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The potential of floating macrophytes as feed and phytoremediation resources to improve the environmental performance of giant gourami production in Indonesia: A Life Cycle Assessment

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Abstract

Over the past few decades, Indonesian freshwater aquaculture has intensified, raising many issues on the associated environmental impacts. In this study, a life cycle assessment (LCA) approach was used to assess the environmental performance of Indonesian giant gourami (*Osphronemus goramy*) aquaculture. We compared two contrasting fish production systems: a traditional monoculture (MoC) or a co-culture with the macrophyte *Azolla filiculoides* used as feed alternative to compounded pellets (CoC). Seven impact categories were considered: climate change, eutrophication, cumulative energy demand, land occupation, acidification, net primary production use (NPPU) and water dependence. The potential impacts were calculated in terms of 1 kg of fish produced by the systems and were also expressed in terms of surface area (m^2 of the farm). Monte Carlo analysis was carried out to evaluate uncertainties in the assessed impacts based on data uncertainties for the systems. Results highlighted notable differences between the two production systems. CoC led to less impact relative to climate change, eutrophication and NPPU per kg of fish produced. These differences were even greater when reporting the impacts per surface area. Nonetheless, the main contributors of the seven impact categories remained constant between the two production systems (CoC and MoC). Overall, our findings suggested that using floating macrophytes as alternative feed resources, even in relatively low proportions, can improve the environmental performance of giant gourami production.

Keywords: Agroecology, Asia, Aquaculture, Freshwater, LCA

1. Introduction

With a production of 4.3 million tons of farmed fish in 2020, Indonesia is the third-largest fish aquaculture producer country in the world (FAO, 2022a). Since the government made aquaculture development a national priority in 2009 (Phillips et al., 2015; Rimmer et al., 2013), fish farming has shown the most rapid expansion of all Indonesian agronomic production sectors, with an average annual growth of 9% over the last decade (FAO, 2022b). This sector indeed plays a significant role in the national economy, ensuring food availability and security and improving living standards for rural communities (Rimmer et al., 2013). Excluding seaweed, freshwater fish farming represents 66% of aquaculture production in Indonesia (FAO, 2022b) and relies mainly on small-scale farms, which represent 90% of all fish farms (Maskur et al., 2013). Small-scale fish farmers usually practice aquaculture using low-input and low-level technology (Pouil et al., 2019). Nevertheless, the increasing demand for freshwater aquaculture products has driven a shift from low-intensive traditional culture methods to semi-intensive monoculture production systems. This intensification was accompanied by an increase in the use of commercial fish pellets (Edwards, 2015; Rimmer et al., 2013), involving a decrease in the proportion of non-fed Asian aquaculture by a factor of two since the 2000s (excluding China; FAO, 2022b). Such changes raise many issues on the actual effectiveness of current production systems regarding the use of resources and the associated negative environmental impacts. These negative impacts are further reinforced by the large amounts of solid effluents (faeces, feed wastes) and dissolved nutrients (waste products) discharged resulting from the use of commercial feeds, which contribute to eutrophication of wild aquatic ecosystems. Several freshwater reservoirs in Java, where fed fish farming has proliferated, experienced water quality degradations leading to the occurrence of disease outbreaks and fish death (Rimmer et al., 2013).

Indonesian aquaculture must become more sustainable to meet the national demand for aquaculture products and also limit their environmental footprint. Henriksson et al. (2019) evaluated possible interventions and innovations to mitigate environmental impacts related to the growth of Indonesian aquaculture. The authors found that improving feed efficiency for white leg shrimp, common carp and tilapia by 20% witnessed major reductions in environmental impacts. Such interventions imply the design of aquaculture systems that use fewer chemical products and commercial feeds, more renewable resources, and make the best use of ecosystem services without impairing their regeneration. Such systems can be called "ecologically intensive" (Griffon, 2010), having a high level of production per surface area but using ecological processes as much as possible to optimize natural resource use and develop ecosystem services (Bonny, 2011). In recent years, a growing effort has been made worldwide to implement ecological intensification in aquaculture (Aubin et al., 2019), particularly by increasing the complexity of rearing systems using different complementary species as in integrated multi-trophic aquaculture (Jaeger and Aubin, 2018). However, the proof of concept must be enhanced, and comparative studies of different production systems for the same species remain scarce.

Among the fish species reared in Indonesia, giant gourami *Osphronemus goramy* is one of the primary freshwater commodities of economic importance due to its high price and local demand (FAO, 2019). With its propensity to consume plant-based feeds, giant gourami is a valuable candidate for low-input aquaculture (FAO, 2019) and for integrating fish production and plant culture. Giant gourami production in Indonesia is mainly located on Java Island (79% of the national giant gourami production; BPS, 2013) and is strongly segmented (FAO, 2019). Rearing takes place in ponds exclusively dedicated to giant gourami or shared with other species (Kristanto et al., 2020). Slembrouck et al. (2018) evaluated *Azolla* as the best candidate among five floating macrophytes species for the ecological intensification of small-scale fish farming in tropical areas. Recently, a study evaluated the feasibility of combining the production of the floating macrophyte *Azolla filiculoides* in giant gourami ponds (Caruso et al., 2021), with the macrophytes being used as an alternative fish feed. Compared with those from a conventional giant gourami monoculture system exclusively based on exogenous commercial feeds (Caruso et al., 2021), the use of *Azolla* proved to be economically advantageous by reducing the amount of commercial pellets used while maintaining a similar growth rate of the fish and biomass gain at the end of the trial. However, this study was not dealing with the environmental impacts of using such alternative production system compared to the conventional monoculture production.

A holistic approach is needed when considering the environmental impacts of production practices, and life cycle assessment (LCA) is considered a suitable tool for analysing aquaculture production systems (for review, see Bohnes et al., 2019). LCA is an international standardized method (ISO, 2006) designed to evaluate the global impact of a product or a process on the environment. Such evaluation implies the assessment of all the phases required for or caused by the product's existence; they include raw material uses and energy production, manufacturing, transport and emissions released into the environment at each stage until the product's end of life. Over the last two decades, LCA has been regularly used to assess the environmental impacts of aquaculture production (e.g., Aubin et al., 2006; Medeiros et al., 2017; Mungkung et al., 2013; Yacout et al., 2016). Several environmental impact categories are regularly used to assess aquaculture systems (Aubin et al., 2006; Bohnes et al., 2019; Henriksson et al., 2012; Papatryphon et al., 2004). One advantage of LCA is that it allows different products or systems to be compared using the same functional unit. Despite the usefulness of LCA, there are various limitations to its application. One of the critical challenges is the necessity to incorporate uncertainty in the calculations to produce more robust outcomes (Mendoza Beltran et al., 2018).

The present study aimed to assess the potential benefits of ecological intensification in Indonesian fish farming. Thus, our objectives were (1) to evaluate the environmental performances of two production systems of giant gourami aquaculture, with or without the integration of a co-cultured floating macrophyte (*A. filiculoides*) and (2) to identify the sources of uncertainties in the environmental impacts. We hypothesized that the use of *Azolla* as an alternative feed should reduce net primary production use, energy demand and climate change impacts by partially substituting commercial feeds while decreasing eutrophication by improving nutrient recycling (Caruso et al., 2021).

2. Materials and Methods

2.1. Description of the production system

2.1.1. Giant gourami production system

Although the giant gourami production cycle is not well standardized in Indonesia (Kristanto et al., 2020), its propagation relies on the natural spawning of captive brooders in ponds and includes the seven following production segments:

1) The hatchery phase lasts 10 days from egg incubation to 8-9 days after hatching. Larvae are kept unfed during this period.
2) The nursery phase lasts until juveniles reach 2 ± 0.5 cm of length (40 days; Prakoso et al., 2019). Tubifex (*Tubifex tubifex*) worms, usually purchased on local markets, are the first and primary food provided during larval rearing (i.e., nursery phase).

3) The pre-growing I stage lasts 150 days until juveniles reach 30 g. Commercial feed (~33% of crude protein) is introduced at the beginning of this segment.

4) The pre-growing II stage, until juveniles reach 180 g (from the "jingo" to the "dampal" stage), is the first stage of the production cycle during which fish are able to eat plant materials (FAO, 2019). This production stage lasts 160 days.

5) The growing phase lasts 120 days. During this phase, fish are fed with commercial pellets and plant materials (mainly giant taro *Alocasia macrorrhizos* leaves). At the end of this production phase, fish of ≤ 500 g are sold, and the biggest fish are selected as future brooders.

6) Brooder selection lasts 210 days, where fish of ≥ 2000 g are sorted by sex and separated. Plant materials become the predominant feed at this stage, and commercial feeds are used as supplements.

