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Environmental impact of non-certified versus certified (ASC) intensive Pangasius aquaculture in Vietnam, a comparison based on a statistically supported LCA☆

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ABSTRACT

Pangasius production in Vietnam is widely known as a success story in aquaculture, the fastest growing global food system because of its tremendous expansion by volume, value and the number of international markets to which Pangasius has been exported in recent years. While certification schemes are becoming significant features of international fish trade and marketing, an increasing number of Pangasius producers have followed at least one of the certification schemes recognised by international markets to incorporate environmental and social sustainability practices in aquaculture, typically the Pangasius Aquaculture Dialogue (PAD) scheme certified by the Aquaculture Stewardship Council (ASC). An assessment of the environmental benefit of applying certification schemes on Pangasius production, however, is still needed. This article compared the environmental impact of ASC-certified versus non-ASC certified intensive Pangasius aquaculture, using a statistically supported LCA. We focused on both resource-related (water, land and total resources) and emissions-related (global warming, acidification, freshwater and marine eutrophication) categories. The ASC certification scheme was shown to be a good approach for determining adequate environmental sustainability, especially concerning emissions-related categories, in Pangasius production. However, the non-ASC certified farms, due to the large spread, the impact (e.g., water resources and freshwater eutrophication) was possibly lower for a certain farm. However, this result was not generally prominent. Further improvements in intensive Pangasius production to inspire certification schemes are proposed, e.g., making the implementation of certification schemes more affordable, well-oriented and facilitated; reducing consumed feed amounts and of the incorporated share in fishmeal, especially domestic fishmeal, etc. However, their implementation should be vetted with key stakeholders to assess their feasibility.

1. Introduction

Fish play a vital role in human nutrition worldwide, and fish consumption per capita increased 1.6 times (from 12 to more than 19 kg) between 1985 and 2012 and is expected reach 22.4 kg in 2022 (FAO, 2014). Most of this increase has come from aquaculture, a sector that has grown to produce 90.4 million tonnes (live weight equivalent) in 2012, in which the food fish aquaculture production (66.6 million tonnes) had expanded about six times since 1985, while global marine and inland capture fisheries production has remained stable (approximately 90 million tonnes) in a similar period (FAO, 2014). Catfish (*Pangasius hypophthalmus*) production from the Mekong delta, in Vietnam, has made inroads into traditional ground fish markets as a cheaply farmed whitefish species. This sector has achieved a ten-fold expansion by volume and a 14-

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fold increase by value during the period from 1985 to 2012 (FishStatJ, 2016). The number of consumer groups has also increased from 11 importing markets in 2001 to 149 markets in 2014 (VASEP, 2014). This expansion is expected to continue, driven by steadily increasing global demand.

In conjunction with increasing production, environmental impacts, such as mangrove destruction, eutrophication, a continued reliance on wild fish stocks, chemical use and antibiotic use, have garnered increased media coverage. This coverage has come to influence consumer attitudes towards farmed fish, where Vietnamese Pangasius is often considered a controversial product (FAO, 2014). In response, aquaculture certification schemes have been introduced to provide assurances of more sustainable aquaculture practices. In 2009, the Vietnamese government addressed concerns about the use of chemicals, water pollution and biodiversity degradation in a 2020 Master Plan for Pangasius production in the Mekong Delta (Bosma et al., 2011). At that moment, a number of sustainability standards for Pangasius production were at different stages of development, e.g., Naturland, Butlers Choice, etc., covering a range of issues: aquaculture production guidelines, environmental management, social, legal and chain-related issues and food safety (Bush et al., 2009). In 2010, the Vietnam Association of Seafood Exporters and Producers (VASEP) and the Vietnam Fisheries Society (VINAFIS) signed a Cooperation Agreement with the World Wildlife Fund (WWF) to support efforts to improve environmental and social responsibility in the Vietnamese Pangasius sector and to achieve ASC certification. According to the agreement, 100% of farms for export should be under one of the several certification schemes by 2015, with 50% of the exporting farms under the ASC by 2015, and 10% by 2012 (WWF, 2012).

Currently, many local Pangasius producers are keen to meet one or several certification schemes recognised by international markets since this opens doors to new markets in the European Union and the United States. It also reinforces their will to embrace environmental and social sustainability in aquaculture practices. Of the many schemes currently available for Pangasius, the following three are generally considered to be the most widespread: Global Partnership for Good Agricultural Practices (GlobalG.A.P.), Pangasius Aquaculture Dialogue (PAD) and Best Aquaculture Practices (BAP) (Belton et al., 2011). GlobalG.A.P. began in 1997 as EUREPG.A.P., an initiative by retailers belonging to the Euro-Retailer Produce Working Group, pledging commitment to good agriculture, livestock and aquaculture farming practices. The BAP scheme, an initiative by the Aquaculture Certification Council (ACC), is aquaculture specific and promotes responsible practices across farms, feed mills, hatcheries and processing facilities. The PAD scheme, certified by the Aquaculture Stewardship Council (ASC), is the most recent and was established in 2010 by the World Wildlife Fund (WWF) and the Dutch Sustainable Trade Initiative (IDH). Today, it is an independent non-profit organisation with the goal of raising the global standards of responsible aquaculture. Presently, there are 37 ASC-certified farms (ASC, 2016), 27 GlobalG.A.P.-certified producers (GlobalGAP, 2016) and 15 BAP-certified (13 farms and 2 hatcheries) Vietnamese Pangasius facilities (BAP, 2016). However, by 2016, all Pangasius farms and companies are required by the Vietnamese government to meet the standards of one of the certification schemes operating in Vietnam, including these three schemes (Marschke and Wilkings, 2014).

Aquaculture is a highly diverse activity with respect to technologies and cultivated organisms. Therefore, as a way to better understand and identify more environmentally sustainable practices, the life cycle assessment (LCA) approach has been increasingly applied to aquaculture, particularly facilitating comparisons between the efficiencies of competing production systems (Pelletier and Tyedmers, 2008). LCA has emerged as a widely used and recommended framework to assess the environmental impact of a product through its life cycle, i.e., from resources extraction until final disposal (ISO, 2006a). LCA research covers global-scale impacts, resulting in new insights into the environmental impact of seafood products (Ziegler et al., 2016). This tool has also been applied to assess the environmental performance of conventional (i.e., intensive non-certified) Pangasius aquaculture and its processing into other products (i.e., frozen and modified atmosphere packaging fillets), evaluating global warming, acidification, eutrophication, and toxicity impacts (Bosma et al., 2011; Henriksson et al., 2015b), as well as resource use (Huysveld et al., 2013; Nhu et al., 2015b). Moreover, to assess the LCA results of 12 different feed types at 10 non-certified and 10 certified farms, equations were developed to easily estimate the cradle-to-gate resource footprint of Pangasius feeds and aquaculture (Nhu et al., 2016). The latter study was limited to the quantification of resource use and did not address concerns about resource use on the certified farms is better than on the conventional farms.

In the present study, we aimed to evaluate the environmental performance of ASC-certified and non-ASC certified Pangasius systems using LCA. A crucial part of comparing production systems is to include data uncertainty, already specifically applied to aquaculture products (Henriksson et al., 2015a, 2015b). In the LCA context, a number of studies have been performed to better assess uncertainty, identifying and taking into account different types of correlation (Lloyd and Ries, 2007). Different types of uncertainty include those relating to parameters (e.g., data inaccuracy, data gaps, and unrepresentative measurements), and those concerning the (LCA) model (e.g., the deviation of characterisation factors or missing of temporal/spatial characteristics in inventory analysis) and the scenario choices (e.g., choices of functional unit, allocation approach, characterisation/weighting methods) (Huijbregts, 2002). Regarding uncertainty at the parameter level, correlations have been addressed among the input parameters, as well as between them and the outcome (Bojaca and Schrevens, 2010), or when comparing production systems controlled by the same parameter set (Henriksson et al., 2015a). Here, we will mainly focus on data uncertainty but will also assess the influence of some model choices. An overview of the key criteria considered in the ASC standard scheme as well as covered in this study can be found in the Supporting information 1 (SI1), Table S1. The environmental categories considered included resource-related (water, land, total resources) and emissions-related (global warming, acidification, freshwater and marine eutrophication) categories.

