AGROCAMPUS OUEST

☐ **CFR Angers**
☑ **CFR Rennes**

Année universitaire : 2018 - 2019

Spécialité :
SML - Biologie

Spécialisation (et option éventuelle) :
Parcours Sciences Halieutique et Aquacole (Option AQUA)

Mémoire de Fin d'Études

☐ d'Ingénieur de l'Institut Supérieur des Sciences agronomiques, agroalimentaires, horticoles et du paysage
☑ de Master de l'Institut Supérieur des Sciences agronomiques, agroalimentaires, horticoles et du paysage
☐ d'un autre établissement (étudiant arrivé en M2)

Environmental impact assessment of freshwater polyculture: balance between productivity and resource mobilization

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Soutenu à RENNES ***le*** 10 Septembre 2019

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REMERCIEMENTS

L’écriture de ce mémoire a été possible grâce au concours de plusieurs personnes à qui je voudrais témoigner toute ma reconnaissance. Je voudrai tout d’abord remercier Joël Aubin et Aurélie Wilfart pour leur patience, leur disponibilité et leur précieux conseils qui ont contribué à alimenter ma réflexion. Je les remercie également pour l’opportunité qu’ils m’ont offerte et la confiance qu’ils m’ont accordée. Je remercie également mon colocataire de bureau Kevin Hoeffner pour les conseils et les discussions plus ou moins constructives que l’on a pu avoir. Je désire également remercier l’ensemble de l’UMR SAS pour leur accueil chaleureux et pour l’ambiance très agréable que cette unité a pu montrer tout au long des six mois de stage.

Nathan Favalier

I- Introduction

Market demand for seafood products and stagnating production volume from fisheries are combined effects that lead to an increased aquaculture production for the past few years (FAO, 2016). Farming methods for aquaculture are highly diverse around the world. Nearly 90% of global production is in Asia and is based mainly on traditional practices (FAO, 2016). However, it appears that more intensive practices have since been adopted by Asian fish farms with the use of commercial pellets. In France there is a notable decrease in the number of ponds used for fish production as recreational activities (hunting, angling) is increasing around these areas. Additionally, in some cases ponds are simply abandoned or dried up, resulting in a loss of biodiversity and landscape modification (Jaeger & Aubin, 2018). Despite these facts and according to Downing and collaborators (2006), ponds represent a huge potential for fish production in France. The most common freshwater aquaculture species are salmonids with the rainbow trout (*Oncorhynchus mykiss*), the sea trout (*Salmo trutta*) and the Atlantic salmon (*Salmo salar*) followed by the Siberian sturgeon (*Acipenser baerii*) and the common carp (*Cyprinus carpio*). In Romania, around 70000ha are dedicated to fish production and aquaculture represents the main source of fish national production. However, most facilities need modernization and farm sites generally constrain producers to rely solely on the natural production of the site (FAO, 2016). According to the FAO, the main reared species are carps with the common carp (*Cyprinus carpio*), the silver carp (*Hypophthalmichtys molitrix*), the bighead carp (*Hypophthalmichtys nobilis*) and the grass carp (*Ctenopharyngodon idellus*) followed by the crucian carp (*Carassius carassius*), the goldfish (*Carassius auratus*) and the sea trout (Salmo trutta). In Indonesia, there is a rapid development of aquaculture in the last 40 years with the introduction of new farming technologies, which contributed to the availability of hatchery-produced seed, and the development of compound feed. The most common species dedicated to freshwater aquaculture are the common carp (*Cyprinus carpio*), the catfish (*Clarias spp.*, *Pangasius spp.*), the Nile tilapia (*Oreochromis niloticus*) and the giant gourami (*Osphronemus goramy*). Almost 251000ha are dedicated to freshwater aquaculture and about 90% of the fish produced are consumed domestically, which makes the aquaculture an essential sector contributing to rural economic development. Moreover, the FAO estimated potential area of 2230500ha of freshwater aquaculture revealing growth potential for this sector in the future.

In a context of global change, sustainable development of aquaculture and the evaluation of its environmental impacts have become a major concern for stakeholders. Environmentally sustainable production can be defined as a production allowing the “maintenance of natural capital” (Bohnes, Hauschild, Schlundt, & Laurent, 2018). In other words, waste generated by this type of production should not exceed the capacity of the environment and natural resources should be exploited at a rate that allows regeneration. Nonetheless, achieving sustainable aquaculture requires the conception of new aquaculture systems with multiple aims: designing environment-friendly production, producing of one or more species for diversification purposes, optimizing the natural production of the farm site (Aubin *et al.*, 2015). Moreover, it is often argued that seafood farming is sustainable and avoids the depletion of wild fish stocks highlighting the potential of aquaculture to meet future food demand (Tlusty & Thorsen, 2017). Nonetheless, aquaculture may lead to negative environmental impact due to its close relation with the immediate environment and depending on producer’s practices fish production can have severe issues (i.e. depending on the species reared, the use or not of artificial feed and the carrying capacity of the ecosystem). From the intensive use of natural resources and waste emissions and pollutant, along with local impacts such as disease transmission, dispersal of non-native species and release of antibiotics and pharmaceutical compounds into the water, aquaculture can influence and destabilize ecosystems and biodiversity (Naylor *et al.*, 2000; Pelletier & Tyedmers, 2008; Read & Fernandes, 2003). For instance, bio deposition occurs near to fish farms and lead to an increase of organic loads and changes in the sediment characteristics. Consequently, shifts in benthic assemblages and a decrease in biodiversity have been recorded near to aquaculture devices (Karakassis *et al.*, 2000; Klaoudatos *et al.*, 2006; Neofitou *et al.*, 2010). Aquaculture also causes indirect effects such as impacts linked to the production of fish-feed ingredients, the production and consumption of energy, infrastructures and buildings. For instance, rearing carnivorous species generally require large inputs of wild fish for feed ingredients because of the protein demand of these species. Thus, it may further deplete wild fisheries stocks (Naylor *et al.*, 2000). It is also well known that many small pelagic fisheries are over-fished and strained by climatic variability (e.g. El Niño Southern Oscillation Events), reducing available food for marine predators as well as valuable species consumed by humans into the bargain *(Naylor et al.*, 2000).

In this context, stakeholders put the emphasis on developing new systems and technologies responding on well-known issues of aquaculture production and try to design the most sustainable production. Lazard *et al.* (2014) argued that this sustainable development could only be operated through the design of integrated production and not with technology-only approaches. Integrated production promotes connections with surrounding activities and the natural environment and put the emphasis on long-term impacts. In other words, stakeholders try to introduce more ecology into aquaculture as defined by the concept of ecological intensification (Jaeger & Aubin, 2018). It defines three levels of integration that consist on (1) focusing on inlet and outlet control, (2) reconsidering the objectives of aquaculture and (3) including ecosystem services through changes in the objectives. Integrated Multitrophic Aquaculture (IMTA) is one of the most promising way for the sustainable development of this sector. It consists mainly on co-producing food and/or other products by recycling aquaculture waste. By using a set of complementary species both in terms of trophic and living habits, organic and inorganic wastes from fed aquaculture species are assimilated by autotrophic (*e.g.* phytoplankton, macroalgae and plants) and/or heterotrophic species (*e.g.* mussels, oysters or even fish species). Consequently, IMTA include a large panel of system based on practices that enhance the complementarity of productive compartments from sea cages with macroalgae and bivalves to onshore monoculture system in series with recirculated water and freshwater ponds where all species are reared together. It therefore seems highly relevant to assess current practices in aquaculture and to determine those that lead to the most environmentally sustainable aquaculture production depending on the location and the constraints associated with it. Indeed, it appears that systemic approaches are mandatory to investigate and elaborate new production system and especially their environmental aspects. In order to provide valuable solutions that reduce the impacts of seafood production, multiple scale environmental assessment methods need to be performed. Existing environmental assessment methods analyse multiple scales (global to local) and allow the use of international standards (Wilfart *et al.*, 2013). These methods display limits that promote the integration of complementary methods to generate consistent performance indicators based on the same set of input data. Thus, we identified two potentially complementary methods to better apprehend and complete multi-scale evaluation of aquaculture systems and identify perspectives for the design of future production. A common method used to investigate environmental sustainability of a production is Life Cycle Assessment (LCA). LCA is an ISO-standardized methodology, which quantifies the impacts on ecosystems, human health and natural resources stemming from products and systems throughout their entire life cycle, from the extraction of raw materials through their production and use or operation up to their final decommissioning and disposal (ISO 2006). LCA can provide assessment for multiple impact categories such as potential eutrophication of aquatic environments, climate change, and toxicity with the release of chemicals on human health or ecosystem. LCA was first developed for industrial products and then widely used for other areas such as agriculture since the 1970s (Nemecek & Ledgard, 2016). A wide range of studies focus on LCA of aquaculture products, from environmental assessment of specific farming methods (Abdou *et al.*, 2017; Aubin et *al.*, 2009, 2006) and comparison of aquaculture practices (Biermann & Geist, 2019; d'Orbcastel *et al.*, 2009; Henriksson *et al.,* 2015; Medeiros *et al.,* 2017) to the consideration of LCA methodological issues for aquaculture products (Bohnes & Laurent, 2019; Henriksson *et al.*, 2012; Samuel-Fitwi *et al.*, 2013). In addition to the LCA we decided to perform Emergy accounting method (EA). The EA is an approach based on the Energy Systems Theory described by Odum in 1983 and which was developed to integrate all system inputs as LCA (resources, services and commodities) using a common unit. It is particularly suitable for agriculture as natural and human contributions interact to obtain a final product (Pizzigallo *et al*., 2008). Emergy is the amount of energy (in solar-energy equivalents) that is directly or indirectly needed to provide a given flow or storage of energy or matter. Thus, it provides indicators to evaluate energy quality and efficiency along the life cycle of a product.

The present study is a part of the project IMTA-Effect which aims to generate and integrate knowledge to provide IMTA strategies for fish farmers being efficient, economically attractive, robust and environmentally friendly in marine as well as in freshwater aquaculture systems. The aims of this specific study are to perform LCA and emergy accounting on freshwater polyculture systems in Indonesia (Java), France (Le Rheu) and Romania. Developing aquaculture in these countries require to design system of production with as many criteria mentioned before for a sustainable and integrated production as possible. To do so we investigate system designs and practices in the three following country: (1) Polyculture of common carp (*Cyprinus carpio*), perch (*Perca fluviatilis*) and roach (*Rutilus rutilus*) in France reared in earthen ponds under three different conditions to investigate the consequence of the use of artificial feed and the addition of a planted lagoon linked to the pond of production (experimental farm, INRA, Le Rheu, France). (2) Polyculture of common carp (*Cyprinus carpio*), grass carp (*Ctenopharyngodon idella*), bighead carp (*Hypophthalmichtys nobilis*), silver carp (*Hypophthalmichtys molitrix*) and crucian carp (*Carassius carassius*) in 2016 and 2017 in Romania with the partner RomFish who investigate the influence of the separation of the pond into one part dedicated to a common carp monoculture fed with artificial feed and another one dedicated to a carp polyculture fed by the natural production of their part directly linked to the monoculture. (3) Mono- and coculture of the giant gourami (*Osphronemus goramy*) with red azolla plants (*Azolla filiculoides* Lam.) in the same pond under practices which have been defined following a survey of several farms in 2018 in west Java.

