marginal inputs accounting for ~1% of aquafeed formulations, such as vitamin and mineral pre-mixes, were excluded from the analysis. Peruvian fisheries inputs (FMFO) were modelled using gross energy content allocation, based on primary data.
- Peru imports most of the soybean meal (~100%), wheat (~90%) and maize (~60%) it consumes. The main sources of those products are Bolivia, US and Canada, and Argentina, respectively (http://www.agrodataperu.com, based on official trade data). System processes of those inputs were constructed as described in Pelletier et al. (2009).
- Peru is almost self-sufficient regarding rice production, importing barely ~7% of its needs. Two different types of rice cultivation were identified as relevant for Peruvian aquafeeds: average Peruvian rice, extensively produced in the north coastal region (with irrigation and high mechanisation), and rice grown in the Amazonas river basin. The latter is produced mostly for local consumption (thus it is used by aquafeed producers in Iquitos), and it is seasonally grown, taking advantage of the annual flooding of the Amazonas and its tributaries. In that case, CH_4 related to flooding shall not be accounted for because they are not changed (or marginally) by

rice cultivation. An unallocated US rice farming process from *ecoinvent* was modified to represent both average Peruvian and the special Iquitos conditions (e.g. no irrigation, low mechanisation). Allocation between co-products (polished rice, bran and shorts, and husk) was carried out according to a mass-weighted GEC criterion. Yield data for Iquitos and Peruvian average rice were taken from 5-year averages (2007-2011) by FAOSTAT (FAO, 2013) and the Peruvian Ministry of Agriculture (MINAG, 2012).

- The Peruvian grid's energy mix was modelled based on the last officially published comprehensive energy dataset (MINEM, 2009). Iquitos is isolated from the national grid system, and generates most of the electricity locally, by means of public and private thermal stations using diesel and heavy (residual) oil. The Iquitos energy mix was modelled using official data disaggregated by region (MINEM, 2012). Electricity use for feed production was included, while its use at farm level was considered unimportant and thus disregarded. The farming stage of both trout in cages and black pacu in ponds has minimal electricity requirements, while data for tilapia was not available. It is common in Peru for fish farms to either generate their own electricity with diesel generators or use fuel-powered pumping and aeration.

Appendix B. Additional results

Table B.1a LCIA of modelled Peruvian scenarios, per t of live weight fish, allocated by gross energy content (see Table 3 for key of feed origins)

Aquaculture scenarios -->		**TrArtS1**	TrComS2	TrComS3	**GaArtS1**	GaComS2	**TiArtS1**	TiArtS2	TiComS3
Species		**Trout**	Trout	Trout	**Black pacu**	Black pacu	**Tilapia**	Tilapia	Tilapia
Rearing system		**Cages, semi-intensive**	Cages, semi-intensive	Cages, semi-intensive	**Ponds, semi-intensive**	Ponds, semi-intensive	**Ponds, semi-intensive**	Ponds, super-intensive	Ponds, super-intensive
Feed production		**artisanal**	commercial	commercial	**artisanal**	commercial	**generic**	generic	commercial
Feed origin		**PE 2012**	PE 2012	CL 2007	**PE 2012**	PE 2012	**PE 2012**	PE 2012	PE 2012
FCR		**1.8**	1.4	1.4	**1.7**	1.4	**1.7**	1.7	1.4
LCIA categories	Unit								
Acidification potential	kg SO_2-e	**48.0**	29.1	33.2	**21.9**	20.6	**18.2**	28.6	36.2
Agricultural land occupation	m^2.yr	**6 843**	4 849	4 882	**7 235**	3 938	**14 256**	14 262	2 808
Biotic resource use	kg C	**31 023**	30 023	52 983	**2 796**	6 550	**5 653**	5 653	6 320
Cumulative energy demand	MJ	**61 810**	42 826	57 060	**27 898**	33 254	**42 164**	40 144	52 798
Eutrophication potential	kg PO_4-e	**80.7**	64.2	76.4	**59.8**	48.3	**51.3**	53.7	36.3
Global warming potential	kg CO_2-e	**2 794**	3 159	3 433	**2 056**	2 460	**1 937**	2 890	4 124
Water depletion	m^3	**15 132**	15 241	15 132	**5 066**	5 561	**3 973**	1 058	1 444
Toxicity LCIA categories	Unit								
Freshwater aquatic ecotoxicity	kg 1,4-DB-e	**472**	392	340	**172**	222	**167**	151	241
Human toxicity	kg 1,4-DB-e	**2 517**	1 305	1 403	**689**	622	**548**	634	811
Terrestrial ecotoxicity	kg 1,4-DB-e	**54.7**	28.9	12.1	**14.0**	7.2	**9.1**	10.3	9.4
Total toxicity	kg 1,4-DB-e	**3 045**	1 726	1 755	**875**	851	**725**	796	1 061
LCIA single score	Unit								
ReCiPe single score (fish)	Pt	**583**	506	584	**436**	439	**398**	488	566
Ranking (1 = best)		**7**	5	8	**2**	3	**1**	4	6
ReCiPe single score (feed)	Pt	**266**	225	259	**196**	212	**156**	156	199
Ranking (1 = best)		**8**	6	7	**3**	5	**1**	1	4