2. Materials and methods

2.1. Goal and scope

The LCA comparison between Pangasius produced on ASC-certified farms (ASCs) and non-ASC certified intensive farms (NFs) in this study was based on data from three independent studies on intensive Pangasius production, i.e., Bosma et al. (2011), Henriksson et al. (2015b) and Nhu et al. (2016). Bosma et al. (2011) evaluated the environmental impact of Pangasius NFs using LCA on the primary data surveyed at 28 farms and 7 feed production companies between 2008 and 2009. Henriksson et al. (2015b) applied LCA, coupled with statistical tests and uncertainty analysis, to compare the environmental impact of Pangasius NFs produced at different farm-scales (i.e., small, medium, large). The primary data were randomly gathered at 110 small-, 64 medium- and 38 large-scale farms from 2010 to 2013. Both of these studies focused on emissions-related categories (e.g., global warming, eutrophication, toxicity impacts, etc.). Nhu et al. (2016) constructed equations to simply predict the resource footprint of both NFs and ASCs by performing linear regressions based on the LCA results of 10 ASCs and 10 NFs, of which the primary data were surveyed in 2013 and 2010.

The studied ASCs and NFs are all intensive pond systems. Table S3 provides an overview of the basic characteristics of the studied farms. The produced wastewater at both the CFs and NFs is often pumped to an adjacent river and is occasionally collected after fish harvesting to fertilise crops; however, its impact was monitored at the ASCs by measuring the nutrient (i.e., nitrogen, phosphorous) contents of wastewater. Regarding sediment disposal, the ASC-farms must follow strict and proper procedures. Sediment from the ASCs is pumped approximately 20 cm every two months, after which it is then properly disposed of (i.e. delivered to a regulated or dedicated landfill or reused as fertiliser or soil conditioner for agricultural production, landfill or other construction-related uses). Dead fish are disposed of through incineration, burial, fermentation, use as fertiliser and production of fishmeal, fish oil or feed for animals other than Pangasius (ASC, 2012). On the other hand, a study of 212 NFs at small-, medium- and large-scales in the framework of the SEAT project, indicated that sediment in the NFs is (i) pumped into canal/wasteland (0–14%), (ii) added to pond dykes (3–10%), (iii) maintained in sedimentation ponds (25–50%), or (iv) pumped into agricultural fields (45–58%). The portion of each disposal tactic differed by farm scale (Henriksson et al., 2014b). A more comprehensive description of farming practices on these farms can be found in the original studies, i.e., Bosma et al. (2011), Henriksson et al. (2015b, 2014b) and Nhu et al. (2016).

One tonne live weight of Pangasius delivered at the farm gate was selected as the overall functional unit (FU). The foreground system, defined as the gate-to-gate production chain, included feed production and fish farming at the farm scale (see Supporting information 2 (SI2)). For comparative purposes, the impacts of (i) hatchery, (ii) nutrients (i.e., total nitrogenous TN and phosphorus TP) released via sediment (but have also been performed for wastewater) and (iii) potential toxins released through wastewater were not covered because of the absence of quantitative data and information about sediment fate at the ASCs. However, these three flows were considered in the identification of the environmental hotspots and were discussed for improvement opportunities based on the data from Henriksson et al. (2015b) and Huysveld et al. (2013) (section 'Results and discussions'). The background system, defined as the part of the production chain outside the gate-to-gate boundary, included industrial processes (agricultural cultivation, chemical production, transport, etc.) necessary to produce and deliver the inputs to the foreground system. Infrastructure was excluded due to its limited contribution towards overall impacts (Ayer and Tyedmers, 2009) and to be consistent with the data sourced e.g., production of fishmeal, fish oil or wheat farming (Henriksson et al., 2015b).

Data uncertainty analysis was then conducted using the Monte Carlo (MC) method, with 1000 iterations, which is a sufficient but not excessive sample size (Henriksson et al., 2015b). We included the assessment of parameter uncertainty characterised by inherent uncertainty, unrepresentativeness uncertainty, and spread uncertainty as well as excluding the correlation between process chains of products (see Tables 1 and 2). Appropriate statistical tests were subsequently performed to determine whether the differences between the environmental impacts of the two farming systems were significant.

2.2. Life cycle inventory (LCI)

In this study, the ASC-certified farms studied by Nhu et al. (2016) were identified as 'c1', whereas the non-ASC certified farms (NFs) studied by Nhu et al. (2016), Henriksson et al. (2015b) and Bosma et al. (2011) were identified as 'n1', 'n2' and 'n3', respectively. The primary data in the 3 NF groups differed as follows: (i) the timing of survey; and (ii) the data characteristics of some important flows, e.g., feed types, water input and nutrient emissions (see SI1, Table S4). Consequently, the 3 NF groups (n1, n2, n3) required separate analysis and were compared with the certified group (c1). Identified flows of the foreground systems (including feed production and fish farming) are presented in SI2. The protocol presented by Henriksson et al. (2014a) was applied to average the inventory data horizontally and to quantify the overall uncertainty (i.e., inherent, spread and unrepresentativeness uncertainties listed in Table 1). The LCI sources for production and processing of feed ingredients (i.e., agricultural farming practices and capture fisheries) that accounted for most of the upstream emissions were mainly modelled using nation-specific secondary data retrieved from other research (SI1, Table S2). The same composition of these feeds was assumed for both non-ASC certified and ASC-certified farms. Lime production was quantified by LCI data derived from Ecoinvent v.2.2. For the additional chemicals (e.g., vitamins, probiotics) used for pond preparation and farming, which were not available in the database, two more generic processes were used as proxies ('chemicals organic, at plant/GLO' and 'chemicals inorganic, at plant/GLO'). Allocation of the environmental impact among co-products can be conducted based on different properties (ISO, 2006a). Exergy allocation, applied to the foreground system and the production/processing of feed ingredients whenever practical, was selected as the basis for discussion since it is one of physical properties covering both the quality (in terms of useful energy) and quantity of material and energy flows (Dewulf et al., 2008). In other words, exergy allocation considers the differences in both weight and specific exergy content per unit (MJex kg^{-1}) of useful products, e.g., by-products from fisheries. The influence of different allocation approaches based on mass or economic value on results was also assessed and is discussed further.

2.3. Life cycle impact assessment (LCIA)

The environmental impact of the two types of Pangasius

Table 1
Types of data uncertainty, specifically for the Pangasius aquaculture case study.

Types	Inherent uncertainty	Unrepresentativeness uncertainty	Spread uncertainty
Definition	Inaccuracies in measurement (Henriksson et al., 2014a)	Mismatch between the representativeness and use of data (Henriksson et al., 2014a)	Variability resulting from horizontal averaging (Henriksson et al., 2014a)
Examples specifically for Pangasius aquaculture	Inaccuracies in measuring foreground data (e.g., quantity of water, feed, chemicals, etc.)	Mismatch with respect to reliability, completeness, temporal correlation, geographical correlation and technological correlation.	Variability in foreground data among the studied farms.
How is this covered in the foreground system of this study	Coefficient of variation (CV) was assumed 5% (Henriksson et al., 2014a)	By the Pedigree matrix approach (Frischknecht et al., 2007)	Coefficient of variation was calculated based on on-site foreground data

Table 2
Types of data correlations, specifically for the Pangasius aquaculture case study.

Types	Correlations between process chains of product systems	Correlations within a process record
Definition	Correlations between 2 different systems sharing several similar unit processes (Henriksson et al., 2014a)	Correlation among parameter inputs, also between them, and the outcome of the considered system (Bojaca and Schrevens, 2010)
Examples specifically for Pangasius aquaculture	The shared background system, e.g., production of feed ingredients, chemicals, electricity, fossil fuels, etc. were derived from the same processes.	- For the feed production system, the share, in mass, of feed ingredients are heavily correlated, while the sum fixes at 100%. - For the farm system, the amount of nutrient discharged and feed added are heavily correlated.
How is this covered in the foreground system of this study	Unit process data were identically randomised for each MC simulation	Not covered

production systems was assessed and compared at the midpoint, including both resource- and emissions-related categories, where the results represent the extent of impacts at an early stage of the cause-and-effect chain and act as straightforward standards for decision making.