II- Methods

A- State of the art and description of the systems

(a) France

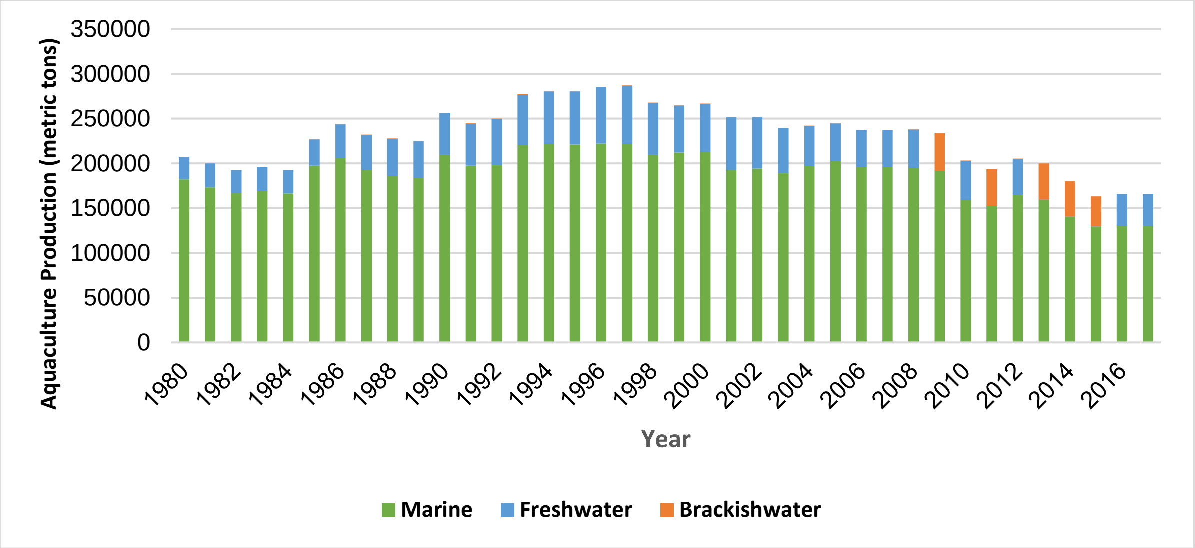

Figure 1: Evolution of the total production of aquaculture (metric tons) in France from 1980 to 2018 (extracted from FAO 2018 annual report).

In France, aquaculture displayed an important growth in 1970 but stagnated or even decreased in certain cases the last 20 years (figure 1). The FAO points out that aquaculture in France is facing many issues. The amount of landscape dedicated to aquaculture is declining due to the increased competition between stakeholders for the use of marine and freshwater areas (tourism, conservation). In addition, administrative and environmental constraints support this decline for instance with the management of bird predation, the conduction of impact study and/or public inquiry. Effectively, these constraints induce the implementation of restraints for the development and growth of the sector in France. Moreover, products from French aquaculture compete with imported products. Nonetheless, 40000ha of ponds are still dedicated to freshwater fish production and are mostly managed by multi-asset operators.

Located at Le Rheu, the experimental facilities (INRA, U3E) are composed by several ponds dedicated to studies. Eight 500 square meter ponds 1m deep with bottoms composed of mix of clay and sediment were used to carry out the experiment. Ponds were filled with water from the river running along the site. Supplementary water was added to compensate evaporation and seepage. To prevent bird predation ponds were equipped with anti-bird net. The deepest end of the ponds was equipped with an overfill pipe connected to a monk outlet, which is a pond draining structure at which fish can be caught as the pond drains. At the end of the experiment, fish were harvested using the monk outlet during the draining of the ponds.

Table 1 : Main characteristics of the extensive, the semi-intensive and the coupled conditions in Le Rheu, France. The extensive practices refer to a non-fed polyculture of common carp, perch and roach, the semi-intensive practices to a fed polyculture of common carp, perch and roach and the coupled practices which refers to the same polyculture as the semi-intensive practices but connected to a planted lagoon.

Characteristics	Extensive	Semi-intensive	Coupled
Water surface (m^2)	1000	1000	1000 + 1000
Fish stocking density ($kg.m^{-2}$)	0,005	0,01	0,01
Artificial feed	no	yes	yes
FCR	NA	1.13	1.33
Cycle duration (day)	365	365	365

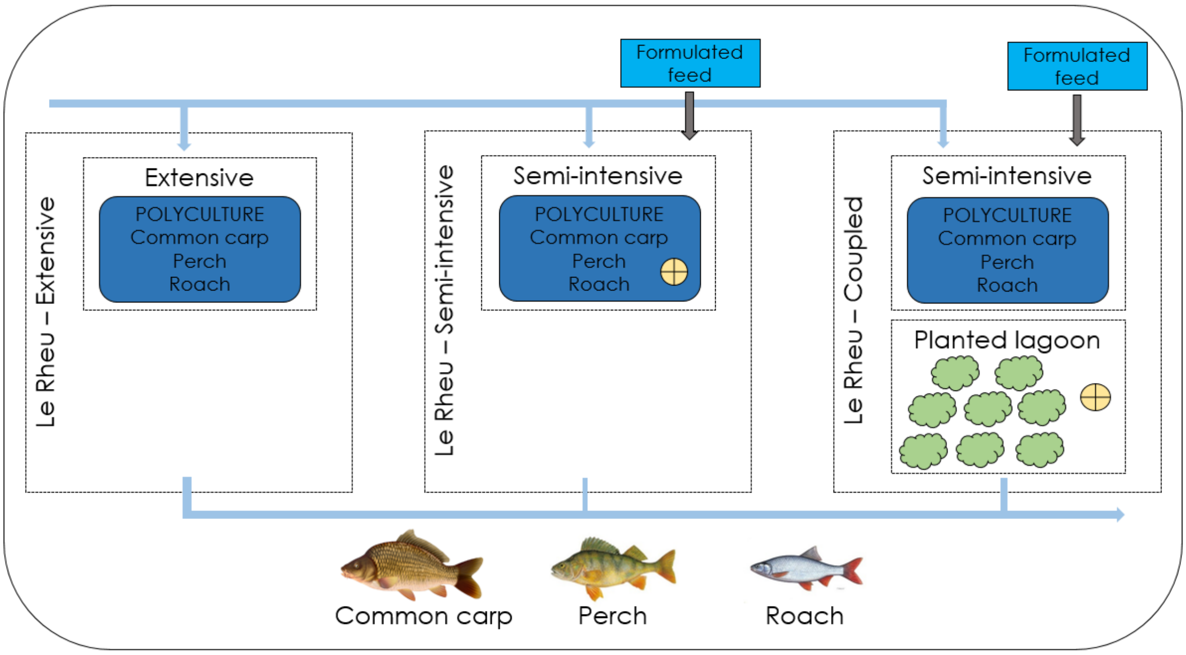

Figure 2: Experimental design of Le Rheu experiments conducted in 2017 for the extensive, the semi-intensive and the coupled practices. The systems correspond to the polyculture of common carp, perch and roach in earthen pond. The crossed circle refers to the use of a pump. The three ponds containing fishes display the same water surface.

Thus, a specific integrated aquaculture system was designed with three fish species (figure 1): the common carp (*Cyprinus carpio*), the roach (*Rutilus rutilus*) and the perch (*Perca fluviatilis*). For each condition, the juvenile production was based on a hypothetical hatchery and nursery derived from the European project PISCEnLIT (https://www.piscenlit.org/). Three different rearing conditions were investigated (figure 2 and table 1). An "extensive" production with an initial fish density of 0.005 $kg.m^{-2}$ supplied solely with the natural production of the ponds (two of $500m^2$). A "semi-intensive" production in which fish density was doubled ($0.01kg.m^{-2}$) compare to the "extensive" conditions and fish were fed with formulated feed. A pump was added in the pond to recreate the flow of water occurring in the "coupled" conditions ponds. The third treatment refer to the same initial fish stocking density as the "semi-intensive" treatment but a planted lagoon was connected to the fishpond. A pump returned the water from the lagoon to the fishpond and water coming from the production pond circulated in the lagoon by gravity. Details on feed and fish composition are available in Annexe 1 and 2.

(b) Romania

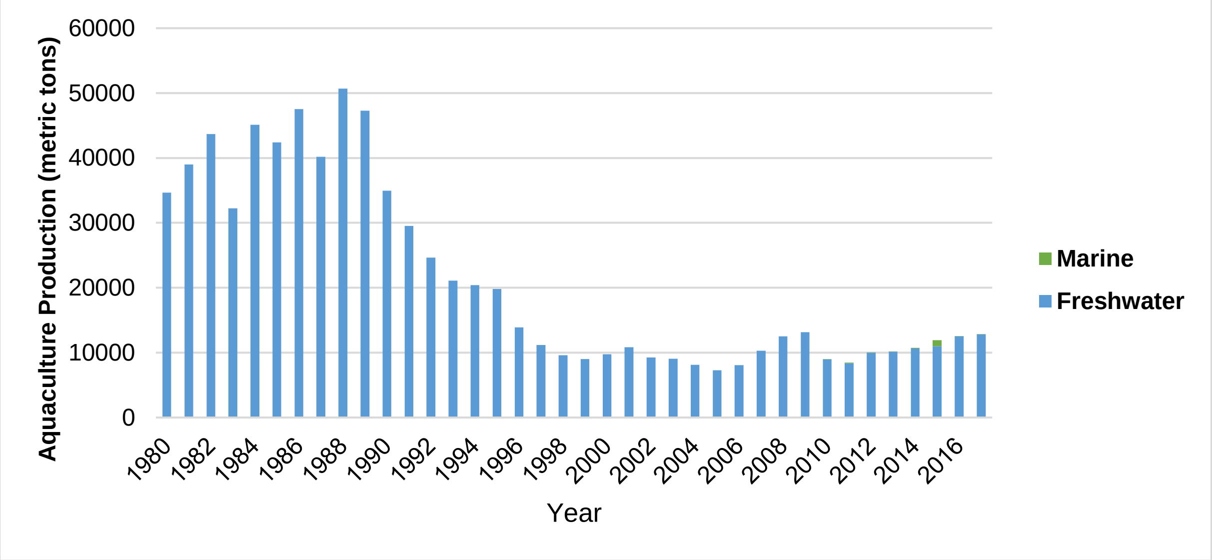

Figure 3: Evolution of the total production (metric tons) of aquaculture in Romania from 1980 to 2018 (extracted from FAO 2018 annual report).