FCR: Feed Conversion Ratio.

Table B.1b LCIA of modelled Peruvian scenarios, per t of edible portion, allocated by gross energy content (see Table 3 for key of feed origins)

Aquaculture scenarios -->		**TrArtS1**	TrComS2	TrComS3	**GaArtS1**	GaComS2	**TiArtS1**	TiArtS2	TiComS3
Species		**Trout**	Trout	Trout	**Black pacu**	Black pacu	**Tilapia**	Tilapia	Tilapia
Rearing system		**Cages, semi-intensive**	Cages, semi-intensive	Cages, semi-intensive	**Ponds, semi-intensive**	Ponds, semi-intensive	**Ponds, semi-intensive**	Ponds, super-intensive	Ponds, super-intensive
Feed production		**artisanal**	commercial	commercial	**artisanal**	commercial	**generic**	generic	commercial
Feed origin		**PE 2012**	PE 2012	CL 2007	**PE 2012**	PE 2012	**PE 2012**	PE 2012	PE 2012
FCR		**1.8**	1.4	1.4	**1.7**	1.4	**1.7**	1.7	1.4
LCIA categories	Unit								
Acidification potential	kg SO_2-e	83.9	49.2	56.5	52.8	48.9	50.6	79.4	100.7
Agricultural land occupation	m^2.yr	11 413	8 082	8 137	17 228	9 376	39 601	39 617	7 799
Biotic resource use	kg C	31 023	50 038	52 983	2 796	14 555	5 653	5 653	17 556
Cumulative energy demand	MJ	122 581	71 847	95 752	70 295	79 176	117 164	111 553	146 776
Eutrophication potential	kg PO_4-e	135.2	107.0	127.3	142.6	114.9	142.6	149.1	100.9
Global warming potential	kg CO_2-e	5 041	5 290	5 755	4 969	5 856	5 384	8 031	11 463
Water depletion	m^3	25 221	25 402	25 221	12 063	13 242	11 036	2 938	4 010
Toxicity LCIA categories	Unit								
Freshwater aquatic ecotoxicity	kg 1,4-DB-e	821.6	655.7	569.6	417.0	527.6	464.5	420.5	668.8
Human toxicity	kg 1,4-DB-e	4 331.5	2 189.6	2 358.5	1663.8	1480.2	1524.6	1762.3	2 257.8
Terrestrial ecotoxicity	kg 1,4-DB-e	92.2	48.5	20.6	33.5	17.1	25.2	28.6	26.1
Total toxicity	kg 1,4-DB-e	5 245.3	2 893.8	2 948.7	2 114.4	2 024.9	2 014.3	2 211.4	2 952.7
LCIA single score	Unit								
ReCiPe single score (fish)	Pt	1045.3	848.6	979.9	1051.9	1045.3	1105.3	1355.4	1573.2
Ranking (1 = best)		3	1	2	5	4	6	7	8
ReCiPe single score (feed)	Pt	290.1	227.3	261.8	199.4	211.9	155.7	155.7	198.9
Ranking (1 = best)		8	6	7	4	5	1	1	3

FCR: Feed Conversion Ratio.