Regarding resource-related categories, the total resource use (TR) from cradle-to-farm gate during the lifecycle of Pangasius, quantified by the Cumulative Exergy Extraction from the Natural Environment (CEENE) v.2013 method (Alvarenga et al., 2013), was statistically compared between the ASCs and the NFs. The selected method, i.e., CEENE, remediates the shortcomings of other resource-oriented methods such as Cumulative Energy Demand (CED) (Frischknecht et al., 2007) and Cumulative Exergy Demand (CExD) (Bosch et al., 2007) by evaluating land occupation and non-energetic resources, in addition to energy carriers (Swart et al., 2015). The CEENE method covers all biotic and abiotic resource types via 8 resource categories, expressed in one common unit: Joules of exergy (Jex), including renewable resources, fossil fuels, nuclear energy, metal ores, minerals, water resources, land and biotic resources and atmospheric resources. Water (WR) and land resources (LR), identified as the hotspots of total resource use (TR) in the two farming systems (Nhu et al., 2016), were also presented for a comparative purpose.

Regarding emissions-related categories, following the work of Bosma et al. (2011) and Pelletier et al. (2007), the impacts on global warming (GW), acidification (AC), freshwater (FE; linked with phosphorous emissions) and marine eutrophication (ME; linked with nitrogenous emissions) were considered using RECIPE midpoint (M) v.1.12. Toxicity impacts were not covered due to data unavailability of specific toxic chemicals used and discharged. The RECIPE method is a recent holistic LCIA methodology that includes impact assessment methods for many impact categories and comprises a harmonised category at both midpoint and endpoint levels. The hierarchical (H) perspective was chosen because it is based on the most common policy principles with regards to time frame and other issues and is thus often encountered in scientific models (Goedkoop et al., 2013b).

2.4. Monte Carlo simulation

LCI models were constructed and characterised using Simapro v.8.1 (Goedkoop et al., 2013a) and propagated over 1000 MC iterations. When comparing systems, based on decision confidence probability (impacts of $X_{ASC} - X_{NF}$), we used dependent (correlated) sampling in which shared unit process data were identically randomised for each MC simulation. In other words, supporting processes (i.e., the same background system) were derived from the same randomised LCI matrix and only data for feed production and farming systems (i.e., the foreground systems) differed per iteration. This approach allows for a higher level of accuracy in comparative studies (A-B) and for the use of more powerful paired significance tests (Henriksson et al., 2015a). The on-farm water inputs and nutrient emissions, however, relied upon independent parameters and were therefore independently sampled in each MC run. The uncertainties of the characterisation factors themselves were not considered. The MC frequency, i.e., the percentage of MC runs in which the differences between their impacts ($X_{ASC} - X_{NF}$) were negative/positive, was calculated to show how often the average ASC system induced a better/worse environmental performance than the average NF system.

2.5. Statistical tests

The Anderson-Darling goodness-of-fit test was applied to determine whether a normal distribution fitted the MC results. Since none of the ranges of results followed a normal distribution, the nonparametric one-sample Wilcoxon-Signed rank test was applied as an alternative to the paired *t*-test for a null hypothesis that the differences between X_{ASC} and X_{NF} derived from a distribution with zero median at a confidence interval (CI) of 95%. The p-value <0.05 indicates a rejection of the null hypothesis, which means that the two farming systems induce significantly different impacts. The statistical tests were conducted with MATLAB v.2013.

3. Results and discussions

The supporting information SI1 (Table S2) and SI2 provides the LCI sources and results.

3.1. Hotspot identification

Regarding the midpoint LCIA results, both ASCs (c1) and NFs (n1, n2, n3) showed similar environmental hotspots for most of the considered categories (Fig. 1). The feed input contributed primarily to the land resources (LR, 99% for ASCs, 90–99% for NFs), global warming (GW, 98% for ASCs, 87–99% for NFs) and acidification (AC, 99% for ASCs, 91–99% for NFs). This highlights the importance of the economic feed conversion ratio (eFCR), which is defined as the ratio of the amount (tonne) of feed used per amount (tonne) of fish net biomass growth over the farming period (ASC, 2012), and the burden of a unit of feed. Grow-out farming (i.e., other inventory flows at the farm scale, except for feed input, and hatchery and nutrient emission through sediment) was the dominant contributor to the water resources (WR, 99% for ASCs, 98–99% for NFs) and freshwater eutrophication impacts (FE, 91% for ASCs, 86–96% for NFs) originating from on-farm water input (i.e., total abstracted/exchanged volume) and total phosphorus discharges throughout production, respectively. Grow-out farming contributed to the total resource use (TR) of ASCs (53%) and NFs (41–56%), which was similar to the contribution of the feed input. However, the major hotspot inducing marine eutrophication impact (ME) was different on each farm types: feed use in the ASCs (67%) and grow-out

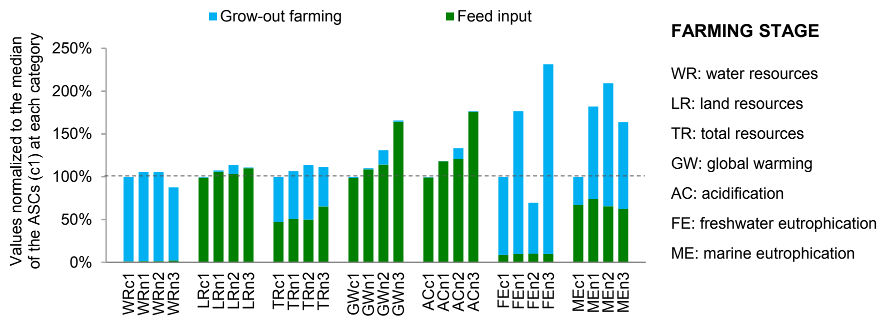

Fig. 1. Contribution of inputs during the farming stage to the considered resource- and emissions-related categories of one tonne of Pangasius produced at the studied ASC-certified (c1) and non-ASC certified (NFs) farms, using exergy allocation. The values were normalised to the median values of the ASCs (c1) in each category. The ASC-certified farms (c1) were selected from Nhu et al. (2016). The non-ASC certified farms: n1 was selected from Nhu et al. (2016), n2 from Henriksson et al. (2015b) and n3 from Bosma et al. (2011). Hatchery and nutrient loss through sediment were excluded.

farming in the NFs (59–69%). The findings on the important role of grow-out farming and feed use in the resource- and emissions-related impacts of the NFs were consistent with the work of Nhu et al. (2016) and Bosma et al. (2011), respectively, despite the differences in LCI modelling (SI1, Table S2).

Our LCA analysis of the 212 NF-n3 farms and the 4 NF farms studied in Huysveld et al. (2013), including hatchery and nutrient emissions through sediment, indicated that juvenile production contributed to a limited extent (lower 10%) to the environmental impact of the NFs (SI1, Fig. S1). Nutrient loss through sediment contributed to only 3% of the marine eutrophication (ME) impact. This loss was shown to be negligible compared to the loss through flushed out wastewater (Anh et al., 2010). Consequently, excluding these flows insignificantly affected the comparative analysis of the ASCs and the NFs with respect to the considered categories.

Regarding the production of commercial Pangasius feeds, crop-derived ingredients, fishmeal and the inputs of milling processes were identified as the hotspots in the considered categories. Crop-derived ingredients, especially soybean meal, rice by-products (bran, meal, broken rice) and wheat by-products (flour and bran) contributed the most to the burden of a unit of feed with respect to LR (93%), TR (67%), GW (41%), AC (41%), FE (82%) and ME (80%) (Fig. 2), mainly due to the amounts used. Fishmeal was determined to mainly contribute to WR (52%), GW (36%) and AC (38%), which was not the finding in Bosma et al. (2011) and Huysveld et al. (2013). This is explained by the differences in modelling of the production of domestic fishmeal. Fishmeal used for Pangasius aquaculture primarily originated in Vietnam (66%), in addition to an imported share (Henriksson et al., 2015b). Fishmeal production in Vietnam was modelled using the LCA Food database by Bosma et al. (2011) or the inventory data of Peruvian production in 2006 by Huysveld et al. (2013). We used the data of fishmeal production in Vietnam surveyed in the SEAT project framework between 2010 and 2013 (Henriksson et al., 2015b), which was more representative of Vietnamese production. Consequently, the actual environmental impact of domestic fishmeal was better quantified. Such a system consumed much diesel and electricity for the fishery (capture and ice production), resulting in a significantly higher environmental impact compared to the Peruvian fishery. Because of the high share of fishmeal (14.8%), the fn3 feed used by the NF-n3 farms, studied in Bosma et al. (2011), extracted WR and induced GW and AC impacts that were drastically higher than the other 3 studied commercial feeds (i.e., the fc1 used by the ASC-c1 farms, the fn1 used by the NF-n1 farms and the fn2 used by the NF-n2 farms) (Fig. 2). The inputs of milling processes were of importance with respect to WR (22%), GW (15%) and AC (12%) due to the high consumption of electricity (hydro-powered 39%, gas 39%, coal 20% and oil 2%, SI2) and fossil fuels (e.g., diesel and hard coal). Moreover, livestock-derived ingredients (i.e., poultry meal, meat and bone meal, blood meal) were also of greater concern, but these ingredients comprised only 3.4% of the mass of the fn2 feed but contributed 8–22% to the considered categories, especially at WR (17%), GW (13%), AC (13%) and FE (22%) (Fig. 2).