Aquaculture based on the semi-extensive culture of common carp along with Chinese carp's species accounting for more than 75% of the total production of the country. FAOs annual report in 2016 reported that 80000ha are dedicated to fish production in Romania and thus represent a great advantage for the development of aquaculture in the country. However, Aquaculture accounted for only 0.0054% of the Gross Domestic Product (GDP) (2005), which makes aquaculture in Romania more a sector of concern for social purposes, for its potential as food sources, for the use of wetlands and for the biodiversity of the Romanian waters. Government legislation encouraged to increase fish consumption as well as the diversification of other cultured species. Local producers are however small-sized, internal fish production covering less than 20% of the total fish consumption in Romania. Nowadays, diversification is mainly directed to high value species as sturgeons, turbot, mussels or freshwater prawns. Current fish farming activities are mostly under "extensive" practices. In most of the case the location of the farm production, induce farmers to rely solely on the natural productivity. Actually, the lack of investments, the degradation of fishery and aquaculture facilities, the increase of production costs, the rhythm of privatizations and the uncertain legal status of the lands have all led to a decrease of the production in aquaculture, that, in 2007, represented only 36.73 percent as compared to 1995 (figure 3). Located at Movileni village in Laşi district, the study case (figure 5) refer to two experimentation conducted in 2016 and 2017 on common carp culture along with Chinese carps in earthen ponds in Romania. Five species were used: common carp (*Cyprinus carpio*), Bighead carp (*Hypophthalmichthys nobilis*), Crucian carp (*Carassius carassius*), Grass carp (*Ctenopharyngodon idella*), Silver carp (*Hypophthalmichthys molitrix*). Systems are composed in both cases (2016 and 2017) of a 4300 m^2 pond. We investigated the traditional system occurring in Romania which is the polyculture of Chinese carps fed with cereal's mixture. We compare the traditional system with the culture of carp fed with cereal's mixture associated with a Chinese carp's polyculture (IMTA practices). A separation net was used to create the two compartments (mono and polyculture). In fact, the polyculture is fed only by the emissions of the monoculture compartment and the natural productivity of the pond. Details on feed and fish composition are available in Annexe 1 and 2.

Table 2: Main characteristics of the four experiments conducted in 2016 and 2017 in Romania. Traditional systems refer to a fed (cereal's mixture) polyculture of common carp, bighead carp, silver carp, grass carp and crucian carp in earthen pond and IMTA practices refers to a fed monoculture of common carp connected to a non-fed polyculture of common carp, bighead carp, silver carp, grass carp and crucian carp. Both practices are performed with the same water surface.

Characteristics	2016		2017	
	Traditional system	IMTA practices	Traditional system	IMTA practices
Water surface (m2)	4300	4300	6650	6548
Fish stocking density (kg.m-2)	0,0762	0,0761	0,0142	0,0140
Artificial feed	no	no	no	no
FCR	1,37	0,64	3,94	1,06
Cycle duration	365	365	365	365

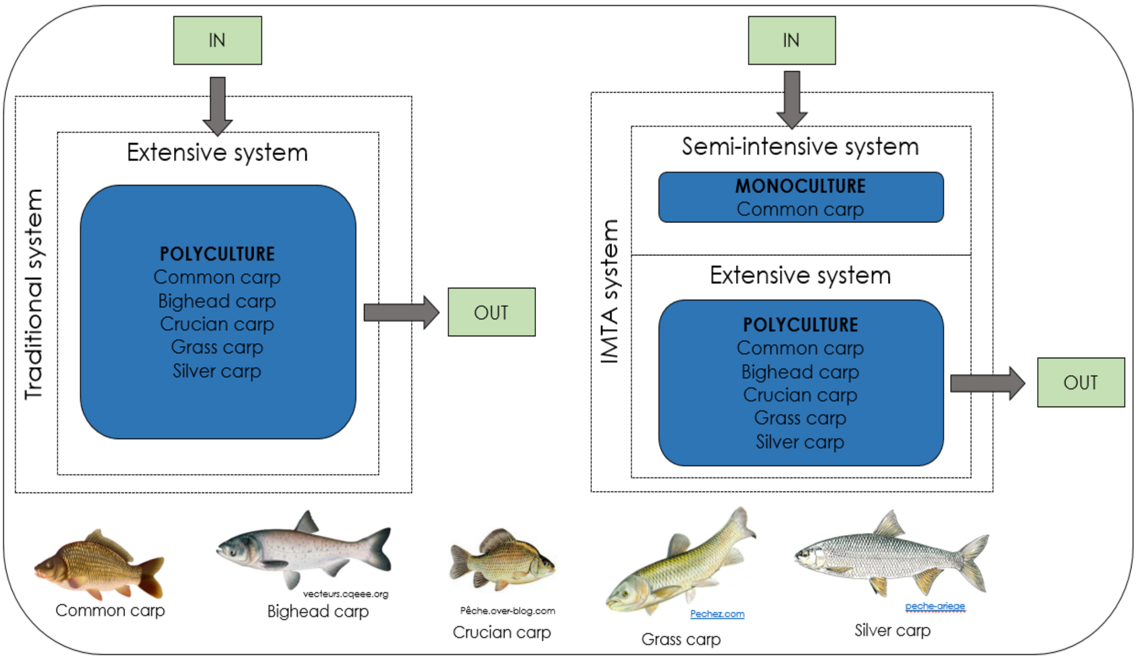

Figure 4: Experimental design of the traditional system (left) and the IMTA system (right) in Romania in 2016 and 2017 corresponding to the polyculture of common carp, bighead carp, crucian carp and silver carp fed with a cereal's mixture in earthen pond (traditional system) and to the monoculture of common carp fed with a cereal's mixture along with the polyculture of bighead carp, crucian carp, grass carp and silver carp relying solely on the emissions of the monoculture and the natural productivity of the pond (IMTA system).

(c) Indonesia

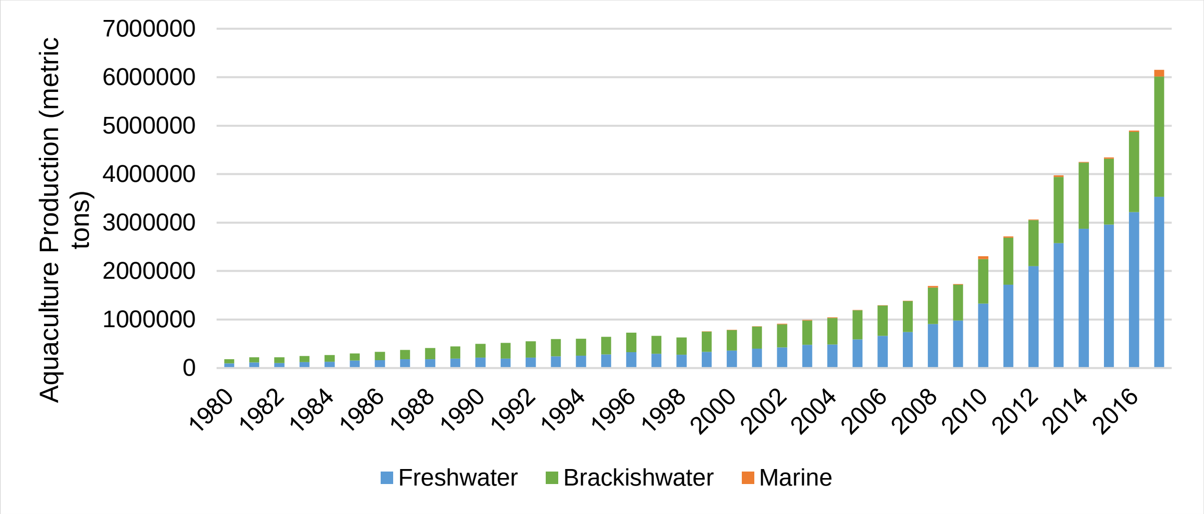

Figure 5: Evolution of the total production of aquaculture (metric tons) in Indonesia from 1980 to 2018. Extracted from FAO 2018 annual report.

Indonesia is an archipelago with more than 17000 islands and a coastline of about 81000km. In fact, this archipelago displays almost 27000000ha of area that can potentially be used for aquaculture development (FAO, 2018). Indonesian aquaculture production in 2016 is six times higher than in 2005 (figure 5). This is explained by government policies favouring significant development of the sector at the national level (Phillips *et al.*, 2015). Similar to Romania, aquaculture is playing a significant role for the improvement of living standards for rural communities, ensuring food availability. However, Indonesia remains the third largest freshwater fish aquaculture producer country even if the production is mainly carried out by micro and small-scale farms, which accounted for more than 90% of all fish farms (FAO, 2018). The most common culture species in freshwater system are common carp (*Cyprinus carpio*), Nile tilapia (*Oreochromis niloticus*) and giant gourami (*Osphronemus goramy*). Traditionally, Indonesian aquaculture is based on low-input and low-level technology. Indeed, traditional practices favour primary productivity and limits the use of commercial pellets thus using resources efficiently through for instance integrated aquaculture-agriculture practices (Pouil *et al.*, 2019*)*. Nevertheless, it appears that Indonesian aquaculture has shifted in recent years from low-intensity traditional culture method to monoculture production systems that promote both intensification and the use of commercial pellets (Rimmer *et al*., 2013). These changes raise many issues about the future of aquaculture in Indonesia especially in terms of effectiveness, sustainability and environmental impacts.

Located at the village of Babakan in Ciseeng in West Java, a group of fish farmers were surveyed in 2018. The survey was conducted on the monoculture of giant gourami (*Osphronemus goramy*) in association with the inland production of giant taro plants (*Alocasia maccrorhizos*) and on the coculture of giant gourami along with the red azolla (*Azolla filiculoides* Lam.) in the same pond also in association with an inland production of giant taro plants. Giant taro leaves are commonly use as supplementary feed for giant gourami as its culture can be easily performed on the banks of the pond. We investigated the influence of red azolla on the fate of the emissions bounded to the monoculture of giant gourami as red azolla can be eaten by the giant gouramy and therefore implying reduction of the use of commercial pellets. In addition, we investigated the capacity of red azolla to maximize the use of nutrients coming from the commercial pellets used in the monoculture. Following this survey, two hypothetical farms were designed (figure 6). A “traditional system” corresponding to the monoculture of giant gourami in earthen ponds using commercial pellets along with the culture of giant taro. A system under "IMTA practices" corresponding to the coculture of giant gourami and the red azolla along with the inland production of giant taro. Giant gourami and red azolla were cultured in the same pond to allow azolla to benefits from the emissions of the monoculture. In fact, the pond is separated in two compartments and azolla is seeded and harvested every week. Details on feed and fish composition are available in Annexe 1 and 2.