Table B.2 LCIA of feeds used in the modelled Peruvian scenarios, per t of feed, allocated by gross energy content

Feed associated to scenarios --> LCIA categories	Unit	TrArtF1 artisanal PE 2012	TrComF2 commercial PE 2012	TrComF3 commercial CL 2007	GaArtF1 artisanal PE 2012	GaComF3 commercial PE 2012	TiArtF1 generic PE 2012	TiComF2 commercial PE 2012
Acidification potential	kg SO_2-e	27.3	18.4	20.4	12.7	13.4	9.6	15.8
Agricultural land occupation	m^2·yr	3 792	3 446	3 469	4 239	2 798	8 369	1979
Biotic resource use	kg C	17 235	21 445	37 845	1864	4 367	3 325	4 514
Cumulative energy demand	MJ	38 015	21 324	29 648	15 705	19 197	10 487	17 412
Eutrophication potential	kg PO_4-e	2.9	4.2	4.6	2.6	3.7	2.6	4.4
Global warming potential	kg CO_2-e	1519	1725	1811	1157	1514	835	1645
Water depletion	m^3	4.8	82.2	4.1	5.4	358.1	3.2	278.4
Terrestrial ecotoxicity	kg 1,4-DB-e	29.2	18.0	5.8	8.1	4.6	4.4	4.1
ReCiPe single score	Pt	290.1	227.3	261.8	199.4	211.9	155.7	198.9

Table B.3 Abridged inventory table and overall environmental impacts (ReCiPe single score) of fishmeal production in Peru

Main inventory items		Prime	FAQ	Residual
Outputs				
Fish meal	t	1.00	1.00	1.00
Fish oil [a]	t	0.19	0.19	<0.19
Inputs				
Fresh fish	t	4.21	4.21	2.11
Fish residues [a]	t	-	-	2.75
Fuel use [b]	MJ	6,389	8,276	11,908
Electricity	MJ	312	208	208
Antioxidants	kg	0.86	1.06	0.50
Emissions to water				
N	kg	0.55	0.55	0.55
P	kg	0.005	0.005	0.005
BOD_5	kg	38.60	75.10	75.10
ReCiPe single score	Pt	92	156	196

[a] Allocation factor fishmeal:fish oil (gross energy content): 73:27.
[b] Considering a 50% inclusion of fish residues (range 50-70%, affected by illegal landings for reduction). [c] Diesel, heavy fuel oil (R500) and natural gas.

Table B.4 Nitrogen and phosphorus releases to water: N, P budgets and fate of nitrogen emissions

		Trout (artisanal feed)	Trout (commercial feed)	Black pacu (artisanal feed)	Black pacu (commercial feed)	Tilapia (artisanal feed)	Tilapia (commercial feed)
Total N emissions	kg/t fish	80.31	66.10	42.15	29.27	56.05	37.17
N solid		28.24	24.54	22.92	18.49	28.14	21.63
N dissolved		52.07	41.56	19.23	10.78	27.92	15.55
Total P emissions	kg/t fish	13.63	9.63	12.33	9.93	7.50	3.74
P solid		9.36	7.28	7.07	5.82	7.78	5.82
P dissolved		4.27	2.35	5.25	4.10	(0.28)	(2.08)
Fates	kg/t fish						
N in sediment		30.52	25.12	16.02	11.12	21.30	14.13
N in water column		0.08	0.07	0.04	0.03	0.06	0.04
N in fish		18.95	17.95	14.77	12.71	16.79	14.48
N in seepage		30.76	22.96	11.33	5.41	17.91	8.53
Digestibility	%						
Protein		92	92	82	82	82	82
Fat		95	95	60	60	93	93
Carbohydrates		71	71	80	80	70	70
Ash		50	50	50	50	50	50
Phosphorus		60	60	60	60	60	60

Calculations are based on the average content of protein, lipids and phosphorus in available feeds and the reference production systems as defined in Table 3.