3.2. Comparative results

Both farming systems had high overall uncertainties in their environmental impact, indicated by the whiskers for the 10th and 90th percentile values in Fig. 3. This was due to the high variability resulting from horizontal averaging (i.e., the spread, inherent

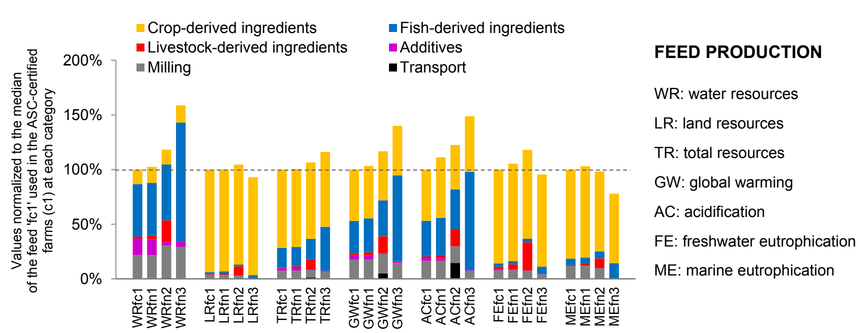

Fig. 2. Contribution of inputs to the feed production in the considered resource- and emissions-related categories for one tonne of the average Pangasius feeds (for all studied commercial feeds), using exergy allocation. Values were normalised to the median values of the average feed 'fc1' used in the ASC-certified farms in each category. Feed fc1: the average feed used on the ASC-certified farms (c1) from Nhu et al. (2016). Feeds fn1, fn2 and fn3: the average feeds used on the non-ASC certified farms (NFs), including n1 from Nhu et al. (2016), n2 from Henriksson et al. (2015b) and n3 from Bosma et al. (2011), respectively.

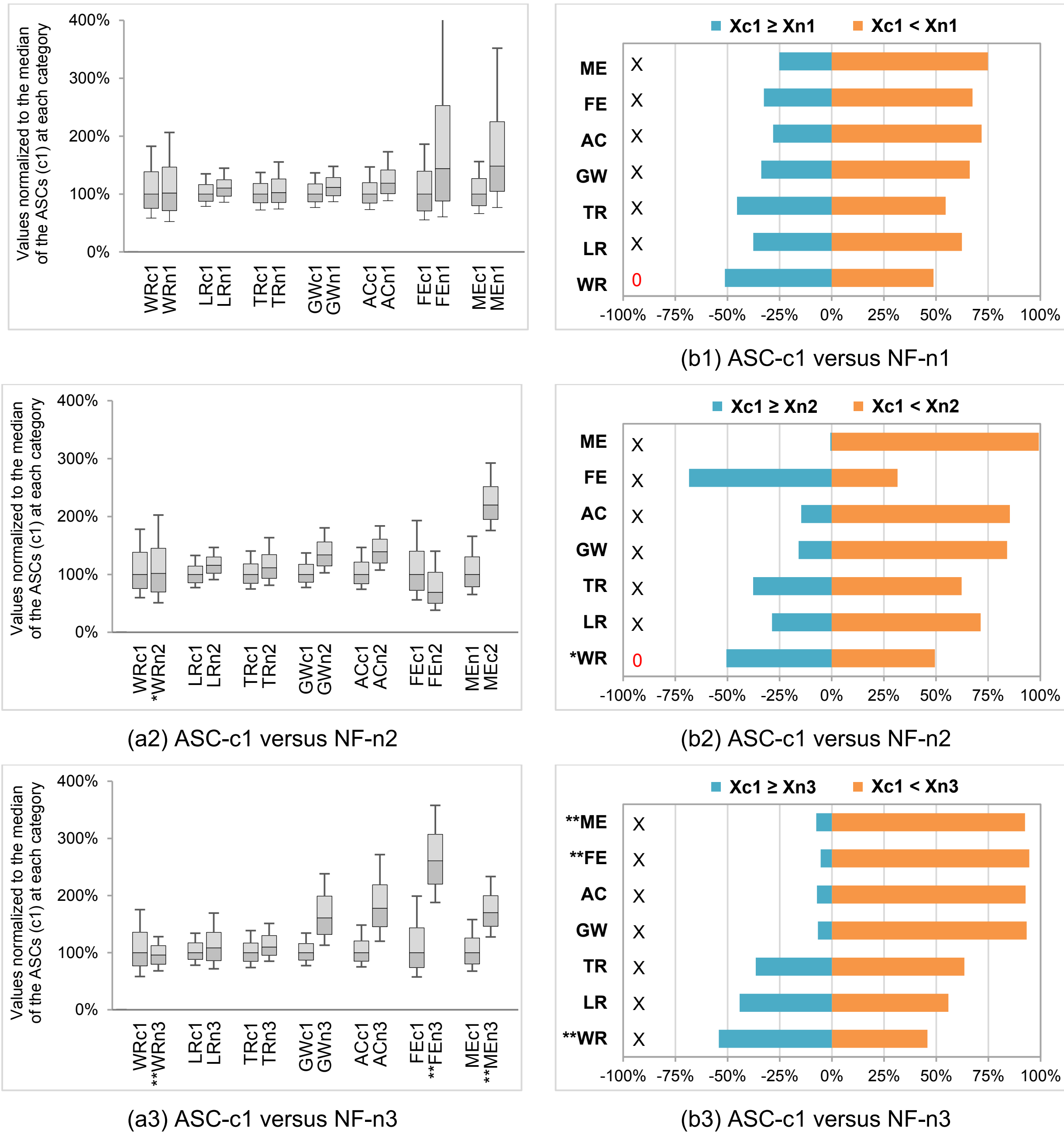

Fig. 3. Cradle-to-gate environmental impact of one tonne of Pangasius produced at the ASC-certified (ASC-c1) and non-ASC certified (NF-n1, n2, n3) systems through exergy allocation, including LCI uncertainty at a confidence interval of 95%. (a) The values were normalised to the median values of the ASCs (c1) in each category. Indicators include the median, the 25th and 75th percentiles (box), and the 10th and 90th percentiles (whiskers). (b) Decision confidence probability (μ) of comparing the impact between the 2 systems. The ASC-certified farms (c1) came from Nhu et al. (2016). The non-ASC certified farms: n1 came from Nhu et al. (2016), n2 came from Henriksson et al. (2015b) and n3 came from Bosma et al. (2011). X refers to a p-value <0.05, obtained from the statistical test, indicating that X_{ASC} and X_{NF} were significantly different, 0 refers to the opposite. Keep in mind that (*) data on the water input of n2 came from n1, (**) the data on water input and nutrient discharges of n3 were estimated through daily water exchange rates and nutrient balances.