7) The egg production period is continuous throughout the year. The average weight of brooders used for egg production is 3.6 kg, and they are usually kept for 10 years of production.

Note: all the values used in our analysis are average values gathered from surveys of approximately 40 giant gourami farms (Kristanto et al., 2020).

Except for hatchery and nursery phases, usually performed in plastic basins and wooden tanks covered by tarpaulin filled with stagnant water, all the production phases are performed in flow-through systems, mainly in earthen ponds of 300-1000 m^2 in size with gravity-flow water supply system from local reservoirs or upstream aquaculture farms. The production chain for giant gourami is shown in Figure 1.

2.1.2. Scenarios of production: experiment details and records

The system under study consisted of a typical small-scale Javanese polyculture fish farm where farmers can quickly shift from one species to another to better adapt to the market and the difficulties encountered. Kristanto et al. (2020) underlined that giant gourami is mainly produced by farmers producing other species in variable proportions. Thus, only about 50% of the surface is dedicated to giant gourami rearing. The production capacity is about 2 tons per year. All the production is sold on local markets (< 10 km of the production site). The farm included in this study is located in Bogor district, West Java, in the village of Babakan (-6°28'S; 106°42'E; alt: 125 m). The farm size (i.e., 2100 m^2) is in the range typically observed locally (Kristanto et al., 2020). While a non-negligible number of aquaculture farms are located in the peri-urban area in West Java (see Kristanto et al. (2020) for details), our study site is mainly bordered by rice fields.

The studied production cycle, which lasts 160 days (i.e., two production cycles per year), consisted in rearing giant gourami from 30 to 180 g of average fresh weight (i.e., from the "jingo" stage to the "dampal" stage). This phase corresponds to the pre-growing stage II described in section 2.1.1 (Figure 1). "Jingo" fish were purchased from the neighbourhood and were stocked at a density of 6 fish m^{-2}.

The production system consisted of four earthen ponds, whose size varied between 353 and 482 m^2 with depths ranging from 0.46 to 0.55 m. Each pond was equipped with PVC pipes for inlet and outlet water; anti-predator nets held by bamboo poles were placed 1 m from the banks. Ponds connected in series were filled by gravity with water from a reservoir located at <1 km from the farm. Before production, ponds were dried; the bottom was levelled and the banks were consolidated with sediment accumulated during the previous production cycle. Then, unwanted species were removed and the water, transported by gravity from a reservoir located at <1 km from the farm, was limed and fertilized using organic fertilizer (typical composition: poultry manure mixed with rice bran at a 0.5:1 ratio on a dry weight basis; Purnomo et al., 2017). Production takes place in open-flow water (average water renewal 4-8% d^{-1}).

Traditionally, giant gourami are reared in a monoculture system (MoC). To evaluate the possibilities of using floating macrophytes for ecological intensification of tropical freshwater fish aquaculture, as suggested by Slembrouck et al. (2018), an experiment was carried out throughout one 160-day production cycle in 2018 to test a new giant gourami rearing system based on co-culture with *Azolla* (CoC). Here, the two production systems (CoC and MoC) were operated as described below.

The MoC system fed fish exclusively on commercial extruded pellets of known composition (Table 2). According to fish growth, the daily ration was 3 to 5% of the estimated wet biomass which is slightly higher than what is usually done by farmers (FAO, 2019). The final feed conversion ratio (FCR) reached 2.8. Fertilizer was regularly added to the ponds (equiv. 6 kg m^{-2} per year) to stimulate primary productivity. The annual fish production volumes reached 2 kg m^{-2} in this production system, and mortality was 8% per production cycle.

In the CoC system, *Azolla* was cultivated in the space available between the banks and the anti-predator net (80 m^2 of production surface) (Figure 2) in earthen ponds managed as described above with slightly higher use of fertilizer than in the MoC system (i.e., 7.5 kg m^{-2} an^{-1}). Fish were fed for two days with extruded pellets as described above, then one day with *Azolla* at a food ration of 8% of the estimated fish biomass. Such rationing corresponds to the amount of

Azolla the fish can ingest within 24h. *Azolla*, coming from an initial stock maintained in two 33 m^2 tarpaulin tanks, was stocked at an initial concentration of 400 g m^{-2}, and *Azolla* growth was checked every three days (before distribution to the fish). *Azolla* was regularly sampled for chemical analyses (Table 2). During our experiment, stable production of *Azolla* was not met as initially planned, and its production regularly collapsed in the ponds. During the 160-day fish production cycle, only two cycles of *Azolla* production occurred for a total of 40 days of production. A complementary experiment was performed to understand better the limiting factors in the mass production of *Azolla* in ponds (Pouil et al., 2020). That experiment suggested that phosphorus (P) was likely the main limiting factor in *Azolla* production, with an average of 0.4 µmol L^{-1} measured in the ponds, with the optimal growth occurring at a concentration of 2.0 µmol L^{-1}. In addition, the occurrence of grazing snails (3-4 adult individuals m^{-2}) may reduce *Azolla* production by 35% (Pouil et al., 2020). Thus, we built a scenario based on the extrapolation of the data (i.e., zootechnical and economic performance, chemical analyses) collected when co-culture was effective (i.e., 40 days) for the entire 160-day production period, and uncertainty related to the production of *Azolla* was included in the uncertainty analysis (see Section 2.6). The mortality and the annual fish production volume were comparable to the MoC system (i.e., 2 kg m^{-2}), and the FCR reached 2.1 given the average reduction of ~25% of the extruded pellets used.

2.2. Assessment methodology

2.2.1. Goal and scope

This LCA study followed ISO standards (ISO, 2006) and aimed at evaluating the environmental relevance of ecological intensification of giant gourami culture by integrating a co-culture of

Azolla, which may provide the ecological services of water depuration and provision of complementary feed for fish. Environmental performances of earthen pond-based production of giant gourami aquaculture were evaluated through: (1) a traditional semi-intensified monoculture system as used in West Java province (MoC), (2) a co-culture production system including *Azolla* (CoC). This study is based on experimental results designed to compare the efficiency of the two rearing systems. The results were expressed per kg of fresh fish and m^2 of surface area. As an additional information, results expressed per kg of protein are also available in the Supplementary Material (Table S1).

The system boundaries used in this study were from "cradle to farm gate" (Figure 2). They included the production of capital goods (infrastructure and equipment), the production of organic fertilizers and lime, the production of fish feed (including the production of ingredients from agriculture or fishery sectors), the production of fish juveniles, farm operations (including the local emission of nutrients and pollutants), the use of energy sources, and the transportation of critical inputs (juveniles, fish feed, equipment), and the transport of fish from the farm gate to the local market by motorcycle or small trucks.

2.2.2. Life cycle inventory

Inventory data for giant gourami fingerling production and brooder management were compiled mainly by collecting the data from fish farms and production centres producing giant gourami fry located in the Bogor and Tasikmalaya regencies (n=37, Kristanto et al., 2020). We also used experimental data from the experiments we performed on giant gourami egg production in the BPPSIGN Center, Tasikmalaya (Arifin et al. 2020; Slembrouck et al., 2019, 2020) and larval rearing in the RIFAFE, Cijeruk (Arifin et al., 2019; Prakoso et al., 2021).

The inventory of the experimental phase was recorded during daily on-site monitoring of one entire production cycle from November 2017 to April 2018. The descriptive data concerning the studied sub-system are summarized in Table 1. The inventory covered farm operations, as well as the following processes: production of farm inputs such as energy carriers, fertilizers, juvenile, exogenous feeds (including ingredient production and processing), and farm equipment and infrastructures (i.e., equipment; construction of buildings and breeding infrastructures) and transportation at all stages. Water flow at the outlet of each pond was measured daily to estimate the water balance. The fate of nitrogen (N) and phosphorus (P) was based on a nutrient-balance experiment performed on-site involving chemical analysis of fish, fertilizers, feeds, inlet and outlet water, water and sediment (Pouil et al., 2019). Data for pond gaseous emissions were adapted from the literature. Gaseous fluxes are influenced significantly by factors such as drainage, primary productivity, and the availability of organic matter in aquaculture ponds (Yang et al., 2018). It is important to note that fish production plays a pivotal role in shaping these variables, especially in the context of our pond production systems, where the absence of drainage, the organic fertilization practice, and the provision of commercial feed are key determinants. Denitrification and ammonia volatilization were assumed to be equivalent to 17.4% and 12.5% of the N inputs, respectively as found in channel catfish ponds (Gross et al., 2000). Values for methane (CH_4) and nitrous oxide (N_2O) emissions were extracted from Yang et al. (2018) who measured fluxes in semi-intensive shrimp ponds: 3.09 mg m^{-2} h^{-1} and 0.5 µg m^{-2} h^{-1} for CH_4 and N_2O emissions, and carbon dioxide (CO_2) fixation in pond sediment was evaluated at 21.56 mg m^{-2} h^{-1} (Yang et al., 2018).