Table 3: Main characteristics of the two hypothetical farms in West Java, Indonesia. The coculture refer to the culture of the giant gourami fed with artificial feed along with the red azolla plants in the same pond in separated compartment with the red azolla plants harvested frequently and used as supplementary feed. The monoculture refers to the culture of giant gourami supplied with artificial feed. Each system comprises the culture of the giant taro plants on the banks of the pond.

Characteristics	**Coculture**	**Monoculture**
Water surface (m^2)	482	386 ± 46
Fish stocking density ($kg.m^{-2}$)	0,35	0,35
Artificial feed	yes	yes
FCR (fish)	1.68	2.31
Cycle duration (days)	161	161
Culture of *Alocasia maccrorhizos*	Yes	Yes
Red azolla	Yes	No
Fish production (kg)	1569	967

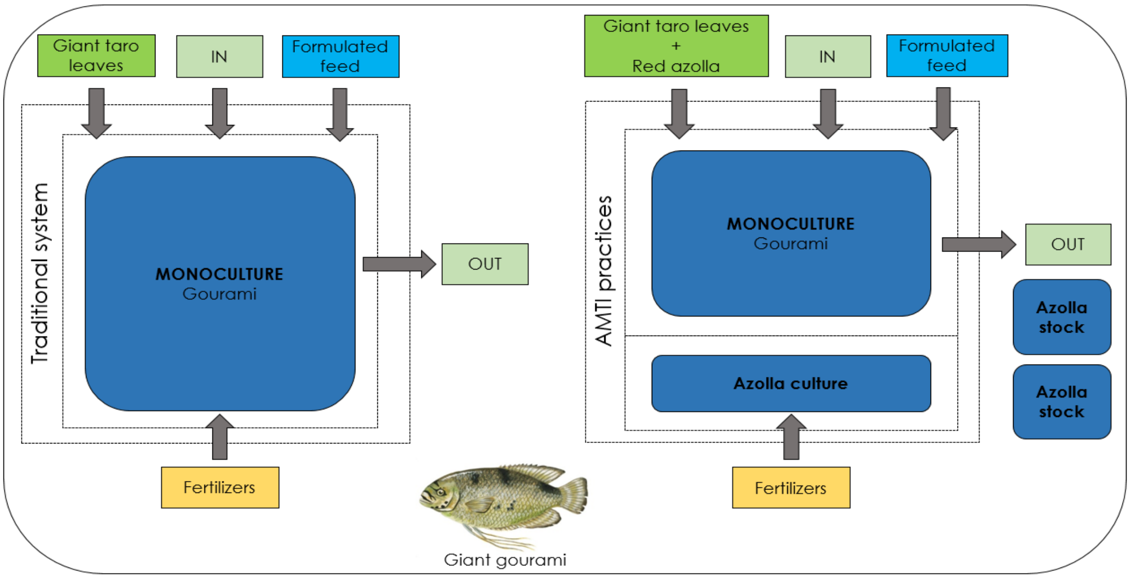

Figure 6: Schema of the hypothetical farm designed following the survey of several farms in West Java, Indonesia. (20 farms). The system refers to the monoculture of giant gourami (left) fed with artificial feed and giant taro leaves and to the coculture of the giant gourami along with red azolla also fed with artificial feed and giant taro leaves. The two compartments of the coculture are separated by a fishing net.

B- Life cycle assessment (LCA) methodology:

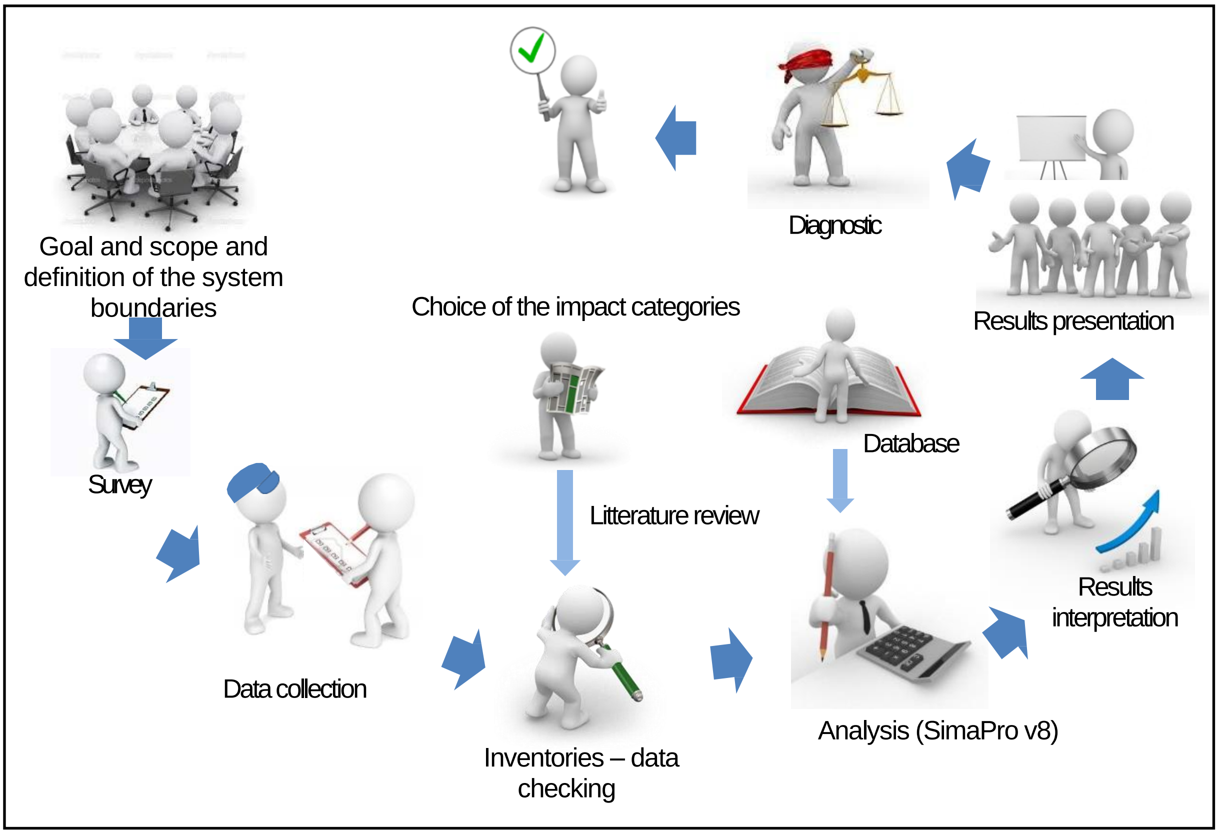

Figure 7: Representative diagram of the Life Cycle Assessment methodology

The life cycle assessment (LCA) methodology consist on pursuing several fundamental steps (figure 7): goals and scope that refer to the definition and delimitation of the system, life cycle inventory and life cycle impact assessment. The analysis in our study cover capital goods (infrastructure and equipment), chemicals production (including agricultural inputs for fertilizers), feed production (including all agricultural inputs), the farm functioning (including the emissions bounded to the farm functioning), the juvenile production, the use of fuel and energy and the transportation of key inputs (juveniles, feed, equipment). The life cycle inventory of a product consists on listing extractions and emissions bounded to the system during the cycle of production to quantify for each steps pollutants emission in the air, water and soil as well as the extractions of renewable and non-renewable resources. Then, the LCA methodology permit to analyse environmental impacts of extractions and emissions through three sub-steps. Classification which is associating emissions to the different categories of impacts selected for the study (potential of climate change, potential of human toxicity, use of resources, …etc). Intermediate categorisation which is weighting the different emissions and extractions inside the different categories in order to put all inputs under the same unit for each category. For instance, the climate change impact category is using CO_2eq as unit and global warming potential. If the production induces the emission of CH_4, these emissions will be multiplied by 24 (characterisation factor) as the greenhouse effect of CH_4 is considered 24 times higher than it of CO_2. Each step of the LCA includes interpretation in order to highlight issues and major contributors to the different impacts and thus developing the best strategy for all stakeholders involved in the process.

(a) Definition of the system and functional unit (FU)

The first step to perform an LCA is the definition of the system and of the functional unit (FU). The functional unit represents the unit on which every extractions and emissions will be based on. This choice represents a fundamental step in LCA as it will determine and orientate consecutive steps. In most cases, study performing LCA in aquaculture displayed functional unit based on the mass of live-weight seafood, therefore conclusions will be directed to the needs and benefits of producers (Aubin *et al.*, 2006; Bohnes *et al.*, 2018; d'Orbcastel *et al.*, 2009; Henriksson *et al.*, 2018). Others used a functional unit based on the mass of edible or processed products hence putting the emphasis on the consumer needs (Henriksson *et al.*, 2015; Mungkung *et al.*, 2013). In fact, the choice of the functional unit will change based on the objectives of the system. To accurately perform environmental impact assessment and to properly compare practices of experiments conducted on the different systems, we performed LCA with two distinct functional units depending on the available database: mass of live-weights products and co-products (*i.e.* impacts per kg of fish and its co-products produced) and the surface used by the farm (*i.e.* impacts per m^2 used by the farm).

(b) Life cycle inventory (LCI)

1- Data collection and models assumptions

To complete inventories of the different systems, all background processes were modelled using the Ecoinvent database v3.1 for most of the case and the different feed were modelled using Ecoalim v2.3 database. In France and Romania, data were obtained from field experiment and measurement: initial and final fish biomass, water consumption, electricity consumption and feed amounts. For feed ingredients (detailed in annexe 1), data were extracted from life cycle inventories in the INRA UMR SAS and AGRIBALYSE databases. Distances for road and boat transports were estimated using Google Maps®. Data used for fishmeal and fish oil (Indonesia case) and the pelletizing and packing processes were based on the study of Boissy *et al.* (2011). Transportation of infrastructure's needs and equipment were also added based mostly on assumptions of distance between the factory and the farm. Indeed, precise and referenced information on the life cycle of the different structures and equipment were missing from the data. The electricity consumption is imputed to the use of a pump. The water balance was calculated using the water input volume from the inlet and rain minus the evaporation and seepage. Body composition of fish were obtained from the literature in France and Romania and from analysis in Indonesia. Data for gaseous emissions are derived from the literature: 2.47 $mg.m^{-2}.h^{-1}$ for methane emissions is derived from the study of refuge fish pond in a rice-fish experiment (Datta *et al.*, 2009), the CO_2 consumption in pond is based on the equation of Smith et al. in 2002 (1.5*pond surface*time). The fate of Nitrogen was assessed using models derived from channel catfish pond study (Gross *et al.*, 2000) with ammonia volatilization of 12.5% and denitrification of 17.4% of total N inputs.