uncertainty). This indicates a high variation among the studied farms with respect to the three identified hotspots: water and feed inputs and especially, the on-farm nutrient (nitrogenous and phosphorous) emissions. For the considered categories (except water resources, WR, and freshwater eutrophication, FE), the decision confidence probabilities (μ), i.e., a Monte Carlo frequency evaluating the chance that the studied environmental impact between the two farming systems was lower than zero ($X_{ASC} < X_{NF}$) were quantified. They indicate that 55–99% of the ASCs were favourable to the NFs with respect to land resources (LR; μ of 62% that Xc1 < Xn1, 71% that Xc1 < Xn2, 56% that Xc1 < Xn3), total resource use (TR, μ of 55% that Xc1 < Xn1, 62% that Xc1 < Xn2, 64% that Xc1 < Xn3), global warming (GW, μ of 66% that Xc1 < Xn1, 84% that Xc1 < Xn2 and 93% that Xc1 < Xn3), acidification (AC, μ of 72% that Xc1 < Xn1, 85% that Xc1 < Xn2, 93% that Xc1 < Xn3), and marine eutrophication (ME, μ of 75% that Xc1 < Xn1, 99% that Xc1 < Xn2, 93% that Xc1 < Xn3) (Fig. 3b). This was a significant trend (the p-values of the Wilcoxon-signed rank test were lower than 1E-4) with the ASCs (c1) outperforming the NFs (n1, n2 and n3) in the considered resource- and emissions-related categories (except WR and FE). This is explained by the advantage of applying the ASC certification scheme compared to the NFs: (i) a better eFCR value, the key flow affecting LR, GW and AC; (ii) lower nitrogenous (i.e., total nitrogen, nitrate, ammonium) discharges, which are the primary flow affecting ME; and (iii) lower inclusion of fish-derived ingredients (fishmeal, fish oil and trash fish) in the feeds used (SI2), especially fishmeal, which is the primary flow affecting GW and AC. The considerable benefit of applying certification standards was highlighted for the emissions-related categories (i.e., GW, AC and ME), especially when comparing the ASC-c1 farms with the NFs in the broad-scale survey (28 NF-n2 farms and 212 NF-n3 farms). The NF-n1 group consisted of only ten non-ASC certified farms of which four farms were well managed by the producer, one of the top Vietnamese exporters of Pangasius products (Huysveld et al., 2013); the ASC-c1 farms were therefore favourable for the NF-n1 farms at lower Monte-Carlo frequencies of 55–75% with respect to the considered categories (except WR) (Fig. 3b1).

The ASC Pangasius standards have considered water use efficiency, an increasingly important global issue with respect to sustainable production. The maximum ratio of total abstracted water (i.e., water removed from the water body and introduced onto the farm) was set at 5000 m^3 per tonne of Pangasius produced, using actual data submitted by ASC Pangasius Standard stakeholders (ASC, 2012). Consequently, the water resource category (WR, quantified by the exergy content of the total water amount extracted from the natural environment) at the ASC-c1 farms dispersed less than that at the NF-n1 farms, which were expressed by a smaller difference between the 10th and 90th percentile values (Fig. 3a1). This result was obtained from the water input measured throughout production on these farms. In the literature, the water input needed for the production of one tonne of Pangasius at the NFs was reported to be highly skewed and ranged from 700 to 59,700 m^3 (6400 m^3 on average), which was estimated from fish production, farm water volume and water exchange rates over a total of 89 farms (Phan et al., 2009). In this study, the water input was measured at 3039 m^3 (standard deviation, SD, 1368 m^3) for the production of one tonne of Pangasius at the 10 NF-n1 farms (Nhu et al., 2016) and was estimated at 2500 m^3 $tonne^{-1}$ of Pangasius based on daily water exchange rates and nutrient balances over the 28 NF-n3 farms (Bosma et al., 2011). This value was 2903 m^3 water (SD 1911 m^3) per tonne Pangasius measured at the 10 ASC-c1 farms (Nhu et al., 2016). Because of such high fluctuation in the water input of the NFs, a Monte Carlo calculation and statistical test showed an insignificant difference in the water resource category (WR) between the ASC-c1 and NF-n1 farms (the MC frequencies where Xc1 < Xn1 of 49% and p-value > 0.05) (Fig. 2b1). However, when comparing WR between the ASC-c1 and NF-n3 farms, these tests presented the opposite result, in that the ASC-c1 farms extracted WR significantly higher compared to the NF-n3 farms but the benefit of the NF-n3 farms was marginal in terms of decision making (the MC frequencies where Xc1 < Xn3 of 46% and p-value < 0.05) (Fig. 2b3). The latter result would be due to the qualified estimation of water input of the NF-n3 farms instead of an on-site measurement throughout production. Consequently, the NFs might be concluded to extract the water resources as efficiently as the ASCs, whereas the water input measured at 9 of the 10 NF-n1 farms studied in Nhu et al. (2016) and estimated in Bosma et al. (2011) was less than 5000 m^3 water $tonne^{-1}$ Pangasius, which is the limitation of water abstraction set by the ASC standards (ASC, 2012).

Moreover, the fresh water eutrophication impact (FE) varied significantly among the NFs (n1, n2 and n3), primarily due to the highly fluctuating discharge of total phosphorus (TP). This resulted in an inconclusive benefits of applying the ASC scheme to FE, representing through the conflicting decision confidence probability (μ) of the Monte Carlo calculation: 68% that Xc1 < Xn1, 95% that Xc1 < Xn3 and 32% that Xc1 < Xn2 when comparing the FE impact between the ASCs (c1) and the NFs (n1, n2 n3). In short, the ASC certification scheme ascertains a low environmental impact, but it is possible that the impact is lower for certain non-ASC certified farms due to the large spread; however, on average this is not common. Moreover, the differences in the timing of a survey of the 3 NF groups (n1, n2, n3) did not affect the statistical results, since a comparison between them and the ASC group (c1) was performed separately (i.e., in pairs). Similar results in a hotspot analysis and comparison with the ASC group were obtained for the 3 NF groups despite their differences in survey timing (except for the freshwater eutrophication impact).

3.3. Sensitivity of methodological choices and limitations

Differences in LCI modelling (e.g., processes of feed ingredients production, electricity, etc., see SI1, Table S2) between this study and the previous studies (Bosma et al., 2011; Huysveld et al., 2013) negligibly affect the findings on the important contribution of feed input to LR, GW, AC and of grow-out farming to WR and FE, as well as to the identified environmental hotspots of Pangasius feed production, except the impact of domestic fishmeal on these categories (section 'Hotspot identification'). The results indicate that more concern should be paid to the Vietnamese capture fishery because of its high consumption of fossil fuels (e.g., diesel, heavy fuel oil). However, it should be noted that such production systems, especially at the small- and large-scales, aim to exploit other high economic-benefit species, i.e., shrimp, squid, crabs, marketable fish, while "trash" fish used for reduction (feed input) is a low economic-benefit by-product requiring a large amount captured. The economic allocation could be interesting for quantifying the burden of Vietnamese fishmeal; however, a physical property (i.e., exergy content) was selected as the allocation base for discussion in this study, following the ISO guidelines (ISO, 2006b). Therefore, we also applied two other allocation approaches based on mass and economic values.

The above-mentioned hotspot identification and comparative results derived from exergy allocation remain valid while the economic and mass allocations were also applied (SI1, Fig. S2), except the 2 following changes identified at the WR, GW and AC categories. First, through economic allocation, the burden of a unit of fn3 feed (used by the NF-n3 farms) was insignificantly higher than that of the other studied commercial feeds (i.e., fc1 used by the ASC-c1 farms, fn1 used by the NF-n1 farms and fn2 used by the NF-n2 farms), which was not the case for the exergy and mass allocation approaches. Consequently, inputs of milling processes contributed more to the burden of a unit of feed, especially at WR, via applying the economic allocation compared to the mass and exergy allocation (SI1, Fig. S3). This is explained by a significantly higher share in fishmeal mass in the fn3 feed (14.8%) compared to the other studied commercial fc1 (6.6%), fn1 (6.6%) and fn2 (7.0%) feeds (SI2). Applying the economic allocation lowered the environmental impact of fishmeal, mainly domestic fishmeal, with respect to WR, GW and AC, where fishmeal was identified as the hotspot, resulting in a considerable decrease in the burden of a unit of the fn3 feed in these categories. Second, the economic allocation decreased the decision confidence probability (μ) implying that Xc1 < Xn2 and Xc1 < Xn3 with about a 10% chance for GW and AC impacts (SI1, Figs. S4 and S5). This is supported by the fact that the fc1 feed (6.6%) used by the ASC-c1 farms contains a lower amount of fishmeal compared to the fn3 feed (14.8%) used by the NF-n3 farms, whereas the NF-n2 farms used a farm-made feed containing fishmeal at 9.3% and "trash" fish at 14.8% in addition to the commercial feed fn2 (SI2). In other words, the allocation choices drastically affect the environmental impact of feeds containing large amounts of fish-derived ingredients, especially domestic fishmeal, and the farms used these feeds.