Background data (i.e., construction materials, fuel, rearing equipment) were based on the ecoinvent v3.8 database (Wernet et al., 2016) and adapted to the local context. The inventory data for Indonesian electricity production were obtained from EIA (2021). Data on feed production were collected based on detailed reports supplied by the feed manufacturer in which all feed ingredients were quantified while proximate analysis were performed to determine nutritional composition (Table 2). The feed formulations were then validated regarding nutritional constraints according to Guillaume et al. (1999). Data on feed processing were supplemented with detailed information from a local feed producer. The inventory data for local fishmeal production (discarded fish) was collected from a local fishery processing plant dedicated to frozen fish (for export), surimi and fishmeal (Palembang, Sumatra Island). Heat energy from wood wastes was used for fishmeal processing (Mungkung et al., 2013). Inventories for crop-based feedstuffs were adapted from the ECOALIM dataset (Wilfart et al., 2016) to consider transportation to Indonesia. Distances for road and boat transport were estimated using Google Maps®. For organic fertilizer, we used the inventory for poultry manure on the global market available in the ecoinvent v3.8 database while inventory of rice produced in China, from the same database, was used for rice bran considering a mass allocation (Ayer et al., 2007).

2.2.3. Life cycle impact assessment

Midpoint impact categories were selected based on previous studies and recommendations for aquaculture LCA (Aubin et al., 2009; Bohnes et al., 2019; Papatryphon et al., 2004; Wilfart et al., 2013):

- acidification (mol H^+ eq), which aggregates substances that release hydrogen ions into the ecosystem;
- cumulative energy demand (CED; MJ), which aggregates the energy used from renewable and non-renewable sources;

- climate change (kg CO_2 eq), which aggregates greenhouse gas emissions;
- eutrophication (kg PO_4^{3-} eq), aggregating nutrient emissions that lead to oxygen depletion, impacting aquatic and terrestrial environments and adding the theoretical oxygen demand (ThOD) calculation for solid wastes from fish farms (Aubin et al., 2009);
- land occupation (m^2 yr) which represents the terrestrial ground area used;
- net primary production use (NPPU, kg C) refers to the use of a net primary producer as a biotic resource in the sense of being unavailable for other purposes, as defined by Papatryphon et al. (2004);
- water dependence (m^3) included the volume of water used in ponds as proposed for aquaculture production systems by Aubin et al. (2009) and the amount of water used in the other production phases.

The impact assessment was conducted according to (1) the International Reference Life Cycle Data System (ILCD) method for acidification and climate change, (2) the CML IA method, version 3.06 for eutrophication potential, and land occupation. Total energy use was calculated using the Cumulative Energy Demand method, version 1.10. Calculations were made using SimaPro software 8.5.4.0 (PréConsultants, Amersfoort, The Netherlands). As mentioned earlier, the ecoinvent version 3.8 database was used for background data, and the Agribalyse® database (Koch and Salou, 2014) was used for agricultural machinery, agricultural products and feed ingredients (ECOALIM dataset; Wilfart et al., 2016). For comparison purpose, we also performed the impact assessment using ReCiPe 2016 Midpoint (H) version 1.08 (Table S2 in the Supplementary Material).

2.6. Uncertainty analysis

The process for determining the uncertainty in the production systems was adapted for primary and secondary data. Among the primary data, the most important source of uncertainties in the CoC system was the production of *Azolla*. Considering the risk of predation and the variation in *Azolla* productivity due to the environmental conditions (light, nutrients) observed in ponds (Pouil et al., 2020), an uncertainty rate of 50% was applied in *Azolla* used as alternative feed in this production system. For other primary data (i.e., other inputs used and fish harvested), the standard deviation of the replicates was used in a normal distribution, as suggested by Medeiros et al. (2017). For secondary data, the pedigree matrix from Ciroth et al. (2016) was used to quantify uncertainty in the values selected from the literature (i.e. ThOD, N volatilization and denitrification and fluxes of CH_4, CO_2 and N_2O). We applied a lognormal distribution to the results generated from the matrix. Monte Carlo (MC) analysis was performed in SimaPro software 8.5.4.0.

2.7. Data analysis

To compare the CoC and MoC systems while considering uncertainty, we ran 1000 interactions in pairs in an MC analysis. This method indicated the number of times one system had higher impacts than the other. We considered that the two systems differed if one had higher impacts in at least 90% of the runs (Medeiros et al., 2017).

3. Results

Figure 3 presents the LCA impacts by category calculated per kg of fish produced (Figure 3A) or by m^2 of the farm (Figure 3B) for the CoC and MoC giant gourami production systems. Overall, we found similar trends regardless of the functional units chosen (i.e., product-based or surface-based). Thus, values presented in the following sections are first provided by kg of fresh fish; values expressed by m^2 are also given in Table 3.

3.1. Impact assessment

Among the impact categories selected, the MoC system had the highest impacts for all of them except land occupation (Figure 3 and Table 3), with 4.7 ± 0.2 m^2 yr^{-1} being required to produce 1 kg of fish in MoC and 4.8 ± 0.3 m^2 yr^{-1} in CoC. The highest differences between CoC and MoC were for NPPU (23-27% less in CoC): the production of 1 kg of fish required 13.8 ± 1.3 kg C in MoC, but the NPPU value of the CoC system was noticeably lower with 9.1 ± 0.9 kg C (i.e. ~25% less NPPU required in CoC). The second largest differences in environmental impacts between the two production systems were for water dependence (12-17% less in CoC) with values of 10.1 ± 3.5 m^3 and 8.7 ± 1.7 m^3 in MoC and CoC, respectively. Similarly, implementing the CoC system reduced eutrophication (i.e., 11-16% less in CoC). Climate change showed a reduction of 10-15% in the CoC with, per kg of fish produced, 6.4 ± 0.3 kg of CO_2 eq compared with MoC where 7.1 ± 0.1 kg CO_2 eq were estimated (Figure 3). Differences between CoC and MoC were less pronounced for the other impact categories. The energy requirements for producing 1 kg of fish from the ponds were slightly reduced in the CoC, with 130 ± 7 MJ vs 139 ± 4 MJ for MoC (i.e. 7-11% less in CoC; Figure 3). The gain provided by CoC in acidification was comparable, with values of 0.14 ± 0.01 mol H^+ eq for CoC and 0.15 ± 0.01 mol H^+ eq for MoC, equivalent to an impact reduction of 6-11% (Figure 3).

Contributions of the rearing system components (energy, exogenous feeds, equipment/infrastructures, farm operations, fertilizers, fish inputs and transport) varied according to the impact category and to the system (Figure 3 and Table 3). Overall, the ranking of the different contributors among the seven impact categories remained constant between the two production systems (CoC and MoC). Results presented in Figure 3 show that for eutrophication and water dependence, farm operations contributed the most to the impacts (81-82% and 52-58%, respectively), and the second largest contributor for these impact categories was fish inputs (11-13% and 42-48%, respectively). For NPPU, climate change and CED, exogenous feeds were the main contributors (83-86%, 37-45% and 31-40%, respectively), followed by fish inputs (14-17%, 20-22% and 18-19%, respectively) and/or fertilizers (15-21% for climate change and 27-35% for CED; Figure 3). For acidification, the main contributors were ranked as follows: 32-34% for fish inputs, 30-32% for farm operations and 15-19% for exogenous feeds, accounting for ~80% of the total acidification. Interestingly, land occupation was mainly driven by fertilizers (49-60%) and exogenous feeds (28-38%; Figure 3).

3.2. Uncertainty analysis

Uncertainty analysis qualifies data according to their origin, considering the uncertainties linked to the production of macrophytes in the CoC and including the variabilities observed between ponds in the LCA. Considering a threshold beyond which the two systems differed if one had higher impacts in at least 90% of the MC runs, there were notable significant differences between the two production systems. The analysis showed that CoC leads to less impact relative to climate change, eutrophication and NPPU on a production basis (per kg of fish produced; Figure 4A). The differences are even more marked on a farm surface basis (per unit area (m^2); Figure 4B), where, in this case, CED was also significantly lower in the CoC.