2- Intermediate categories

Prior to investigate the different impact at the farm-level and following the description of processes involved at the farm gate. "Objects" used in the life cycle of the product have been classified into sub-categories: "Infrastructure and equipment" which regroups all type of infrastructure (ponds, tanks, buildings) and equipment (oxygenator, pumps, tools…). "Feed" which regroup the ingredients of feed and process linked to its creation (background agricultural processes), "Farm functioning" which refers to the emissions and extractions directly linked to the farm functioning (fish faeces, CH_4 emission, pond stocking of CO_2..etc), "Juvenile production" for the production of fry, "Transport" which regroup both road and sea transport of products needed by the production, "Chemicals" which refers to the production and use of fertilizers and lime and "Energy" which refers to the production and consumption of energy differing by the electricity mix of the different country.

(c) Life cycle impact assessment

1- Impact categories

Impact categories were selected based on previous studies and recommendations for aquaculture LCA (Aubin *et al.*, 2009; Bohnes & Laurent, 2019; Papatryphon *et al.*, 2004; Wilfart *et al.*, 2013). Climate change that assess potential impact of gaseous emissions or heat-radiation absorption in the atmosphere using global warming potential (kgCO_2-eq). Potential eutrophication of high levels of nutrients in the environment especially for nitrogen and phosphorus compounds (kgPO_4^{-}-eq). Potential acidification which refers to the negative effects on soils, ground, surface water and ecosystems of acidifying pollutants (kg $SO_4^{2—}$eq). Cumulative energy demand that concerns the consumption of fossil fuels, wood, uranium or other source of electricity (MJ). Land competition, net primary production use and water dependence that represent the water input relative to aquatic products biomass production at the farm level (m^2). Water dependence calculation among farm practices (*i.e.* land-based system VS open sea systems), in our case it corresponds to the total water input per fish growth measured (Aubin *et al.*, 2006).

(d) Allocation principle

Some products involved in our systems can be considered as multifunctional products (e.g. the fish derived compounds, the creation of fish oil is bounded to the creation of fish meal as coming from the same resource) which complicate environmental impact assessment and induce the use of allocation. Environmental burdens associated with the materials and energy must be allocated to each of its co-products. Indeed, such approach is mandatory to accurately reflect their individual contributions to the environmental impact of the system under study. ISO 14044 provides recommendations for dealing with co-products allocation. The first possibility is trying to avoid it by dividing the multifunction process into sub-processes and collecting the data related to sub-processes. Otherwise, environmental burdens of the system should be first allocated according to an underlying physical relationship (physical allocation). Finally, when nor subdivision or physical allocation can be applied, the allocation should reflect other relationships between products such as economic value. Mass-weighted economic allocation was thus used in order to compute the relative impacts of some products and its associated co-products as well as for the “main” fish species reared and its associated production as each species reared in our system are intended to be sold and thus represent economic benefits for the producers. The multi-functionality concerns mostly the production phase and therefore physical allocation such as energy content or mass allocation can be used instead of economic criteria. This is recommended by Ayer *et al.* (2007) who argued that the most scientifically accurate solution is to use the gross-energy allocation as the main objective of seafood production is to provide energy to consumers. However due to missing data on the energy content of system products and co-products we decided to perform LCA following mass-weighted economic allocation to highlight the interest of rearing different species which can harbour different price per kilos. Authors mostly chose to allocate environmental burdens based on economic value over others. Several researchers have argued that allocation according to physical properties such as mass or energy is arbitrary and unjustified. Economic allocation is therefore prevalent in most LCA studies as it fits with the fact that fishmen will exert a greater fishing effort or profits when more valuable species are available.

C- Emergy methodology

Emergy accounting (EA) is a method developed in 1983 by Odum based on Energy Systems Theory. It was developed for integrating all system inputs (resources, services and commodities) using a common unit. It is particularly suitable to investigate and assess systems at the interface between the “natural” and the “human” spheres. In fact, emergy is the amount of energy (in solar-energy equivalents) that is directly or indirectly required for all the components of the production. EA can provide indicators to evaluate energy quality and efficiency along the life cycle of a product.

(a) Emergy accounting procedure

Emergy accounting consist on convert all inputs of a system into their equivalent in solar energy content. Using system description and the spatial and temporal boundaries defined in the LCA, the first step of Emergy is to draw an energy system diagram. In this way we can encompass all inputs to and outflows from system processes. The main aim is to organise all relations among systems components and allow representations of systems on an environmental basis including its connection with the economy (Cavalett *et al.*, 2006; Pizzigallo *et al.*, 2008). By putting all system components under the same unit and provides system description with a standardized method we can compare systems to each other, in our cases, the different practices under study. The second step refers to the construction of tables that organise the different inputs. Each flow displays a specific unit (J, kg, €, etc.) that is convert into solar-energy equivalents by multiplying it with appropriate unit emergy value (e.g. sej.J^{-1}, sej.kg^{-1}, sej.$€^{-1}$, etc.). UEVs were derived from previous literature or calculated according to Odum (1996) when they were not available or transferable to our system components. Emergy inputs were grouped into two main categories: one group considered “local” which inputs from natural contributions (I) and another one considered “external” with inputs purchased from the economy. In other words, the F group refers to external resources such as the electricity, formulated feed or liquid oxygen; everything that is coming from outside the system. This group is divided into two sub-categories that are material (M) and services (S). The I group comprises solely inputs from natural sources such as wind, solar and rain. The partial renewability of resources was also added in this study according to Agostinho *et al.* (2008) who split the I, M and S groups into renewable (R) and non-renewable (N) resources and the renewability fraction values were coming from previous work (Agostinho *et al*, 2008; Cavalett *et al.*, 2006). Finally, the total emergy input is designed by Y.

(b) Emergy indicators

To provide evaluation of systems and allow comparisons of the different investigated practices, emergy indicators were calculated as referenced in table 4. The transformity is considered as a performance indicator of the systems. It expresses the quantity of products that we obtain with the given total energy input Y of the system (Wilfart *et al.*, 2013; Odum, 1996). The percentage of renewability refers to the percentage of renewable emergy used by the system. The higher this percentage is, the more the system will be considered sustainable. The Emergy Yield Ratio gives a measure of the ability of the system to use local resources as well as of the system efficiency in using purchased inputs (“external” resources). The Emergy Investment Ratio permit a comparative test for alternative uses of the same resources as it represents the ratio between the purchased inputs and renewable plus non-renewable local resources. The Emergy Loading Ratio (ELR) is the ratio between renewable and non-renewable resources giving clues on ecosystem services as it can highlight a high exploitation of non-renewable resources compared to locally renewable emergy (Cavalett *et al.*, 2006; Wilfart *et al.*, 2013). ELR values <2, from 2 to 10 and >10 indicate low, moderate and high environmental respectively. The Emergy Sustainability Index, which is the ratio between EYR and ELR, aggregates measures of yield and environmental loading as a measure of sustainability for a given process occurring in the system.

Table 3: Emergy indicators used in the study for the emergy accounting procedure with (Y) the total emergy used, (E) the total amount of aquatic products produced (in kg or J), (R) the total emergy from renewable resources from nature, (N) the total emergy from non-renewable resources, (M) the total emergy from materials, (S) the total emergy from services. R and N indices refer to renewable and non-renewable resources.

Emergy indicators	**Equation**
Transformity	$Tr = Y/E$
Percentage of renewability	$\%R = 100 \times (R + M_R + S_R)/Y$
Emergy Yield Ratio	$EYR = Y/(M + S)$
Emergy Investment Ratio	$EIR = (M_N + S_N)/(R + N)$
Environmental Loading Ratio	$ELR = (M_N + S_N + N)/(R + M_R + S_R)$
Emergy Sustainability Index	$ESI = EYR/ELR$

III- Results (Life Cycle Assessment)

A- France

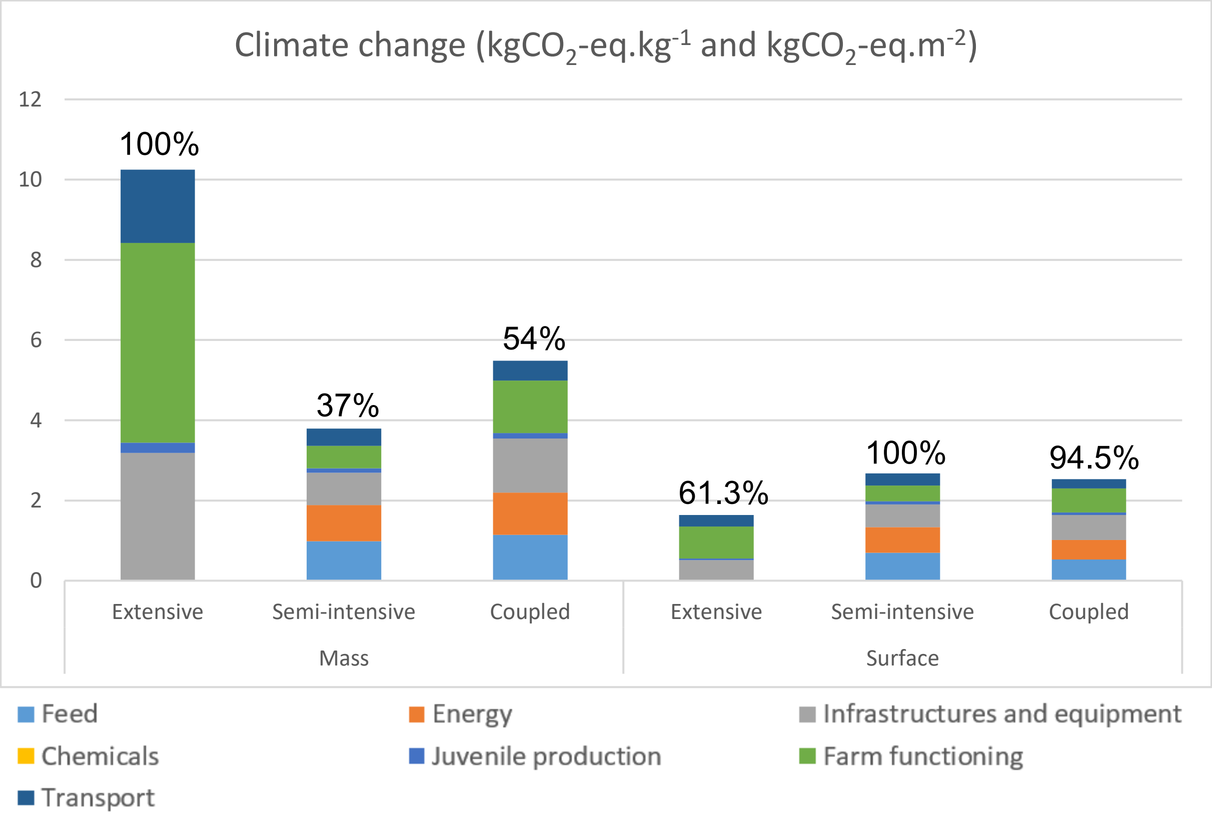

Figure 8: Relative contributions of the system components in the climate change impact category (kg CO_2eq.kg^{-1} and kgCO_2.m^{-2}) for the extensive (E), semi-intensive (SI) and coupled (C) conditions in France with the use of mass of living fresh weight or the use of one square meter of surface as functional unit. Results have been performed by the software SimaPro v.8.