Furthermore, the sample size included 10 of the currently 37 ASC-certified farms in Vietnam. While the spread among farms and the influence of post-normal uncertainty were accounted for, Monte Carlo simulations generate indefinitely large sample sizes and thus achieve statistical significance for almost any comparison (Henriksson et al., 2015a). Therefore, we limited ourselves to a sample size of 1000 iterations (see Section "Monte Carlo simulation"). However, we encourage further studies to reproduce our outcomes, based upon larger datasets and accounting for farm size, which could hopefully be made available for all ASC certified farms in the future. We also advocate for the proper interpretation of p-values and their limitations (Wasserstein and Lazar, 2016).

Moreover, the CEENE method requires a better assessment of the environmental impacts of wild caught fish, inspired by the work of Luong et al. (2015), in which the resource footprint of harvested species, e.g., wild catches, is quantified by combining specific net primary production (NPP) required to produce the fish and the amount with the real productivity of NPP.

3.4. To certify or not to certify?

The statistical test (i.e., Wilcoxon signed rank test) indicated that applying the ASC certification scheme garnered a significantly lower environmental impact with respect to certain resource- (LR, TR) and emissions-related categories (GW, AC and ME) due to better farming efficiency (i.e., a lower eFCR) and the management of nitrogenous emissions. However, based upon the MC frequencies, the studied ASCs were outstandingly more favourable than the studied NFs in terms of decision-making in only the emissions-related categories (see section 'Comparative results'). Although the ASCs obtained no clear benefit with respect to water resources (WR) and freshwater eutrophication impact (FE), following the ASC certification scheme better manages the high fluctuation in water inputs and nutrient (nitrogen and phosphorous) discharges at the NFs. For Pangasius aquaculture, the ASC standards limit the feed and water usage to a maximum amount of 1.69 tonne feed (eFCR) and 5000 m^3 water in the production of one tonne of Pangasius. Water effluent quality and nutrient utilization efficiency are better monitored by developing specific requirements for the most important nutrient parameters, i.e., nitrogen and phosphorus, which affect the eutrophication impact. The maximum amounts of total nitrogen and phosphorus discharged from ponds are restricted to 27.5 and 7.2 kg per tonne Pangasius produced, respectively (ASC, 2012).

Moreover, a large share of the wild fish in aqua-feed has been reported as one of the primary causes of global warming and eutrophication in many Asian aquaculture systems, including the Vietnamese Pangasius (Henriksson et al., 2015b). This study also found that the share of fishmeal in Pangasius feed primarily drives the environmental performance of Pangasius aquaculture, including both ASCs and NFs, with respect to water resources (WR), global warming (GW) and acidification (AC), in addition to crop-derived ingredients (section 'Hotspot identification'). While finding more sustainable sources of fishmeal as aqua-feed is challenging with regard to product origin, production technology, nutritional quality, etc., limiting the inclusion of fishmeal itself could be feasible and efficient. The inclusion of fishmeal and fish oil in Pangasius feeds was accounted for in the ASC scheme as the maximum Feed Fish Equivalency Ratio (FFER) of 0.5. FFER, which is defined as the product of eFCR and the mass percentage of fish products (i.e., fishmeal and fish oil) in feed composition per yield of fish products from wild caught fish (global average of 22.22% for fishmeal and 5% for fish oil); this represents the efficiency with which fish products used in the feed are converted to live fish (ASC, 2012).

As mentioned above (section 'Introduction'), the certification schemes have established a course for transforming conventional Pangasius farming and production in Vietnam to a more environmentally friendly market under the important support of the Vietnamese government since 2010. Large-scale farms might be more influenced. This was presented through, for example, higher values of eFCR (1.86) and fishmeal-FFER (1.24) at the 28 NFs (n3), which were surveyed before 2010. These values were lower for the NFs surveyed after 2010: 1.67 and 0.49 for the 10 NFs (n1) and of 1.68 and 0.54 for the 38 large-scale farms studied in Henriksson et al. (2015b); they nearly met the ASC standards (eFCR of 1.69 and FFER of 0.5). The large-scale farmers were more able to participate in certification standards (and hence obtained more benefit), whereas the small- and medium-scale farms did not benefit because of the demands associated with written documentation, technical requirements (e.g., equipment, waste treatment, etc.) and auditing fees (Marschke and Wilkings, 2014). This practical limitation of certification may also explain why non-certified farms do not always have a higher impact compared with certified ones; maybe they have just not been audited. However, in a broad-scale survey, compared to the small- and medium-scale farms, large-scale farms consumed less feed (i.e., lower eFCR) and emitted fewer nutrients into freshwater and air (SI2), resulting in a significantly lower environmental impact with respect to global warming, eutrophication and freshwater eco-toxicological impacts (Henriksson et al., 2015b).

On the other hand, more sustainable development certification schemes have been recently launched for aquaculture production in general and more specifically for the Pangasius sector at both a worldwide coverage (e.g., GlobalG.A.P., ASC, etc.) and country scale (e.g., Vietnamese Good Agricultural Practices VietG.A.P.). Pangasius products must also meet different certification schemes depending on import markets (e.g., GlobalG.A.P. in the United States, ASC in the European Union, etc.). This may leads to difficulties in identifying certificates for producers, and confusion among producers, retailers and consumers in recognizing a credible scheme, and may also lead to higher costs due to the need for multiple audits. The Global Sustainable Seafood Initiative (GSSI) therefore officially launched the Global Benchmark Tool in October 2015 which provides the following: (i) producers with more options to choose the right scheme and reduce the cost of multiple audits; (ii) buyers with simpler, more consistent data to guide their purchasing decisions; (iii) NGOs with more open and vetted information to promote the environmental sustainability of seafood; and (iv) consumers with confidence in certified seafood (GSSI, 2016). The three certification schemes relevant to Pangasius: ASC, BAP and VietG.A.P. were partnered with GSSI for the Global Benchmark Tool pilot, which was road-tested in 2015.

Jonell et al. (2013) indicated that certification schemes have limited influence on reducing the environmental impact of the growing aquaculture sector in general because they focus on species (e.g., salmon, shrimp) predominantly consumed in the European Union and the United States, with limited coverage of Asian markets where seafood consumption is predicted to increase substantially. Certified products also currently constitute a minor share in the market, whereas standards for species that have the potential to be produced in large quantities with marginal environmental impact, e.g., carp, have not been established. Other issues include the inequitable and non-uniform applicability of certification across the sector, a lack of incentives for improvements among the worst performers, and incomplete coverage of the studied environmental impacts (e.g., lacking of biophysical and ecosystem sustainability). However, certification seems to be a good approach for Pangasius production to ascertain adequate environmental sustainability, as shown in this study; however, implementation should be unified (one certification scheme), facilitated and made more affordable.

3.5. Further improvements for Pangasius farms, inspiring certification schemes

In light of current certification standards, further improvements are possible and could raise the bar, inspiring improvement and development of certification criteria. First, it is important to note that current LCA methodology cannot cover all aspects of sustainability and thus not all aspects of a certification scheme (SI1, Table S1). Simplified/inferred equations could be used for certification to estimate the environmental impacts of an agriculture/aquaculture production system based on key factors (Avadí et al., 2016; Nhu et al., 2016). Care should be taken as these equations are only usable for similar farm systems and data collection/modelling as those from which they are derived. The feed input was identified as the most important factor driving the environmental sustainability of intensive Pangasius aquaculture, for both the resource- (LR, TR) and emissions-related (GW, AC) categories. Increasing fish farming efficiency by (further) reducing the eFCR could be challenging but is feasible as the eFCR values of Pangasius aquaculture were reported to vary within a range of 1.0–3.0 in commercial pellet feeds and 1.3–3.0 for farm-made feeds (Phan et al., 2009). Moreover, more attention should be paid to the most important feed ingredients, which drive the environmental sustainability of Pangasius feeds: crop-derived (i.e., soybean meal, rice and wheat by-products) and fish-derived ingredients. Domestic fishmeal was more profitable to Pangasius feed producers than imported fishmeal (e.g., Peru) due to lower prices. However, its environmental burden was also significantly higher per unit of fishmeal, regardless of the applied allocation approach (i.e., exergy, mass or economic allocation). This is a result of the higher fuel consumption by the Vietnamese fishery compared to that of the Peruvian fishery (section 'Sensitivity of methodological choices'). This implies that more attention to the mass of domestic fishmeal in Pangasius feed composition is essential, though the inclusion of fishmeal and fish oil was restricted in the ASC scheme via the FFER limit of 0.5. The inclusion of livestock-derived ingredients in Pangasius feeds should also be a priority, since small amounts (e.g., 3.4% in the fn2 feed) made substantial environmental contributions with respect to WR, GW, AC and FE (section 'Hotspot identification').