4. Discussion

4.1. Product-based vs area-based LCA approach

The functional unit is the basis of comparison in LCAs and influences allocation decisions at the farm gate (Henriksson et al., 2012). Here, we used a descriptive product-based functional unit (kg of fish) that is appropriate for comparisons between studies (Bohnes et al., 2019). Van Der Werf et al. (2020) highlighted the interest in combining product-based and area-based LCA when studying agricultural systems that provide a broad range of ecosystem services. For instance, although organic agriculture generally emits fewer pollutants per unit of land occupied than conventional agriculture (an area-based approach), it may have higher impacts per unit of product (e.g., land occupation, eutrophication and acidification). Thus, we also expressed the environmental impacts using an area-based functional unit (m^2 of farm), an original approach in LCA aquaculture studies (Bohnes et al., 2019; Henriksson et al., 2012). Our results show that the choice of the functional unit did not result in significant differences in environmental impacts for the LCA impact categories considered. Nevertheless, even if the conclusions remain similar comparing the two production systems (CoC and MoC), a greater difference between the systems was observed using the area-based functional unit for the following impact categories: acidification, CED and NPPU.

4.2. Comparison of production systems

The responses in environmental impacts between the two studied production systems differed according to the impact category considered. The two systems remained similar considering land occupation and water dependence, although CoC showed slightly lower impacts for the latter category. Using CoC as an alternative to MoC was expected to reduce land utilization by decreasing the quantity of extruded pellets used. Nevertheless, the beneficial effects of reducing exogenous feed were attenuated by the higher quantity of organic fertilizer from the intensive poultry production system and rice culture (Purnomo et al., 2017) for *Azolla* production in CoC.

Such results highlight the need to better control the origin and the quantity of fertilizers used for pond fertilization.

Between the two production systems, the differences observed in acidification, CED, climate change eutrophication and NPPU were mainly explained by the lower use of exogenous feed in CoC (-25% on average per kg of fish produced). Our study confirms previous investigations highlighting that feed production is the major contributor to different impact indicators in semi-intensive aquaculture production systems (e.g., Wilfart et al., 2013; Yacout et al., 2016). The difference reflects the high impact of feed production, from the extraction of raw materials up to manufacturing processes, which require large amounts of energy and resources (Ghamkhar and Hicks, 2020). The processing of feed is by far the highest contributor to NPPU. Such results are in accordance with Mungkung et al. (2013), who pinpointed feed production as the unique contributor to NPPU (100%) in Indonesian tilapia-carp production systems. In addition to its predominant environmental impact, fish feed has a significant economic impact on the aquaculture farm because some ingredients are imported, which is frequently the case for small-scale fish farming practised in Indonesia (Slembrouck et al., 2018).

The importance of FCR, and hence of extruded feeds in general, has been highlighted by numerous LCA aquaculture studies. In literature reviews, Aubin (2013) and Bohnes et al. (2019) have concluded that feed production is the primary source of environmental impacts. In the present study, FCR for commercial pellets was relatively high in giant gourami compared with other omnivorous species like carp and tilapias (Fry et al., 2018).

In small-mouthed fish like giant gourami, uneaten feeds can represent 30% of the feed supplied (Bosma and Verdegem, 2011; Van Der Meer et al., 1997; Verdegem, 2013). In giant gourami, Pouil et al. (2019) suggested that a significant proportion of the nutrients in pond sediments comes from uneaten commercial pellets. Nevertheless, FCR can be improved in the co-culture system (2.1 vs 2.8 for CoC and MoC, respectively) by using *Azolla* as a partial alternative feed resource. Here, we assumed that the improvement of FCR, calculated for commercial feeds, in CoC is related to the changes in feeding practices. The alternance between feeding with *Azolla*, a less nutritive resource, and commercial pellets may contribute in reducing the quantity of uneaten feed in particular. Indeed, Narimbi et al. (2018) also found very high FCR (6.4) in daily-fed GIFT tilapia while FCR was six times lower in weekly-fed fish suggesting wastage of feed when fish were daily fed. Lower FCR decreases the amount of feed delivered as well as the excess nutrients released in the water, influencing eutrophication.

Eutrophication is a primary concern among farmers and local populations due to the risks for water quality in reservoirs (Mungkung et al., 2013). A broad range of eutrophication potential has been reported in the literature for different aquaculture systems (i.e., 0.01 to 0.3 kg PO_4 eq per kg of fish; Ghamkhar et al., 2021; Medeiros et al., 2017; Mungkung et al., 2013; Pelletier and Tyedmers, 2010; Yacout et al., 2016). The differences in eutrophication between MoC and CoC can be identified through the nutrient concentrations measured in the water outlet with a notable decrease in P released from the CoC ponds (Table 1). Here, the differences in eutrophication is a consequence of the lower FCR in the CoC system that limits the impacts related to the farm operations (i.e. reducing on-farm nutrient emissions). Indeed, the nutrient emissions resulting of biological activity of fish, is the major contributor to eutrophication (see, e.g., Mungkung et al., 2013; Wilfart et al., 2013), and is driven by the quality and the amount of feeds used.

Interestingly, our results regarding the contribution of exogenous feeds in acidification and climate change differ from the literature. Indeed, in previous studies, exogenous feeds explain 64 to 95% of the acidification potential observed in different aquaculture pond systems, including Indonesian intensive tilapia monoculture (Pelletier and Tyedmers, 2010) or tilapia-carp polyculture (Mungkung et al., 2013) and Egyptian intensive and semi-intensive tilapia monoculture (Yacout et al., 2016). Similarly, most LCA aquaculture studies, carried out in production systems that are sometimes very different from fertilized ponds, report that feeds are drivers of climate change (Bohnes et al., 2019; Wilfart et al., 2023). In this study, we found a relatively low contribution of exogenous feeds to acidification (15-18%), with fertilizers and fish inputs contributing to more than 40% of the total acidification. A similar trend was observed for climate change, where fertilizers and fish inputs explain 35-43% of the impacts, with exogenous feeds also accounting for ~40%. Such findings can be explained by the origin of the organic fertilizer (i.e., poultry manure mixed with rice bran; Purnomo et al., 2017), a co-product from intensive agriculture used in large quantities in our production systems. Furthermore, the fish used in this experiment, as described in Section 2.1.1, are already six months old, meaning that their own production also required exogenous feeds and other inputs, which explains their significant contributions to the estimated global impacts on our production systems. Such findings differ from LCAs performed in aquaculture systems where the fish inputs are based on younger life stages (eggs or larvae for example).

Recent studies reported that one of the leading production constraints in the Indonesian aquaculture sector, in addition to the dependence on imported feed ingredients (Henriksson et al., 2017), is energy sources (Henriksson et al., 2019, 2017). Previous studies have also pointed out that energy consumption during fish feed production is one of the significant contributors to CED (e.g., Mungkung et al., 2013; Pelletier and Tyedmers, 2010; Yacout et al., 2016). Overall, the estimated CED are comparable to other semi-intensive aquaculture production systems. For instance, Yacout et al. (2016) found 238 MJ eq per kg of fish produced in an Egyptian Nile tilapia (*Oreochromis niloticus*) semi-intensive production system, compared with a tilapia intensive production system being almost fivefold more efficient in energy use, with 53 MJ eq per kg of fish production than a semi-intensive system. In this study, we found that ecological intensification performed in the CoC could also significantly improve energy efficiency in giant gourami pond production.

4.3. Origins of the uncertainties

The uncertainty in this study was similar to other LCA aquaculture studies (Dekamin et al., 2015; Medeiros et al., 2017). Nevertheless, comparisons between studies remain challenging due to the heterogeneity in the studied systems and rearing practices and the origin of the data. Here, we compared similar production systems, except for including *Azolla* in the CoC system as a partial alternative to extruded pellets. However, the stable production of this floating macrophyte was more challenging than expected and inadequate in the present experiment, presumably due to the predation by snails and nutrient deficiency (Pouil et al., 2020). Nevertheless, the scenario built for CoC, designed based on experience gained in the production of *Azolla* on this farm (Caruso et al., 2021), made it possible to estimate uncertainties related to the exogenous feed gain in the implementation of such a production system. The uncertainties related to *Azolla* production mainly affect the impact categories in which exogenous feeds contribute strongly. Therefore, unsurprisingly, we observed higher variability in the CoC systems for NPPU, climate change, CED and, to a lesser extent, land occupation.

In addition to *Azolla* production, the other sources of uncertainties for all impact categories include variability among the two replicates of each system, the inherent variability already accounted for in the ecoinvent database and the assumptions made for mass-balance modelling. Interestingly, most of the data we recorded from the replicates of the two systems were, overall, comparable. There was a relatively high uncertainty on water dependence, particularly for the MoC system. Indeed, the ponds used, connected in series and fed by the same river, experienced fluctuating flows during the production cycle. Although this only had a minor effect on fish production, the water inputs in the study were highly variable, especially for MoC.