Figure 8 shows the relative contributions of the components of the polyculture in France for the climate change damage category. For the mass as functional unit, results demonstrate that the extensive (E) practices have the highest impact following by the coupled (C) and the semi-intensive (SI) practices. For the use of surface (right of the figure), results demonstrate the opposite *id est* that the extensive practices lead to the lowest impact. Concerning contributions with the use of mass as functional unit, the “farm functioning” (green) category is the main contributor for the extensive and the coupled practices. It refers mainly to CH_4 emissions and CO_2 stocking associated with the use of a fishpond. The second main contributor for the extensive and the coupled practices is the infrastructure and equipment followed by the transportation of key inputs. The use of energy occurs by a pump under the semi-intensive and the coupled practices and represent respectively 24% and 19% of the climate change impact. We can observe the same with the use of feed with contributions for SI and C respectively of 26% and 21%. In the case of the use of one square meter as functional unit, we can see that results draw the same conclusion as the use of mass as functional unit concerning relative contributions. However, the percentages differences in the impacts related to the systems are less contrasted with the use of surface than that of the mass as a functional unit with percentages differences up to 39.7% for the surface and 63% for the mass.

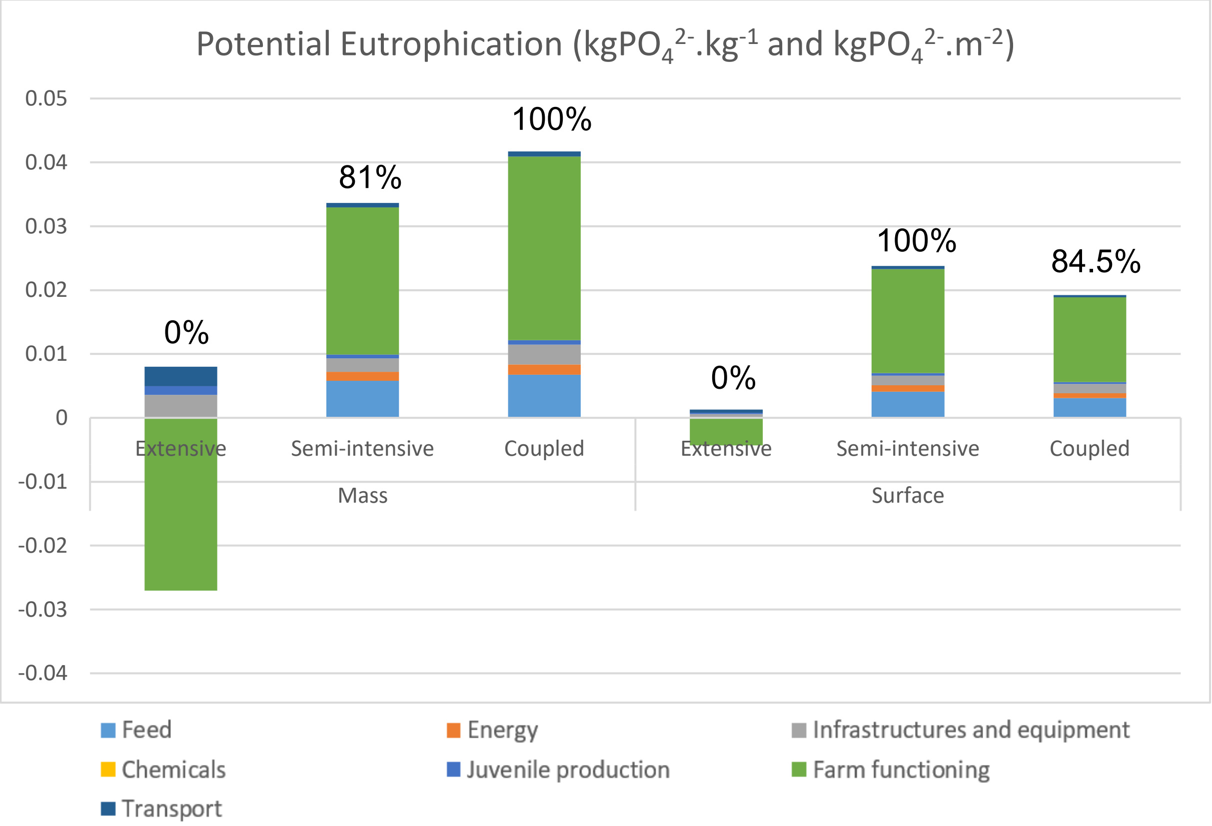

Figure 9: Relative contributions of the system components for the potential eutrophication damage category (kg PO4.kg-1 and kg PO4.m-2) for the extensive, semi-intensive and coupled practices in France with the use of mass of living fresh fish or the use of one square meter of surface as functional unit. Results have been performed by the software SimaPro v.8.

Figure 9 shows the relative contributions of the components of the polyculture in France for the potential eutrophication of water. Results demonstrate that the extensive practices display the lowest impact and even diminish the potential eutrophication of water. The coupled practices display contrasting results according to the functional unit; indeed, the use of surface induces show semi-intensives practices as the highest impact whereas with the use of mass the coupled practices demonstrate the highest impact. Independently of the functional unit and the practices, the main contributor to the impact here is the “farm functioning” category with percentages comprised between 68% and 95% followed by “feed” under SI and C practices with respectively 17% and 16% of the total impact.

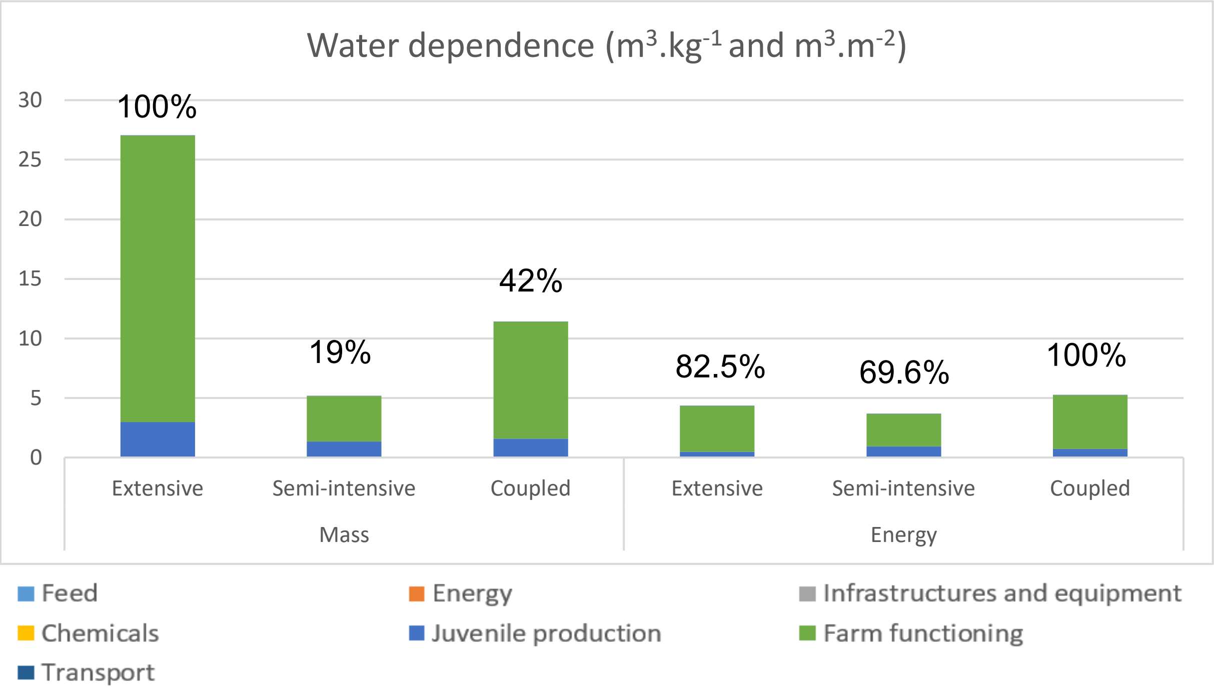

Figure 10: Relative contributions of the system components for water dependence impact category ($m^3.kg^{-1}$ and $m^3.m^{-2}$) for the extensive, semi-intensive and coupled practices in France with the use of mass of living fresh fish or the use of one square meter of surface as functional unit. Results have been performed by the software SimaPro v.8.

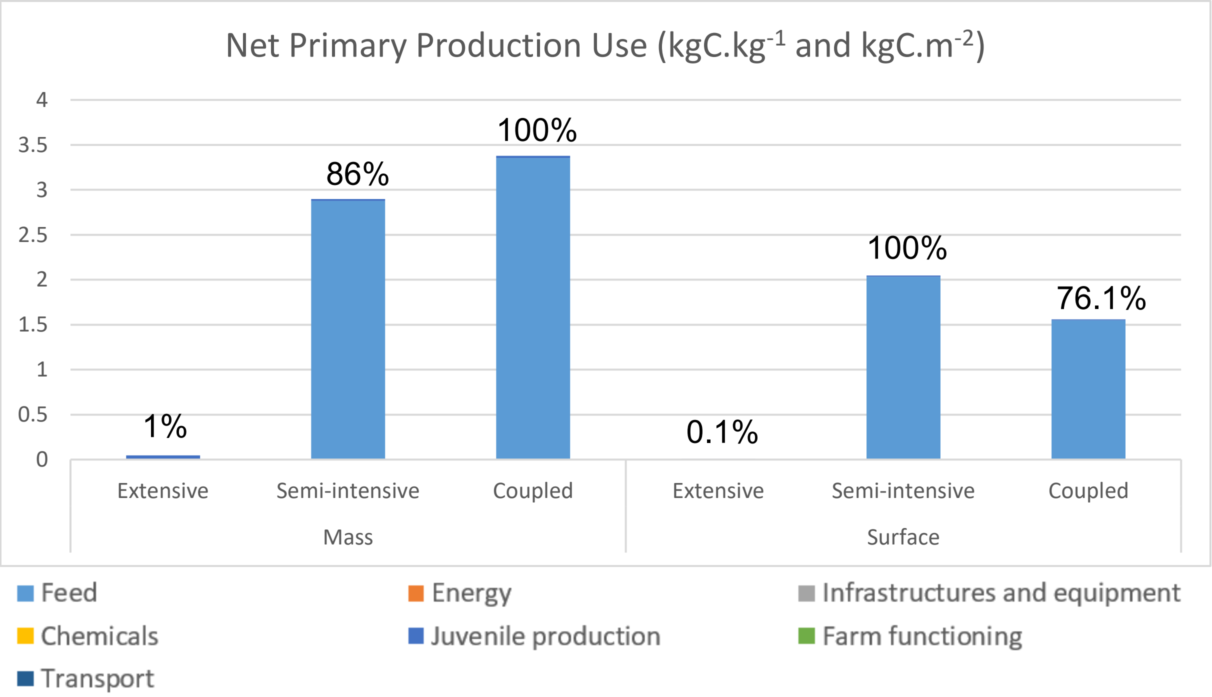

Figure 11: Relative contributions of the system components for Net Primary Production Use impact category ($kgC.kg^{-1}$ and $kgC.m^{-2}$) for the extensive, semi-intensive and coupled practices in France with the use of mass of living fresh fish or the use of one square meter of surface as functional unit. Results have been performed by the software SimaPro v.8.