Recycling pond sediment as agricultural fertiliser can avoid the consumption of similar-function alternatives, i.e., agricultural fertiliser. The substitution of pond sediment for fertiliser generates an "avoided credit" of 147 MJex kg^{-1} N in sediment and 118 MJex kg^{-1} P in sediment. The quantification was based on the replacement ratio of nutrient contents between pond sediment and the most widely fertilisers used in Vietnam, i.e., urea for nitrogen and superphosphate for phosphate (Nhu et al., 2015a). Leaving sediment in place (e.g., fish ponds, sedimentation ponds, etc.) could be another option since the nutrient discharge and related impacts, e.g., eutrophication and the energy consumption for pumping, are reduced (Bosma et al., 2011). However, such applications are not superior to, e.g., composting, since the use of (semi)intensive unaerated fish ponds as waste management and valorisation systems might result in increased methane emissions, which contribute significantly to global warming (Astudillo et al., 2015; Chen et al., 2016).

It is important to acknowledge that the impacts of veterinary medicines, feed additives and probiotics to the considered categories were quantified here based on their total amount used and were represented by the generic organic/inorganic chemicals (including process numbers) from the Ecoinvent v.2.2 database. They were found to be regularly used in Vietnamese Pangasius farms in total quantities, relative to production, that were comparable or even lower than those reported for other animal commodities (Rico et al., 2013). Henriksson et al. (2015a) presented that on-farm chemical use in the Pangasius NFs made limited contributions towards the overall life-cycle freshwater ecotoxicity (FWET) impact; however, benzalkonium chloride (BAC) and other chlorine-releasing compounds, the most commonly used disinfectants, are an exception, especially BAC, for which the emissions (56.5 mg/kg Pangasius) to the environment induced 16% of the FWET impact.

GlobalG.A.P imposed a Maximum Residue Limit (MRL) of BAC at 0.5 mg/kg until August 2015, after which this was lowered to 0.1 mg/kg for food or feed (GlobalGAP, 2016). However, no specific restrictions, with respect to the quantity of BAC used or discharged, were established in the ASC or GlobalG.A.P guidelines. Certification schemes can be further improved based on our advice, but at best, stakeholders must be consulted to assess their feasibility.

4. Conclusions

Similar environmental hotspots were identified for both ASC-certified and non-ASC certified Pangasius farms: feed inputs for land resources (LR), global warming (GW) and acidification (AC) categories and other farm inputs (i.e., growing-farming, except feed input and hatchery) for water resources (WR) and freshwater eutrophication (FE) categories. However, feed and growing-farming inputs contributed near equally to the total resource use (TR) and respectively dominated the marine eutrophication impact (ME) of the ASC and non-ASC systems, respectively. The ASCs induced a significantly lower environmental impact at most considered categories but obtained no clear benefit regarding the WR and FE categories. The ASCs were also outstandingly more favourable than the NFs in terms of impacts in some emissions-related categories (GW, AC, ME). Selecting the mass, exergy content or economic value as an allocation approach only drastically influenced the environmental impact of feeds containing relatively large amounts of fish-derived ingredients and consequently impacted the metrics for the farms using these feeds. Possible improvements, inspiring new certification standards, are as follows: decreasing the amount of feed used (i.e., a lower economic Feed Conversion Ratio) and lowering the impact of a unit of feed by restricting the shares of high-impact ingredients, e.g., fishmeal or livestock-derived ingredients. These options are best reviewed with key stakeholders.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.envpol.2016.10.006.

References

Alvarenga, R.A.F., Dewulf, J., Van Langenhove, H., Huijbregts, M.A.J., 2013. Exergy-