Nutrients (N and P) fluxes can be an important source of uncertainties in LCA aquaculture studies. Here, most of the data used were extracted from chemical analysis of each compartment included in the production systems (i.e. water, feeds, fertilizer and fish), and the N and P quantities stored in sediments were taken from Pouil et al. (2019) that gives nutrient budgets in the same ponds with an MoC system of giant gourami. Assuming the occurrence of *Azolla* in the CoC was not drastically affected by particulate N and P in sediments (related to uneaten feed, faeces, plankton sedimentation, dead fish, etc.), the overall N and P values we used in the study are reliable. Digestibility determines the fate of nutrients and the amounts of nutrients in the water column (digestible wastes) and sediment (non-digestible wastes) (Medeiros et al., 2017). Here, we calculated ThOD, an interesting parameter to refine the impacts related to eutrophication as suggested by Aubin et al. (2009), using digestibility values for protein, carbohydrates, lipids, ash and fibre. Only protein digestibility values have been found for giant gourami in literature (Andriani et al., 2019). Thus, other digestibility information (i.e. fat, carbohydrates, ash, P) came from an experiment based on Nile tilapia, another omnivorous species (Schneider et al., 2004). This lack of data in the literature reduces the accuracy of the estimates. However, the release of nutrients (N and P) from the two production systems was derived mainly from chemical analysis allowing a relatively accurate determination of the nutrient budgets.

Gaseous emissions to the atmosphere were the parameters with higher uncertainties in the pedigree matrix. The processes considered were denitrification and ammonia volatilization, which directly influence eutrophication. Denitrification and ammonia volatilization rates were based on Gross et al. (2000), a reference cited in some LCA aquaculture studies (e.g., Medeiros et al., 2017; Wilfart et al., 2013). This reference indicates a loss of roughly 40% of N inputs through these processes in channel catfish ponds. Nevertheless, in the literature, variability in N emissions in the air from aquaculture ponds is huge. For instance, NH_3 volatilization represents ~1% to total N input in feed for snakehead and bighead carp polyculture ponds (Hou et al., 2018), but NH_3 volatilization is equivalent to 10-66% of the N input in feed in shrimp ponds (Dien et al., 2018; Li et al., 2019; Lorenzen et al., 1997; Páez-Osuna et al., 1999). Such differences can be explained by the variety of the pond aquaculture systems studied, with diverse locations, species and rearing practices. Overall, these discrepancies highlight the need to consider such uncertainties of these processes in aquaculture LCA studies.

Other sources of uncertainties qualified through the pedigree matrix were the emissions of CH_4 and N_2O and the CO_2 fixation in the ponds. Indeed, high variability of such emissions is expected in aquaculture ponds: reported pond emissions to air vary from 0.01 to 20 mg CH_4 m^{-2} h^{-1} and 1 to 252 μg N_2O m^{-2} h^{-1} (Kosten et al., 2020; Yang et al., 2022; Yuan et al., 2019). Interestingly, high greenhouse gas (GHG) emissions from aquaculture ponds have been reported in some studies during the culture period (Chen et al., 2016, 2015; Datta et al., 2009), suggesting the importance of including them in LCA. In our analysis, we used values from Yang et al. (2018), which include measurements during the culture and non-culture period of Chinese shrimp polyculture and earthen carp ponds based on a stocking density comparable to that in our study and a semi-intensive production strategy. Overall, we hypothesized that the presence of *Azolla* in the CoC system has no significant impact on CH_4 and N_2O emissions from the ponds. Nevertheless, some sources suggest that *Azolla* plays a role in these flows. For example, previous studies have shown that *Azolla* application in flooding rice paddy can either increase (Chen et al., 1997; Ying et al., 2000) or have no influence or decrease (Ali et al., 2015; Kimani et al., 2018; Liu et al., 2017; Singh and Strong, 2016) CH_4 and N_2O emissions from rice soils. Similarly, *Azolla* can also contribute to CO_2 sequestration in ponds (Hamdan and Houri, 2022). Nevertheless, despite the discrepancy between these studies associated with the difficult comparison between rice paddies and aquaculture ponds, we considered the assumption reasonable. The overall conclusions of this study would not change if pond GHG emissions were excluded, but we include them in the LCA we performed given their importance to climate change, as previously suggested by Medeiros et al. (2017).

5. Conclusion

The development of Indonesian freshwater pond aquaculture in recent years has shifted from low-intensity traditional culture methods to monoculture production systems, with increasing intensification accompanied by the use of commercial feed pellets. Here, for most of the impact categories investigated, the co-culture system (CoC) with *Azolla* appeared to be more efficient than the semi-intensive monoculture (MoC) of giant gourami *O. goramy*. The observed improvements can be directly related to reducing the use of commercial pellets and a better control of the origin of the fertilizer used for enriching the ponds. Overall, we found that environmental performances for giant gourami production can be enhanced by using floating macrophytes as an alternative feed resource, even in relatively low proportions. Nevertheless, the production of this macrophyte species has still to be optimized to enhance its efficiency for use as a feed supplement while the economic repercussions of a shift to a production system based on co-culture with *Azolla* have to be investigated.

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Figure captions

Figure 1. Schematic view of the production chain of semi-intensive giant gourami aquaculture. Weights and size provided are means are average values gathered from surveys of approximately 40 giant gourami farms (Kristanto et al., 2020).

Figure 2. System boundaries for giant gourami (A) monoculture (MoC) and (B) co-culture (CoC) production systems.

Figure 3. Contribution of each input or production step in environmental impacts per (A) kg of fish and (B) m^2 of the farm in traditional giant gourami monoculture (MoC) and co-culture with the floating macrophyte *Azolla filiculoides* (CoC) systems. CED: cumulative energy demand; NPPU: net primary production use.

Figure 4. Uncertainties in the environmental impacts per (A) kg of fish and (B) m^2 of the farm in the traditional giant gourami monoculture system (MoC) and the co-culture system with the floating macrophyte *Azolla filiculoides* (CoC) for each impact category. Asterisks denote significant differences between the two production systems. We considered that the two systems differed if one had higher impacts in at least 90% of the runs. CED: cumulative energy demand; NPPU: net primary production use.