Figure 10 refers to the water dependence impact category and the relative contributions of the components of the system. Per kg of fish produced, the extensive practices display the highest water dependence followed by the coupled (42% of the “extensive” impact) and the semi-intensive (19% of the “extensive” impact) practices. We observe per square meter differences between practices much less clear and it appears that coupled practices display the highest water dependence followed by the extensive (82.5% of the “coupled” impact) and the semi-intensive (69.6% of the “coupled” impact) practices. Independently of the functional unit, two components are mainly involved in water dependence: “Juvenile production” and “Farm functioning” with contribution for the latter far higher than for the first (between 11% and 26% for the juvenile production and between 74% and 86% for the farm functioning).

Figure 11 represents the relative contributions of the components of the system in the Net Primary Production Use impact category. Similar to the other impacts above, coupled practices display the highest impact per kg of fish produced and the second highest impact per m2 of surface used. Two components are involved in this impact, which are the “juvenile production” and the “feed” with respectively 0 to 1% and 99 to 100% of the impact.

B- Romania

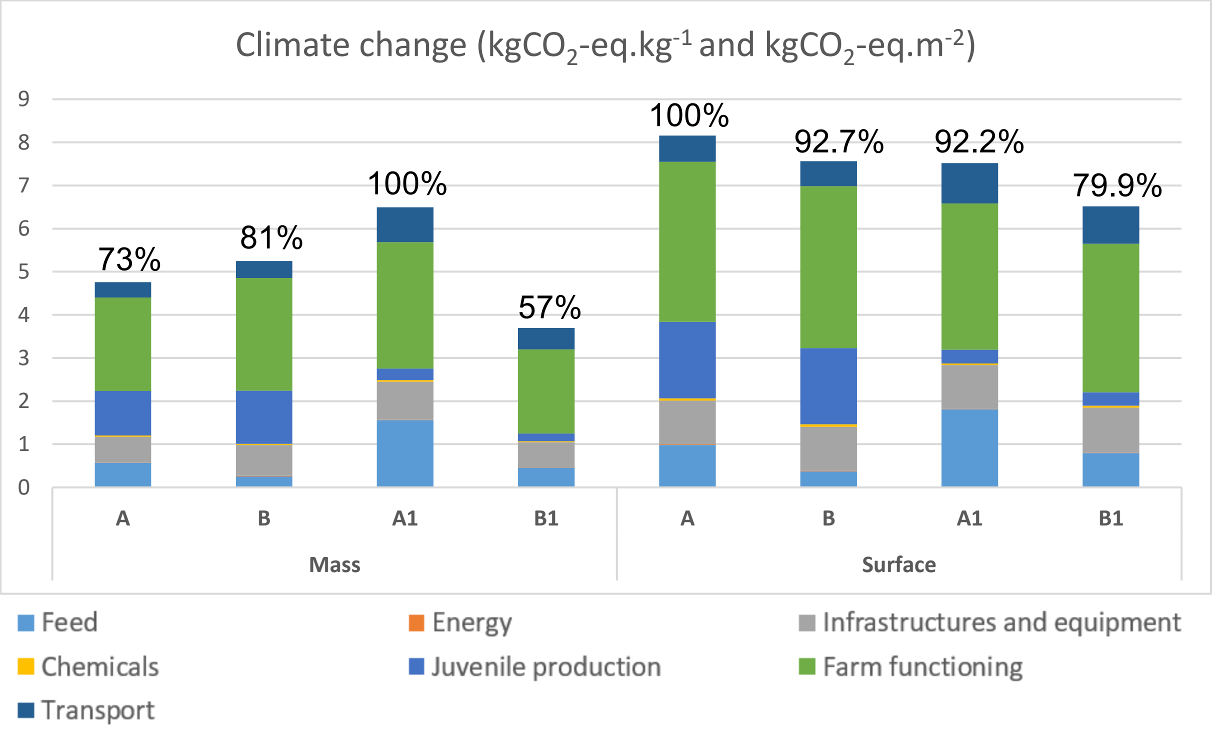

Figure 12: Relative contributions of the system components in the climate change impact category (kg CO$_2$eq.kg^{-1} and kgCO$_2$.m^{-2}) for the traditional practices in 2016 (A) and 2017 (A1) and for the IMTA practices in 2016 (B) and 2017 (B1) in Romania with the use of mass of living fresh fish or the use of one square meter of surface as functional unit. Results have been performed by the software SimaPro v.8.

Figure 12 presents the contributions of the system components in the climate change impact. We will only compare practices within the year 2016 and 2017 and not between for the rest of the result and differences are considered significant when higher than 3%. For 2016, traditional practices (A) lead to lower climate change impact per kg of fish produced compared to IMTA practices (B). On the contrary, in 2017, traditional practices lead to higher impact per kg of fish produced compared to IMTA practices. Concerning the use of surface, IMTA practices in both 2016 and 2017 lead to the lowest impact. The main contributors of this impact are the farm functioning, the feed, the juvenile production, the infrastructures and equipment and the transport. In 2016 and 2017, “farm functioning” accounted for 45% to 53% of the global warming impact with higher percentage for IMTA practices in both years. The juvenile production demonstrates variable contributions between the two years with 22% and 29% of the global warming impact in 2016 and 4% and 5% in 2017 explained by the initial weight of the fish (higher in 2016). Percentage differences are less contrasted with the use of surface as functional unit with a maximum percentage of 12.3% and of 43% for the mass (both between A1 and B1).

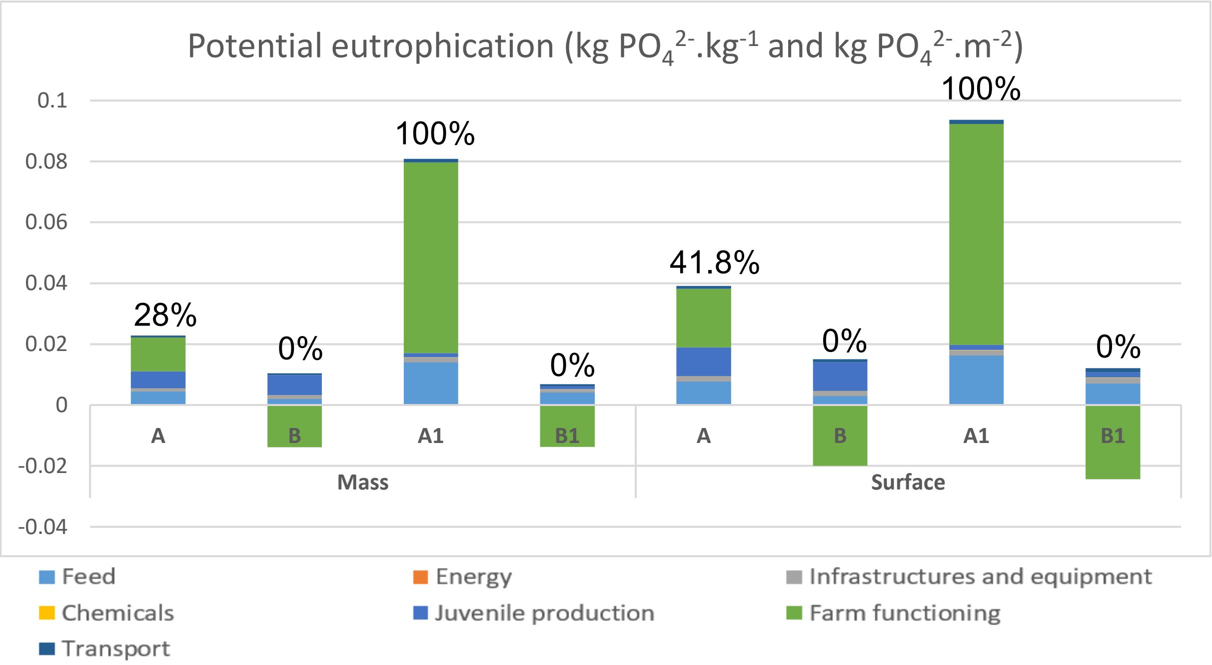

Figure 13: Relative contributions of the system components in the potential eutrophication impact category (kg $PO_4^{2-}.kg^{-1}$ and $PO_4^{2-}.m^{-2}$) for the traditional practices in 2016 (A) and 2017 (A1) and for the IMTA practices in 2016 (B) and 2017 (B1) in Romania with the use of mass of living fresh fish or the use of one square meter of surface as functional unit. Results have been performed by the software SimaPro v.8.