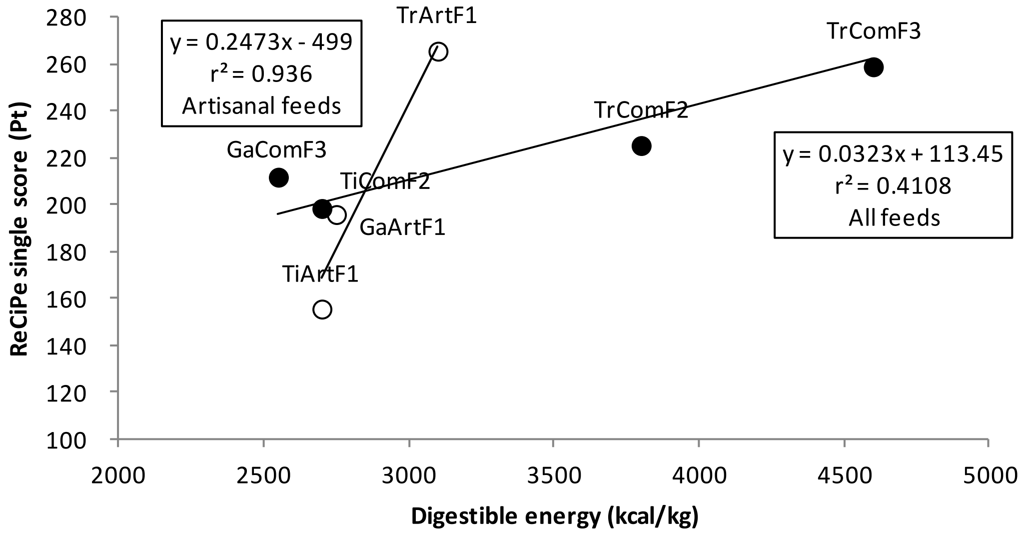

Fig. B.1 Digestible energy vs. environmental impacts (ReCiPe single score) of Peruvian feeds