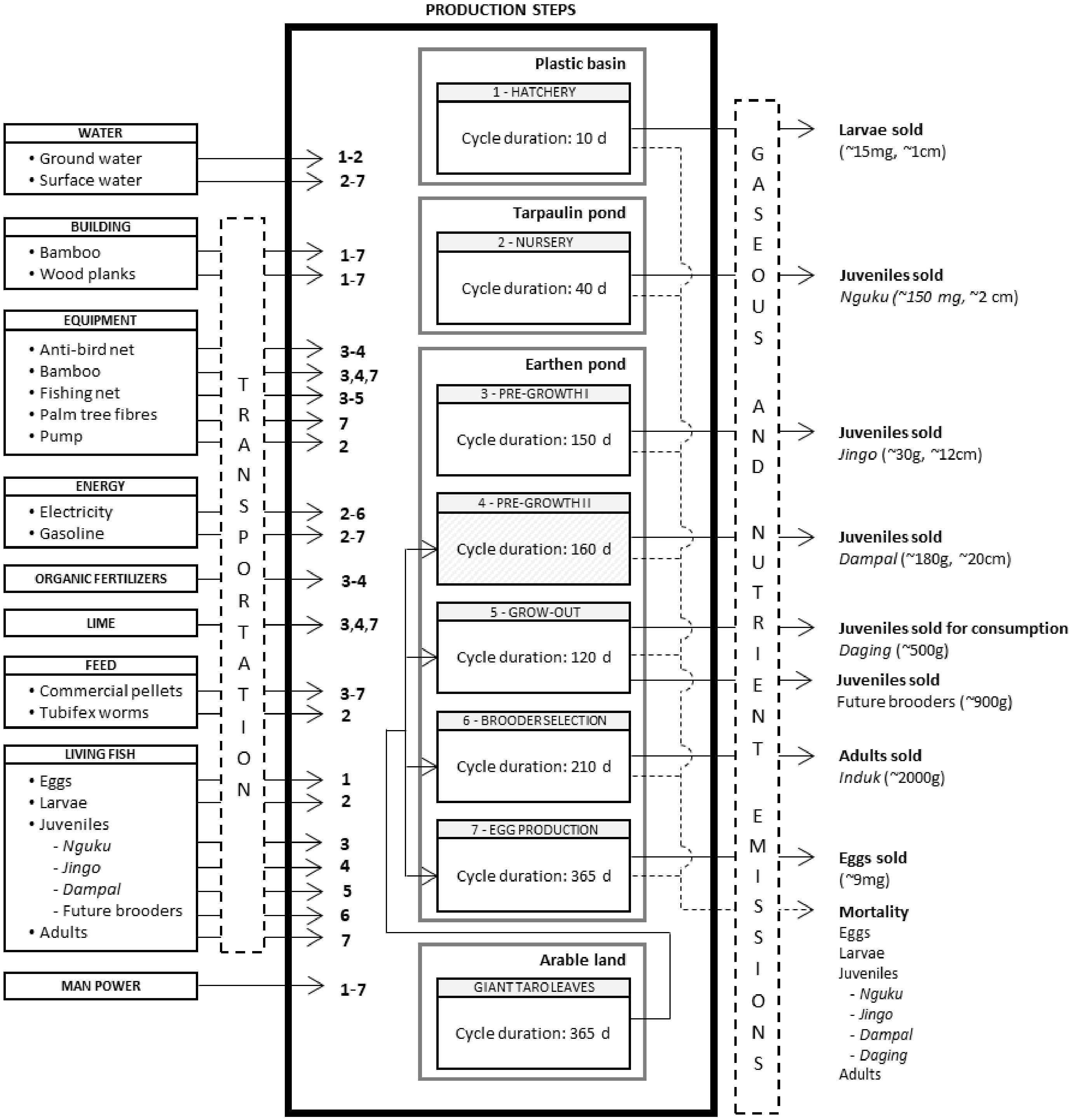

PRODUCTION STEPS
WATER
• Ground water
• Surface water
BUILDING
• Bamboo
• Wood planks
EQUIPMENT
• Anti-bird net
• Bamboo
• Fishing net
• Palm tree fibres
• Pump
ENERGY
• Electricity
• Gasoline
ORGANIC FERTILIZERS
LIME
FEED
• Commercial pellets
• Tubifex worms
LIVING FISH
• Eggs
• Larvae
• Juveniles
- Nguku
- Jingo
- Dampal
- Future brooders
• Adults
MAN POWER
TRANSPORTATION
1-2
2-7
1-7
1-7
3-4
3,4,7
3-5
7
2
2-6
2-7
3-4
3,4,7
3-7
2
1
2
3
4
5
6
7
1-7
Plastic basin
1 - HATCHERY
Cycle duration: 10 d
Tarpaulin pond
2 - NURSERY
Cycle duration: 40 d
Earthen pond
3 - PRE-GROWTH I
Cycle duration: 150 d
4 - PRE-GROWTH II
Cycle duration: 160 d
5 - GROW-OUT
Cycle duration: 120 d
6 - BROODER SELECTION
Cycle duration: 210 d
7 - EGG PRODUCTION
Cycle duration: 365 d
Arable land
GIANT TARO LEAVES
Cycle duration: 365 d
GASEOUS AND NUTRIENT EMISSIONS
Larvae sold
(~15mg, ~1cm)
Juveniles sold
Nguku (~150 mg, ~2 cm)
Juveniles sold
Jingo (~30g, ~12cm)
Juveniles sold
Dampal (~180g, ~20cm)
Juveniles sold for consumption
Daging (~500g)
Juveniles sold
Future brooders (~900g)
Adults sold
Induk (~2000g)
Eggs sold
(~9mg)
Mortality
Eggs
Larvae
Juveniles
- Nguku
- Jingo
- Dampal
- Daging
Adults

Figure 1

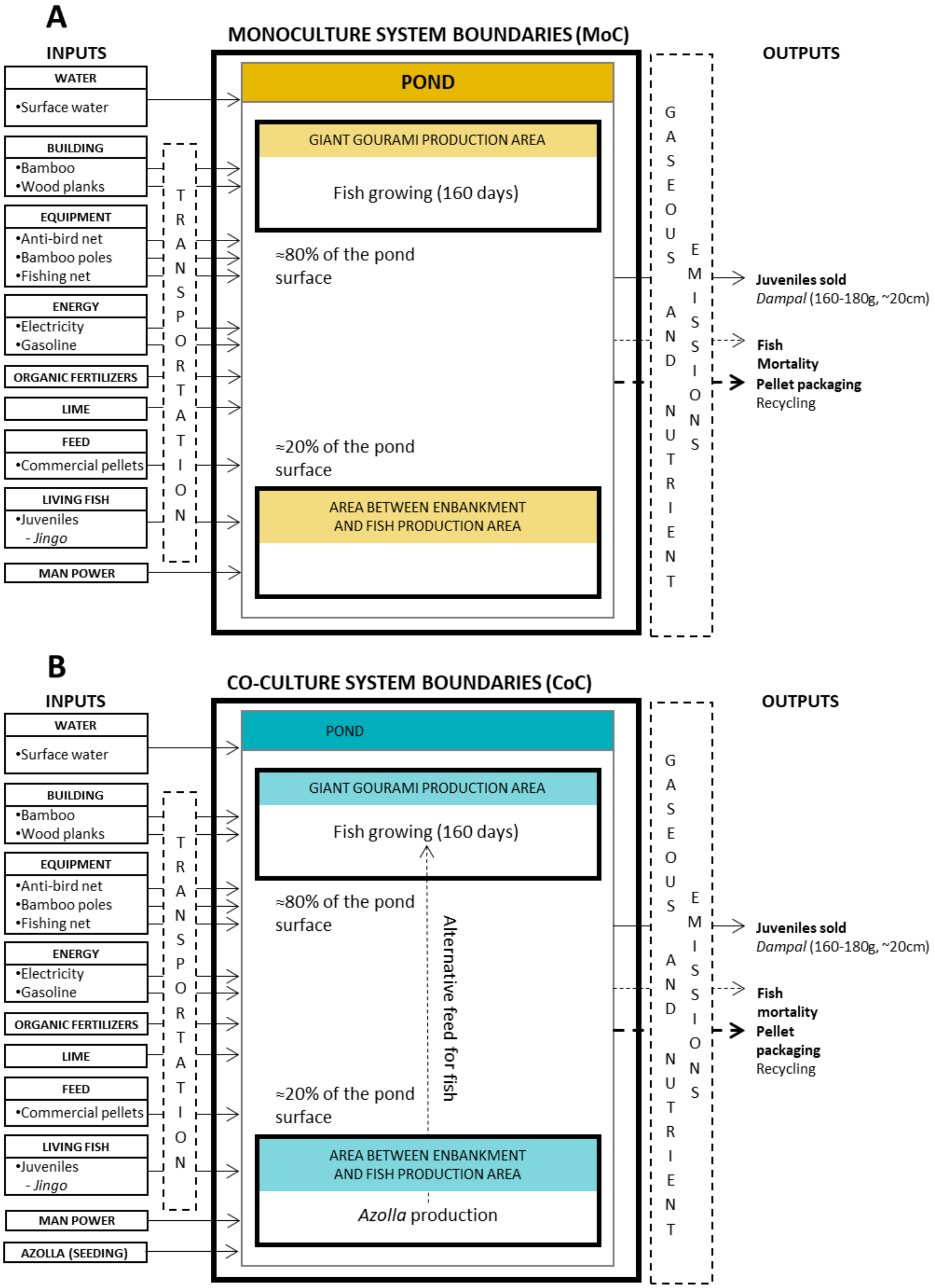

A
INPUTS
WATER
•Surface water
BUILDING
•Bamboo
•Wood planks
EQUIPMENT
•Anti-bird net
•Bamboo poles
•Fishing net
ENERGY
•Electricity
•Gasoline
ORGANIC FERTILIZERS
LIME
FEED
•Commercial pellets
LIVING FISH
•Juveniles
- Jingo
MAN POWER
TRANSPORTATION
MONOCULTURE SYSTEM BOUNDARIES (MoC)
POND
GIANT GOURAMI PRODUCTION AREA
Fish growing (160 days)
≈80% of the pond surface
≈20% of the pond surface
AREA BETWEEN ENBANKMENT AND FISH PRODUCTION AREA
GASEOUS AND NUTRIENT EMISSIONS
OUTPUTS
Juveniles sold
Dampal (160-180g, ~20cm)
Fish Mortality
Pellet packaging
Recycling
B
INPUTS
WATER
•Surface water
BUILDING
•Bamboo
•Wood planks
EQUIPMENT
•Anti-bird net
•Bamboo poles
•Fishing net
ENERGY
•Electricity
•Gasoline
ORGANIC FERTILIZERS
LIME
FEED
•Commercial pellets
LIVING FISH
•Juveniles
- Jingo
MAN POWER
AZOLLA (SEEDING)
TRANSPORTATION
CO-CULTURE SYSTEM BOUNDARIES (CoC)
POND
GIANT GOURAMI PRODUCTION AREA
Fish growing (160 days)
≈80% of the pond surface
Alternative feed for fish
≈20% of the pond surface
AREA BETWEEN ENBANKMENT AND FISH PRODUCTION AREA
Azolla production
GASEOUS AND NUTRIENT EMISSIONS
OUTPUTS
Juveniles sold
Dampal (160-180g, ~20cm)
Fish mortality
Pellet packaging
Recycling