based accounting for land as a natural resource in life cycle assessment. Int. J. Life Cycle Assess. 18, 939–947. http://dx.doi.org/10.1007/s11367-013-0555-7.
Anh, P.T., Kroeze, C., Bush, S.R., Mol, A.P.J., 2010. Water pollution by Pangasius production in the Mekong Delta, Vietnam: causes and options for control. Aquac. Res. 42, 108–128. http://dx.doi.org/10.1111/j.1365-2109.2010.02578.x.
ASC, 2012. ASC Pangasius Standard Version 1.0. Aquaculture Stewardship Council, The Netherlands, p. 70.
ASC, 2016. http://www.asc-aqua.org/[accessed: 20.04.2016].
Astudillo, M.F., Thalwitz, G., Vollrath, F., 2015. Modern analysis of an ancient integrated farming arrangement: life cycle assessment of a mulberry dyke and pond system. Int. J. Life Cycle Assess. 20, 1387–1398. http://dx.doi.org/10.1007/s11367-015-0950-3.
Avadí, A., Nitschelm, L., Corson, M., Vertès, F., 2016. Data strategy for environmental assessment of agricultural regions via LCA: case study of a French catchment. Int. J. Life Cycle Assess. 21, 476–491. http://dx.doi.org/10.1007/s11367-016-1036-6.
Ayer, N.W., Tyedmers, P.H., 2009. Assessing alternative aquaculture technologies: life cycle assessment of salmonid culture systems in Canada. J. Clean. Prod. 17, 362–373. http://dx.doi.org/10.1016/j.jclepro.2008.08.002.
BAP, 2016. http://bap.gaalliance.org/[accessed: 20.04.2016].
Belton, B., Haque, M.M., Little, D.C., Sinh, L.X., 2011. Certifying catfish in Vietnam and Bangladesh: who will make the grade and will it matter? Food Policy 36, 289–299. http://dx.doi.org/10.1016/j.foodpol.2010.11.027.
Bojaca, C.R., Schrevens, E., 2010. Parameter uncertainty in LCA: stochastic sampling under correlation. Int. J. Life Cycle Assess. 15, 238–246. http://dx.doi.org/10.1007/s11367-010-0150-0.
Bosch, M.E., Hellweg, S., Huijbregts, M.A.J., Frischknecht, R., 2007. Applying cumulative exergy demand (CExD) indicators to the ecoinvent database. Int. J. Life Cycle Assess. 12, 181–190. http://dx.doi.org/10.1065/lca2006.11.282.
Bosma, R., Anh, P.T., Potting, J., 2011. Life cycle assessment of intensive striped catfish farming in the Mekong Delta for screening hotspots as input to environmental policy and research agenda. Int. J. Life Cycle Assess. 16, 903–915. http://dx.doi.org/10.1007/s11367-011-0324-4.
Bush, S.R., Khiem, N.T., Sinh, L.X., 2009. Governing the environmental and social dimensions of pangasius production in vietnam: a review. Aquac. Econ. Manag. 13, 271–293. http://dx.doi.org/10.1080/13657300903351594.
Chen, Y., Dong, S., Wang, F., Gao, Q., Tian, X., 2016. Carbon dioxide and methane fluxes from feeding and no-feeding mariculture ponds. Environ. Pollut. 212, 489–497. http://dx.doi.org/10.1016/j.envpol.2016.02.039.
Dewulf, J., Van Langenhove, H., Muys, B., Bruers, S., Bakshi, B.R., Grubb, G.F., Paulus, D.M., Sciubba, E., 2008. Exergy: its potential and limitations in environmental science and technology. Environ. Sci. Technol. 42, 2221–2232. http://dx.doi.org/10.1021/Es071719a.
FAO, 2014. The State of World Fisheries and Aquaculture, Italy, p. 243.
FishStatJ, 2016. http://www.fao.org/fishery/statistics/software/fishstatj/en [accessed: 09.03.2016].
Frischknecht, R., Jungbluth, N., Althaus, H.J., Doka, G., Dones, R., Heck, T., Hellweg, S., Hischier, R., Nemecek, T., Rebitzer, G., Spielmann, M., Wernet, G., 2007. Overview and Methodology (ecoinvent report No. 1). Swiss Centre for Life Cycle Inventories, Dubendorf, p. 68.
GlobalGAP, 2016. http://www.globalgap.org/[accessed: 20.04.2016].
Goedkoop, M., Oele, M., Leijting, J., Ponsioen, T., Meijer, E., 2013a. Introduction to LCA with SimaPro Version 8 (Report v.5.1). PRé sustainability, p. 80.
Goedkoop, M.J., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., Van Zelm, R., 2013b. ReCiPe 2008-A Life Cycle Impact Assessment Method Which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level (revised). Report I: Characterisation, The Nederlands, first ed., p. 133
GSSI, 2016. http://ourgssi.org/[accessed: 08.02.2016].
Henriksson, P.J.G., Guinee, J.B., Heijungs, R., de Koning, A., Green, D.M., 2014a. A protocol for horizontal averaging of unit process data-including estimates for uncertainty. Int. J. Life Cycle Assess. 19, 429–436. http://dx.doi.org/10.1007/s11367-013-0647-4.
Henriksson, P.J.G., Heijungs, R., Dao, H.M., Phan, L.T., de Snoo, G.R., Guinee, J.B., 2015a. Product carbon footprints and their uncertainties in comparative decision contexts. Plos One 10. http://dx.doi.org/10.1371/journal.pone.0121221.
Henriksson, P.J.G., Rico, A., Zhang, W., Ahmad-Al-Nahid, S., Newton, R., Phan, L.T., Zhang, Z.F., Jaithiang, J., Dao, H.M., Phu, T.M., Little, D.C., Murray, F.J., Satapornvanit, K., Liu, L.P., Liu, Q.G., Haque, M.M., Kruijssen, F., de Snoo, G.R., Heijungs, R., van Bodegom, P.M., Guinee, J.B., 2015b. Comparison of Asian aquaculture products by use of statistically supported life cycle assessment. Environ. Sci. Technol. 49, 14176–14183. http://dx.doi.org/10.1021/acs.est.5b04634.
Henriksson, P.J.G., Zhang, W., Nahid, S.A.A., Newton, R., Phan, L.T., Dao, H.M., Zhang, Z., Jaithiang, J., Andong, R., Chaimanuskul, K., Vo, N.S., Hua, H.V., Haque, M.M., Das, R., Kruijssen, F., Satapornvanit, K., Nguyen, P.T., Liu, Q., Liu, L., Wahab, M.A., Murray, F.J., Little, D.C., Guinée, J.B., 2014b. Primary Data and Literature Sources Adopted in the SEAT LCA Studies. Final LCA case study report, p. 132.
Huijbregts, M., 2002. Uncertainty and variability in environmental life-cycle assessment. Int. J. Life Cycle Assess. 7, 173, 173. http://dx.doi.org/10.1007/Bf02994052.
Huysveld, S., Schaubroeck, T., De Meester, S., Sorgeloos, P., Van Langenhove, H., Van Linden, V., Dewulf, J., 2013. Resource use analysis of Pangasius aquaculture in the Mekong delta in vietnam using exergetic life cycle assessment. J. Clean. Prod. 51, 225–233. http://dx.doi.org/10.1016/j.jclepro.2013.01.024.
ISO, 2006a. ISO 14040: Environmental Management - Life Cycle Assessment - Principles and Framework. Switzerland, p. 20.
ISO, 2006b. ISO 14044: Environmental Management - Life Cycle Assessment - Requirements and Guidelines. Switzerland, p. 46.
Jonell, M., Phillips, M., Ronnback, P., Troell, M., 2013. Eco-certification of farmed seafood: will it make a difference? Ambio 42, 659–674. http://dx.doi.org/10.1007/s13280-013-0409-3.
Lloyd, S.M., Ries, R., 2007. Characterizing, propagating, and analyzing uncertainty in life-cycle assessment - a survey of quantitative approaches. J. Ind. Ecol. 11, 161–179. http://dx.doi.org/10.1162/jiec.2007.1136.
Luong, A.D., Schaubroeck, T., Dewulf, J., De Laender, F., 2015. Re-evaluating primary biotic resource use for marine biomass production: a new calculation framework. Environ. Sci. Technol. 49, 11586–11593. http://dx.doi.org/10.1021/acs.est.5b02515.
Marschke, M., Wilkings, A., 2014. Is certification a viable option for small producer fish farmers in the global south? Insights from Vietnam. Mar. Policy 50, 197–206. http://dx.doi.org/10.1016/j.marpol.2014.06.010.
Nhu, T.T., Dewulf, J., Serruys, P., Huysveld, S., Nguyen, C.V., Sorgeloos, P., Schaubroeck, T., 2015a. Resource usage of integrated Pig-Biogas-Fish system: partitioning and substitution within attributional life cycle assessment. Resour. Conserv. Recycl. 102, 27–38. http://dx.doi.org/10.1016/j.resconrec.2015.06.011.
Nhu, T.T., Le, H.Q., ter Heide, P., Bosma, R.H., Sorgeloos, P., Dewulf, J., Schaubroeck, T., 2016. Inferred equations for predicting resource usage throughout cradle-to-gate life cycle of Pangasius feeds and intensive Pangasius aquaculture in Vietnam. Resour. Conserv. Recycl. 115, 42–49. http://dx.doi.org/10.1016/j.resconrec.2016.08.023.
Nhu, T.T., Schaubroeck, T., De Meester, S., Duyvejonck, M., Sorgeloos, P., Dewulf, J., 2015b. Resource consumption assessment of Pangasius fillet products from Vietnamese aquaculture to European retailers. J. Clean. Prod. 100, 170–178. http://dx.doi.org/10.1016/j.jclepro.2015.03.030.
Pelletier, N., Ayer, N., Tyedmers, P., Kruse, S., Flysjo, A., Robillard, G., Ziegler, F., Scholz, A., Sonesson, U., 2007. Impact categories for life cycle assessment research of seafood production systems: review and prospectus. Int. J. Life Cycle Assess. 12, 414–421. http://dx.doi.org/10.1065/lca2006.09.275.
Pelletier, N., Tyedmers, P., 2008. Life cycle considerations for improving sustainability assessments in seafood awareness campaigns. Environ. Manag. 42, 918–931. http://dx.doi.org/10.1007/s00267-008-9148-9.
Phan, L.T., Bui, T.M., Nguyen, T.T.T., Gooley, G.J., Ingram, B.A., Nguyen, H.V., Nguyen, P.T., De Silva, S.S., 2009. Current status of farming practices of striped catfish, Pangasianodon hypophthalmus in the Mekong Delta, Vietnam. Aquaculture 296, 227–236. http://dx.doi.org/10.1016/j.aquaculture.2009.08.017.
Rico, A., Phu, T.M., Satapornvanit, K., Min, J., Shahabuddin, A.M., Henriksson, P.J.G., Murray, F.J., Little, D.C., Dalsgaard, A., van den Brink, P.J., 2013. Use of veterinary medicines, feed additives and probiotics in four major internationally traded aquaculture species farmed in Asia. Aquaculture 412, 231–243. http://dx.doi.org/10.1016/j.aquaculture.2013.07.028.
Swart, P., Alvarenga, R.A.F., Dewulf, J., 2015. Chapter 13: abiotic resource use. In: Hauschild, M.Z., Huijbregts, M.A.J. (Eds.), Life Cycle Impact Assessment. Springer, London, p. 339.
VASEP, 2014. Pangasius 26 Q & a (second ed.), Ha Noi, p. 84.
Wasserstein, R.L., Lazar, N.A., 2016. The ASA's statement on p-values: context, process, and purpose. Am. Stat. 70, 129–131. http://dx.doi.org/10.1080/00031305.2016.1154108.
WWF, 2012. http://wwf.panda.org/[accessed: 09.03.2016].
Ziegler, F., Hornborg, S., Green, B.S., Eigaard, O.R., Farmery, A.K., Hammar, L., Hartmann, K., Molander, S., Parker, R.W.R., Skontorp Hognes, E., Vázquez-Rowe, I., Smith, A.D.M., 2016. Expanding the concept of sustainable seafood using Life Cycle Assessment. Fish Fish. n/a-n/a http://dx.doi.org/10.1111/faf.12159.