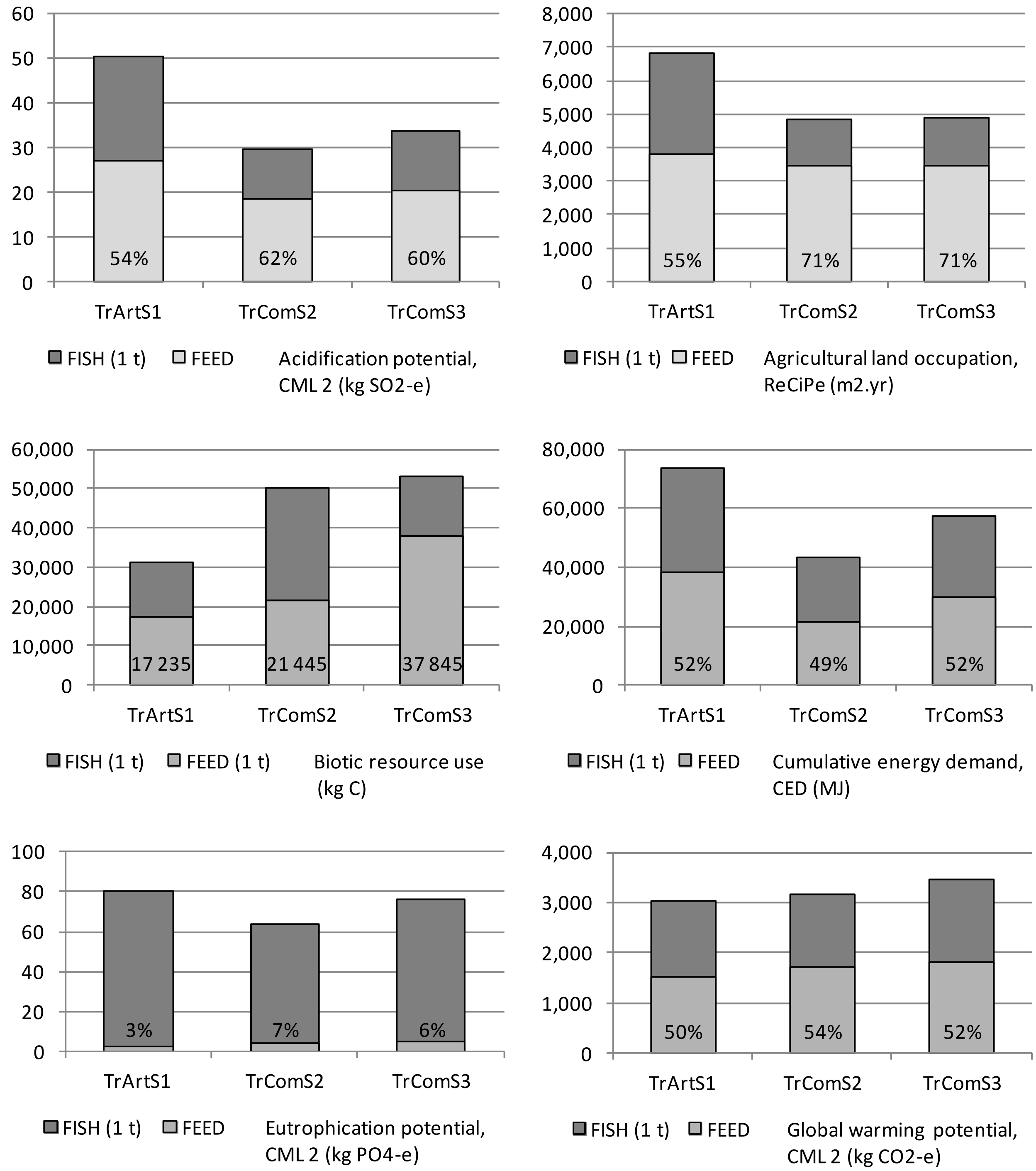

Fig. B.2 Detailed impact category analysis of Peruvian trout scenarios, per tonne of live weight fish at farm gate

Appendix C. Uncertainty and sensitivity analyses

Table C.1 Re-calculated FCRs for Peruvian aquaculture scenarios, based on dry matter (DM) of feeds and fish

Species	Scenarios	DM feed	FCR	DM fish[a]	Dry FCR
Trout	TrArtS1	85%	1.8	26%	5.9
	TrComS2	86%	1.4		4.6
	TrComS3	88%	1.4		4.7
Black pacu	GaArtS1	85%	1.7	29%	5.0
	GaComS2	86%	1.4		4.2
Tilapia	TiArtS1/TiArtS2	85%	1.7	19%	7.6
	TiComS3	86%	1.4		6.3

[a] Trout: USDA (2012), Black pacu: Average of values from Bezerra (2002), Torry Research Station (1989) and Machado and Sgarbieri (1991), tilapia: USDA (2012).

Table C.2 Changes in emissions to water by Peruvian aquaculture systems in response to a ±20% change in FCRs

FCR Δ	FCR	Emissions (kg/t fish)	Trout	Black pacu	Tilapia
FCR +20%	1.7	N	86.3	37.3	48.2
		P	12.6	12.1	5.4
FCR	1.4	N	66.1	25.8	34.7
		P	9.6	9.7	3.0
FCR-20%	1.1	N	45.9	14.3	21.3
		P	6.6	7.3	0.6