Figure 2

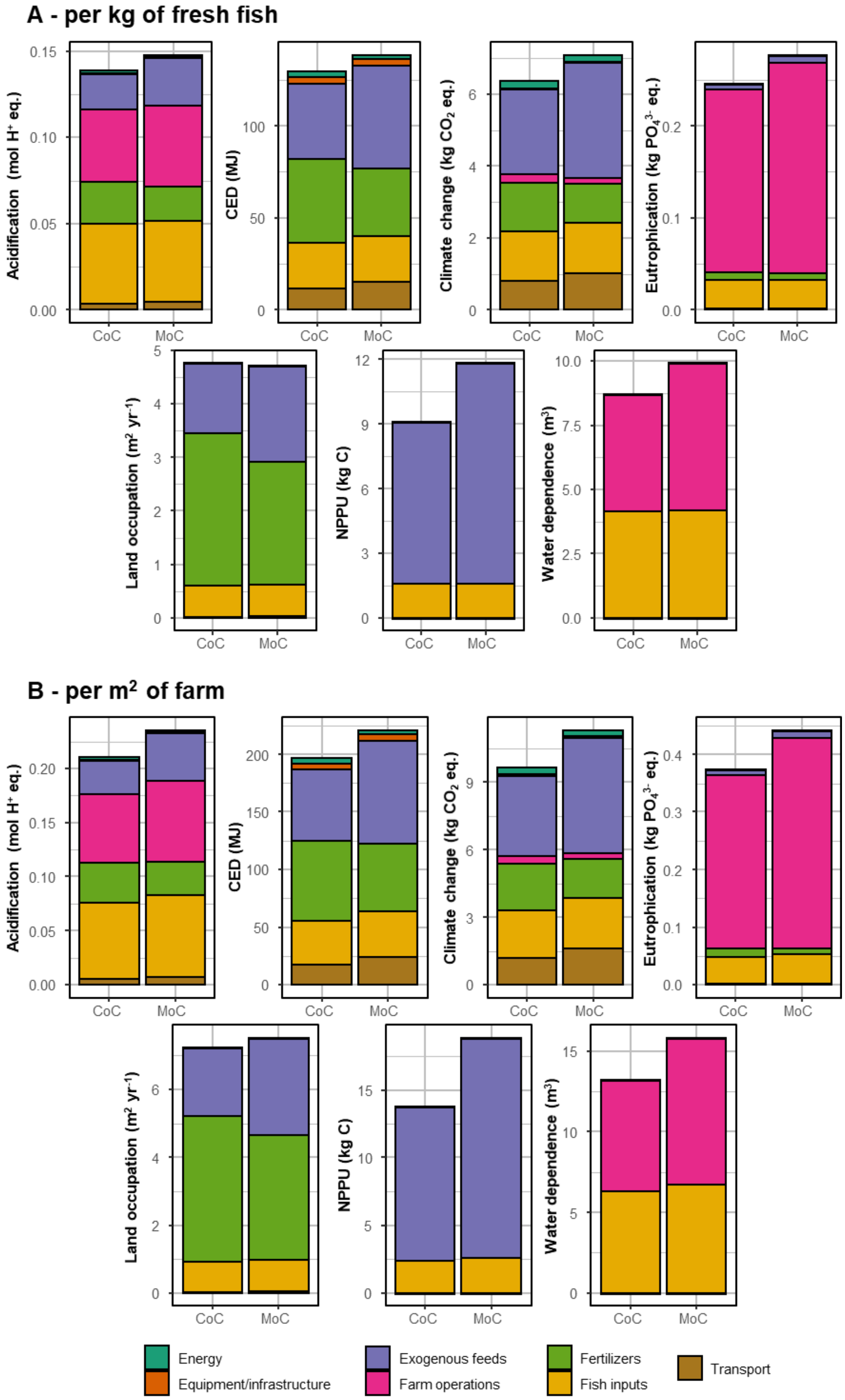
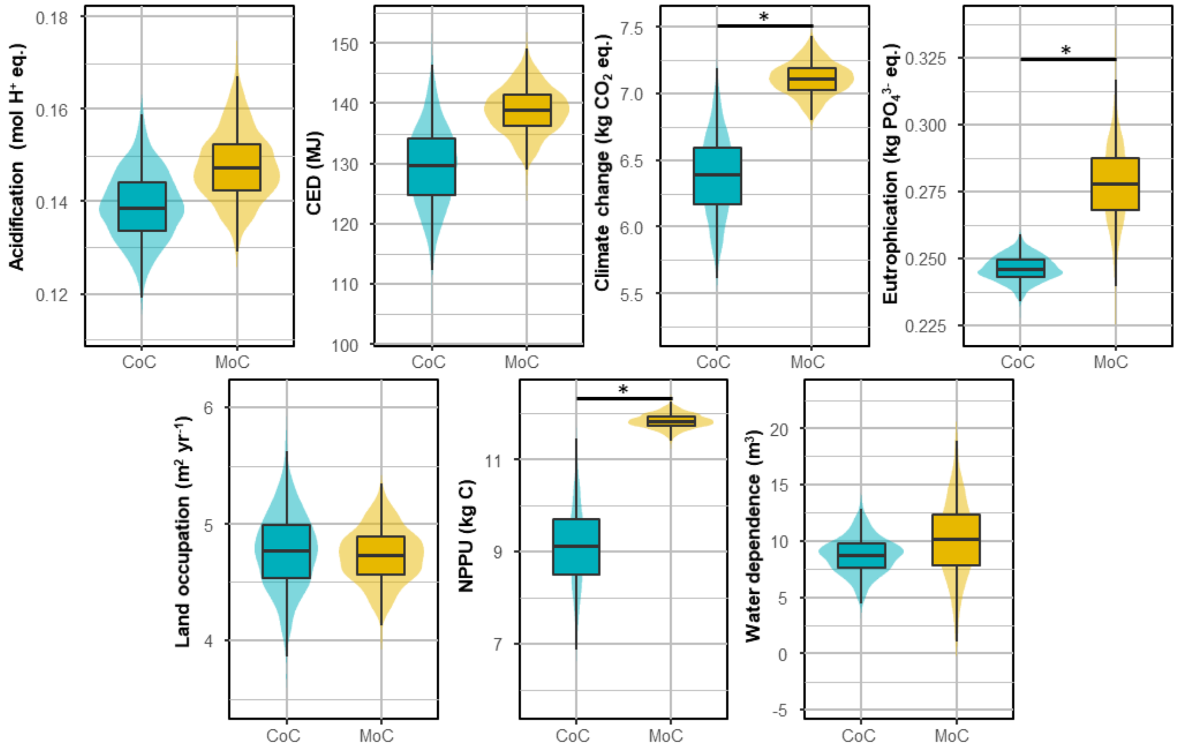

A - per kg of fresh fish
Acidification (mol H⁺ eq.)
0.00
0.05
0.10
0.15
CED (MJ)
0
50
100
Climate change (kg CO₂ eq.)
0
2
4
6
Eutrophication (kg PO₄³⁻ eq.)
0.0
0.1
0.2
Land occupation (m² yr⁻¹)
0
1
2
3
4
5
NPPU (kg C)
0
3
6
9
12
Water dependence (m³)
0.0
2.5
5.0
7.5
10.0
CoC
MoC
B - per m² of farm
Acidification (mol H⁺ eq.)
0.00
0.05
0.10
0.15
0.20
CED (MJ)
0
50
100
150
200
Climate change (kg CO₂ eq.)
0
3
6
9
Eutrophication (kg PO₄³⁻ eq.)
0.0
0.1
0.2
0.3
0.4
Land occupation (m² yr⁻¹)
0
2
4
6
NPPU (kg C)
0
5
10
15
Water dependence (m³)
0
5
10
15
CoC
MoC
Energy
Equipment/infrastructure
Exogenous feeds
Farm operations
Fertilizers
Fish inputs
Transport