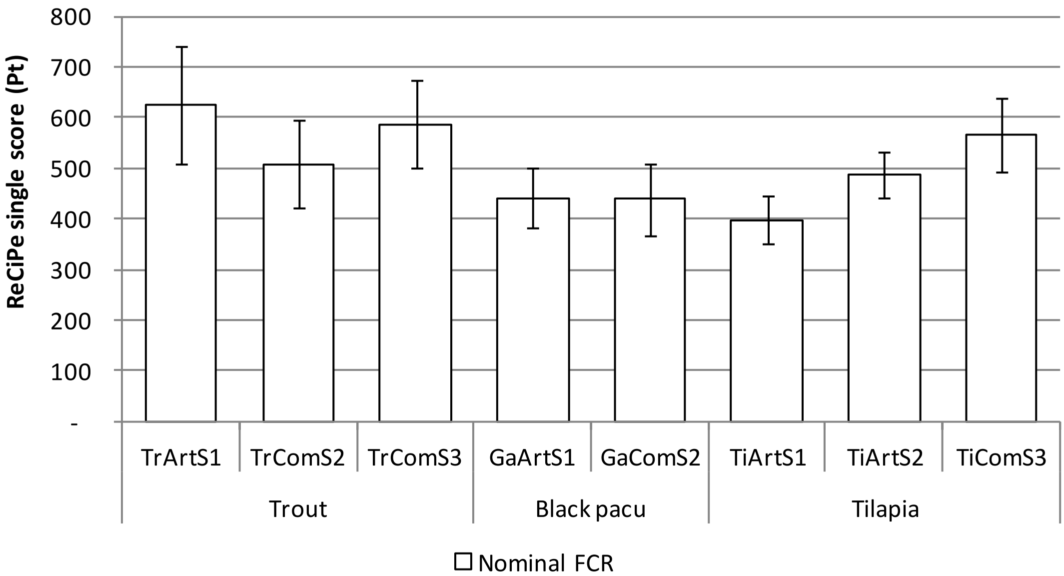

Fig. C.1 Changes in ReCiPe single scores of Peruvian aquaculture scenarios, per tonne of live weight fish, in response to a ±20% change in FCRs

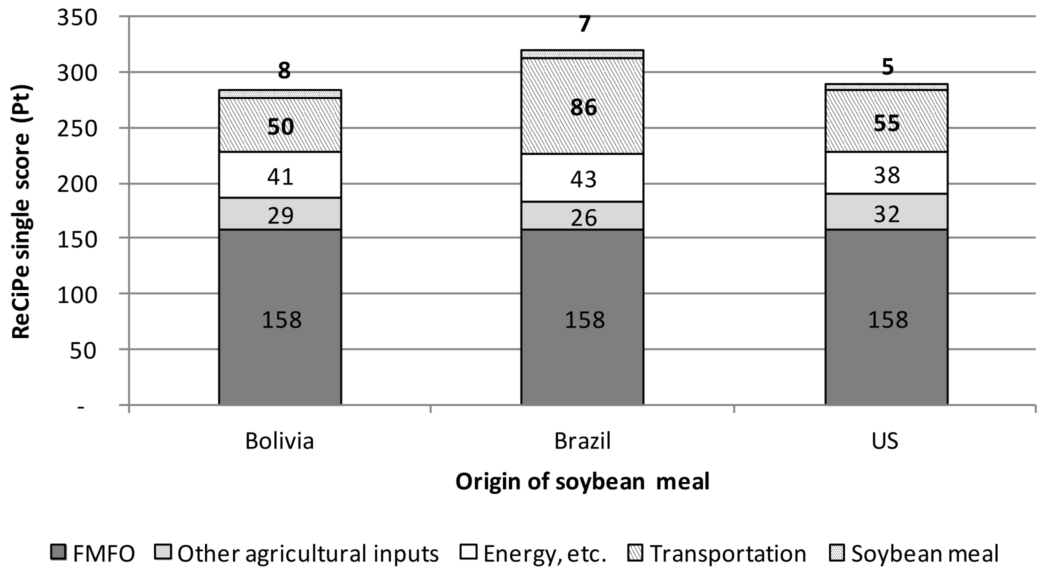

Fig. C.2 Relative performance of the use phase of the reference Peruvian trout scenario TrArtS1 with alternative sourcing for soybean meal in feed (TrArtF1, 15% soybean meal)

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