Figure 3

A - per kg of fresh fish



B - per m^2 of farm

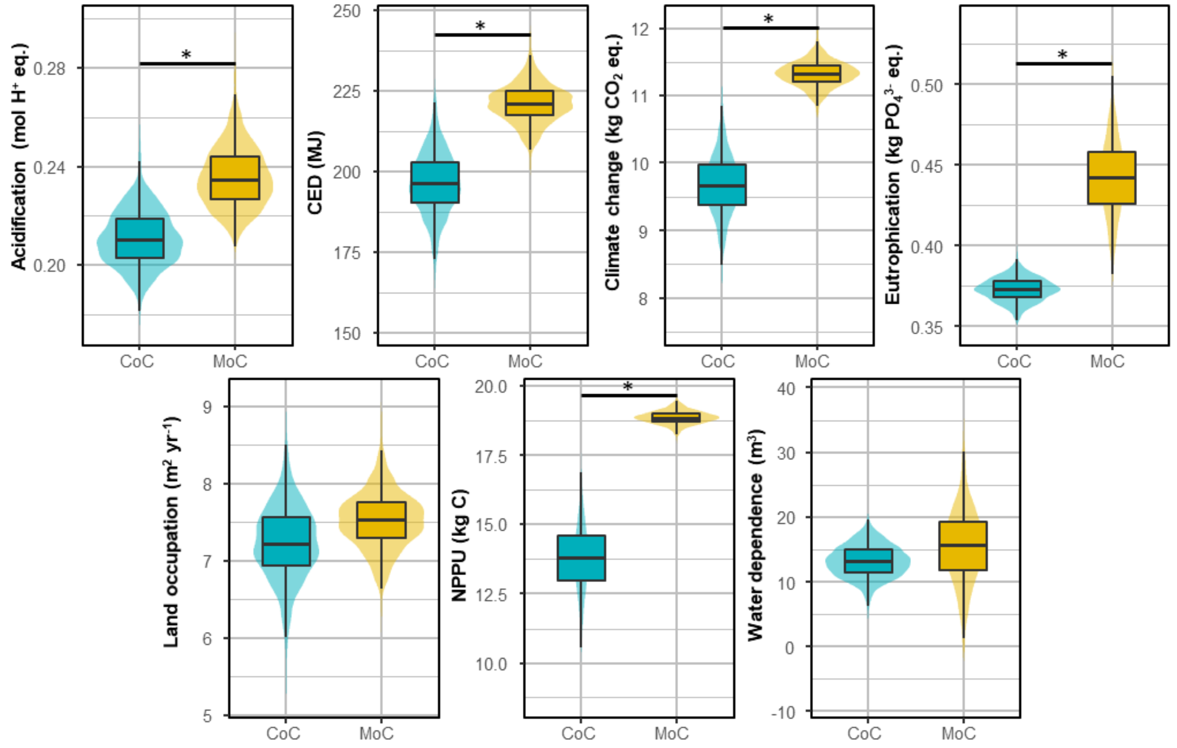


Figure 4

Table 1. Pond characteristics, rearing performances and electricity and water consumption used in the LCA of the monoculture (MoC) and the co-culture with the floating macrophyte *Azolla filiculoides* (CoC) of giant gourami (mean ± 1 standard deviation).

	CoC	**MoC**
Pond characteristics and inputs		
Surface (m^2)	771	840
Depth (m)	0.5	0.5
Rearing structures	earthen ponds tarpaulin tanks	earthen ponds
Equipment	PVC pipes bamboo pools anti-predator nets fishing net happas	PVC pipes bamboo pools anti-predator nets fishing net
Fertilizers (kg)	5802 ± 580	5020 ± 502
Pellets (kg)	2874 ± 302	3811 ± 59
Azolla (kg)	2848 ± 1424	-
Rearing performances		
Initial body weight (g)	29 ± 6	28 ± 5
Fish stocking density (fish m^{-2})	6	6
Stocked fish biomass (kg yr^{-1})	274	297
$FCR_{pellets}$ (wet weight)[1]	2.1	2.8
Final body weight (g)	193 ± 52	183 ± 39
Fish productivity (tonne ha^{-1} yr^{-1})	19.9	19.6
Energy and water inputs		
Electricity consumption (kWh yr^{-1})	422	403
Water (m^3 yr^{-1})	6985 ± 2544	9425 ± 5863
Nutrient releases from water		
N (mg L^{-1})	1.4 ± 0.5	1.5 ± 0.4
P (mg L^{-1})	0.167 ± 0.258	0.026 ± 0.031

[1] $FCR_{pellets}$ = feed conversion ratio, considering only the commercial feed (extruded pellets) and calculated as the ratio between the amount of distributed pellets (kg) and the biomass gain (kg) over the production cycle

Table 2. Ingredients and composition values of the feeds (n = 5 and n = 30 samples analysed for pellets and *Azolla*, respectively) used in monoculture (MoC) and co-culture with the floating macrophyte *Azolla filiculoides* (CoC). Except for moisture, composition values are expressed on a dry matter basis.

Composition (%, Mean ± SD)	**Extruded pellets**	***Azolla filiculoides***
Moisture	7.95 ± 0.49	92.06 ± 1.17
Proteins	32.72 ± 0.23	20.29 ± 5.47
Lipids	5.29 ± 0.17	1.76 ± 0.61
Carbohydrates	47.29 ± 0.25	50.89 ± 4.72
Ash	10.01 ± 0.36	11.49 ± 1.75
Fibres	4.70 ± 0.20	15.58 ± 3.03
Phosphorus	1.47 ± 0.12	0.25 ± 0.13
Ingredients (% [origin])		
Fish meal	10 [Chili]	
Fish meal	11 [East Java]	
Soybean meal	15 [Argentina]	
Meat and bone meal	10 [Australia]	
Wheat bran	20.5 [Australia	
Rice bran	25 [West Java]	
Fish oil	2 [East Java]	
Plant oil	2.5 [Banten/West Java]	
Choline chloride	0.5 [China]	
Premix vitamin	2 [China]	
Premix mineral	1.2 [China]	
Butylated hydroxytoluene (BHT)	0.3 [Central Java]	

Table 3. Results of the Monte Carlo analysis (n = 1000) applied to the two production systems: monoculture (MoC) and co-culture with the floating macrophyte *Azolla filiculoides* (CoC) for each impact category. We considered that the two systems differed if one had higher impacts in at least 90% of the 1000 runs (see values in bold in the last column).

Functional unit	Category	System	Median	Q1 (25%)	Q3 (75%)	Mean	SD	MoC > CoC (%)
Fish weight (kg)	**Acidification (mol H^+ eq.)**	CoC	0.139	0.134	0.144	0.139	0.007	
		MoC	0.147	0.142	0.152	0.148	0.008	78.8
	Cumulative energy demand (MJ)	CoC	129.787	124.828	134.099	129.565	6.653	
		MoC	138.986	136.27	141.493	138.897	3.889	88.6
	Climate change (kg CO_2 eq.)	CoC	6.394	6.165	6.595	6.383	0.306	
		MoC	7.108	7.027	7.191	7.109	0.125	**98.4**
	Eutrophication (kg PO_4^{3-} eq.)	CoC	0.246	0.243	0.25	0.246	0.005	
		MoC	0.278	0.268	0.287	0.278	0.014	**98.3**
	Land occupation (m^2 year)	CoC	4.773	4.538	4.989	4.766	0.328	
		MoC	4.732	4.569	4.888	4.728	0.236	46.5
	Net primary production use (kg C)	CoC	9.123	8.489	9.714	9.116	0.87	
		MoC	11.833	11.731	11.949	11.837	0.157	**100**
	Water dependence (m^3)	CoC	8.791	7.609	9.732	8.708	1.659	
		MoC	10.255	7.808	12.345	10.117	3.484	64.4
Farm surface (m^2)	**Acidification (mol H^+ eq.)**	CoC	0.21	0.203	0.219	0.211	0.011	
		MoC	0.235	0.227	0.244	0.236	0.013	**93.8**
	Cumulative energy demand (MJ)	CoC	196.47	190.368	202.691	196.505	9.813	
		MoC	221.05	217.39	224.814	221.098	6.095	**97.9**
	Climate change (kg CO_2 eq.)	CoC	9.672	9.378	9.97	9.674	0.453	
		MoC	11.327	11.204	11.443	11.323	0.19	**100**
	Eutrophication (kg PO_4^{3-} eq.)	CoC	0.373	0.368	0.378	0.373	0.007	
		MoC	0.442	0.426	0.458	0.442	0.024	**99.9**
	Land occupation (m^2 year)	CoC	7.227	6.937	7.562	7.237	0.48	
		MoC	7.529	7.292	7.751	7.52	0.374	67.9
	Net primary production use (kg C)	CoC	13.827	12.958	14.584	13.793	1.275	
		MoC	18.864	18.708	19.016	18.864	0.237	**99.9**
	Water dependence (m^3)	CoC	13.168	11.37	14.957	13.165	2.463	
		MoC	15.663	11.911	19.249	15.519	5.814	64.0