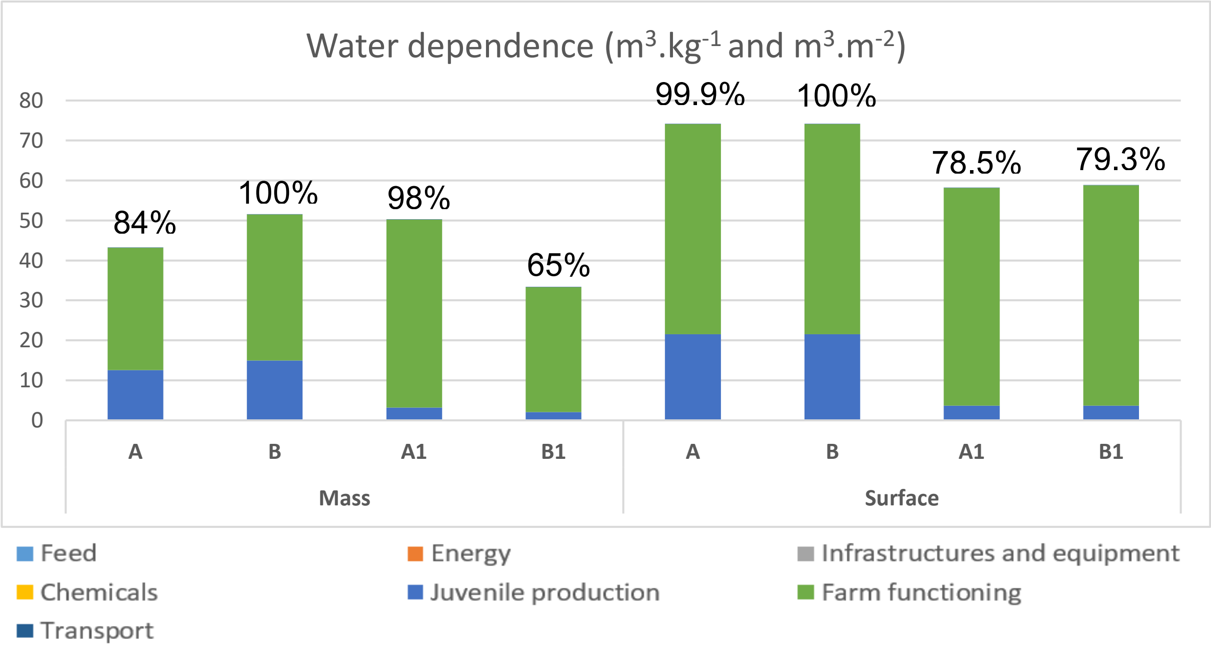

Figure 14: Relative contributions of the system components in the water dependence impact category ($m^3.kg^{-1}$ and $m^3.m^{-2}$) for the traditional practices in 2016 (A) and 2017 (A1) and for the IMTA practices in 2016 (B) and 2017 (B1) in Romania with the use of mass of living fresh fish or the use of one square meter of surface as functional unit. Results have been performed by the software SimaPro v.8.

Figure 13 describe the relative contributions of the system components for the potential eutrophication of water in Romania in 2016 and 2017 experiments. Per kg of fish produced and per m^2 of surface used IMTA practices lead to the lowest impact and the production even decrease the natural potential eutrophication of water. This is mostly due to the “farm functioning” and it appears that “feed” impact is lower under IMTA practices than under traditional practices which is consistent with a better FCR under IMTA practices than under traditional practices (1.37 vs 0.64 in 2016 and 3.94 vs 1.06 in 2017 [table 2]). This is explained by a decrease of the use of feed leading to the diminution of pollutants emissions in the water. As for the potential global warming, the juvenile production contribution is higher in 2016 than in 2017 explained by the initial size/age of the fish. Changes in the functional unit influence the percentage differences between practices (28% for the mass and 41.8% for the surface between A and B).

Figure 14 represents the water dependence impact for the two years of experimentation in Romania. We observe contrasting results between 2016 and 2017; IMTA practices lead to higher impact compared to traditional practices in 2016 whereas in 2017 we observe the opposite. Contrasting results are also observed between the two functional units; indeed, changing practices lead to different impact per kg of fish produced but not per m^2 used by the production. Concerning contributions, two main components are involved in this impact as what is observed in France: the “farm functioning” and the “juvenile production”. “Farm functioning” contribute in the impact from 71% in 2016 to 94% in 2017 independently of the practices as it does not change the amount of water used by the system (consist only on the separation of the pond into two compartments). Again, we observe between the two years different relative contributions of the juvenile production with a much higher contribution in 2016 (29%) than in 2017 (6%). Percentage differences change along with the functional unit, we observe significant differences only with the use of mass (16% in 2016 and 33% in 2017) and no differences can be observed with the use of surface between practices for both years.

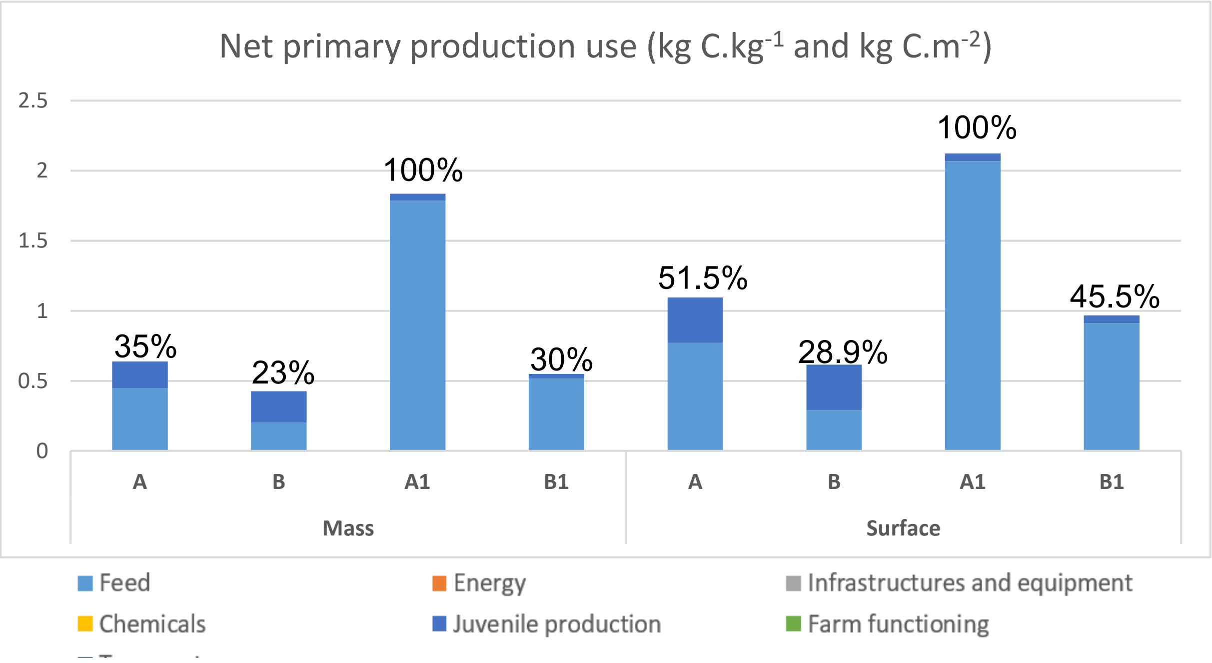

Figure 15: Relative contributions of the system components in the Net Primary Production Use impact category (kgC.kg^{-1} and kgC.m^{-2}) for the traditional practices in 2016 (A) and 2017 (A1) and for the IMTA practices in 2016 (B) and 2017 (B1) in Romania with the use of mass of living fresh fish or the use of one square meter of surface as functional unit. Results have been performed by the software SimaPro v.8.

Figure 15 refers to the Net Primary Production Use impact and the relative contributions of the components of the Romanian system. The IMTA practices imply a decrease in the total impact for both years. Two components are involved in this impact category: “Feed”, “juvenile production”. Juvenile production is influencing this impact by using artificial feed. “Feed” is the major contributor in this impact and its related impact is diminished under IMTA practices mostly due to the decrease of the use of feed. The contribution of juvenile is independent of the practices as fish initial stocking density is the same between traditional and IMTA practices. Overall, the relative contributions do not change according to the functional unit.

C- Indonesia

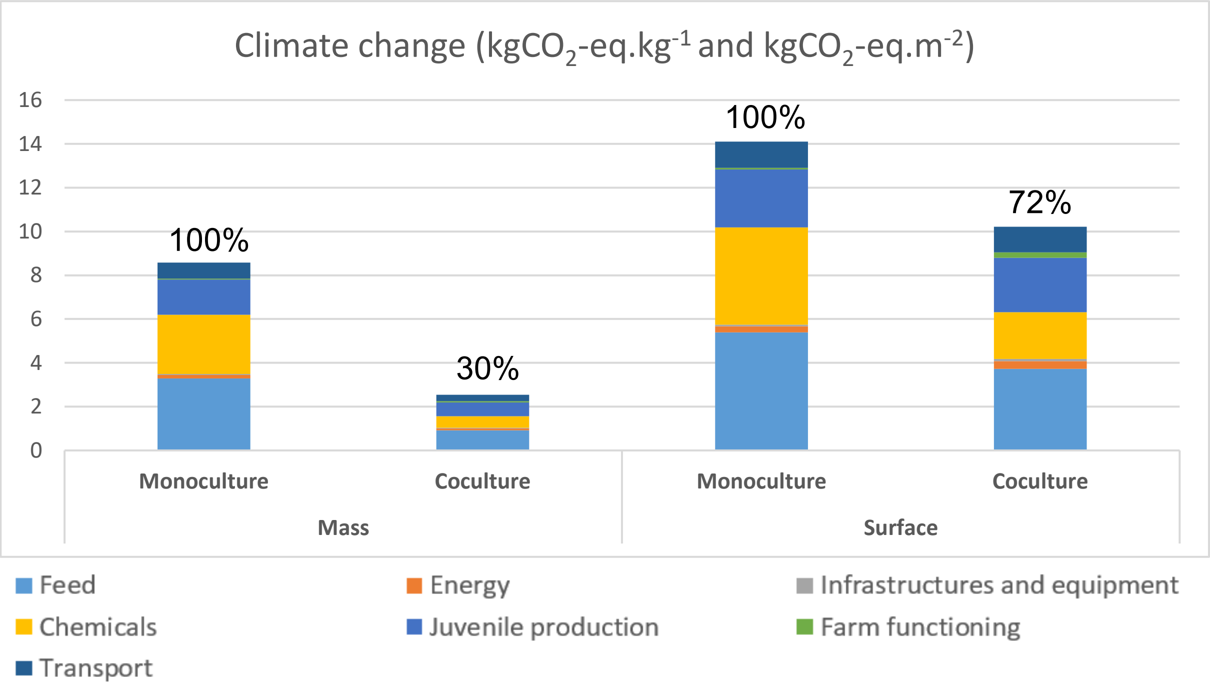

Figure 16: Relative contributions of the system components in the climate change impact category (kg CO_2eq.kg^{-1} and kgCO_2.m^{-2}) for the monoculture of Giant gourami and the coculture of giant gourami and the red azolla in Indonesia with the use of mass of living fresh aquatic products or the use of one square meter of surface as functional unit. Results have been performed by the software SimaPro v.8.

Figure 16 presents the potential global warming impact for the monoculture and the coculture of giant gourami and the red azolla in Indonesia. Both functional units demonstrate that the coculture lead to the lowest global warming impact per kg of fish produced and per m^2 of surface used by the production. Concerning the relative contributions, it appears that the main contributor to this impact is the feed with 38% for the monoculture and 36% for the coculture (same for both functional units). Follows the “chemicals” (in this case mixture of poultry manure and rice at a ratio 1:1.5) with percentage values of 31% for the monoculture and 21% for the coculture. Then we observe the “juvenile production” which accounted for 19% of the impact for the monoculture and 24% for the coculture. “Transport” can also be noted with 9% of the impact for the monoculture and 11% for the coculture.

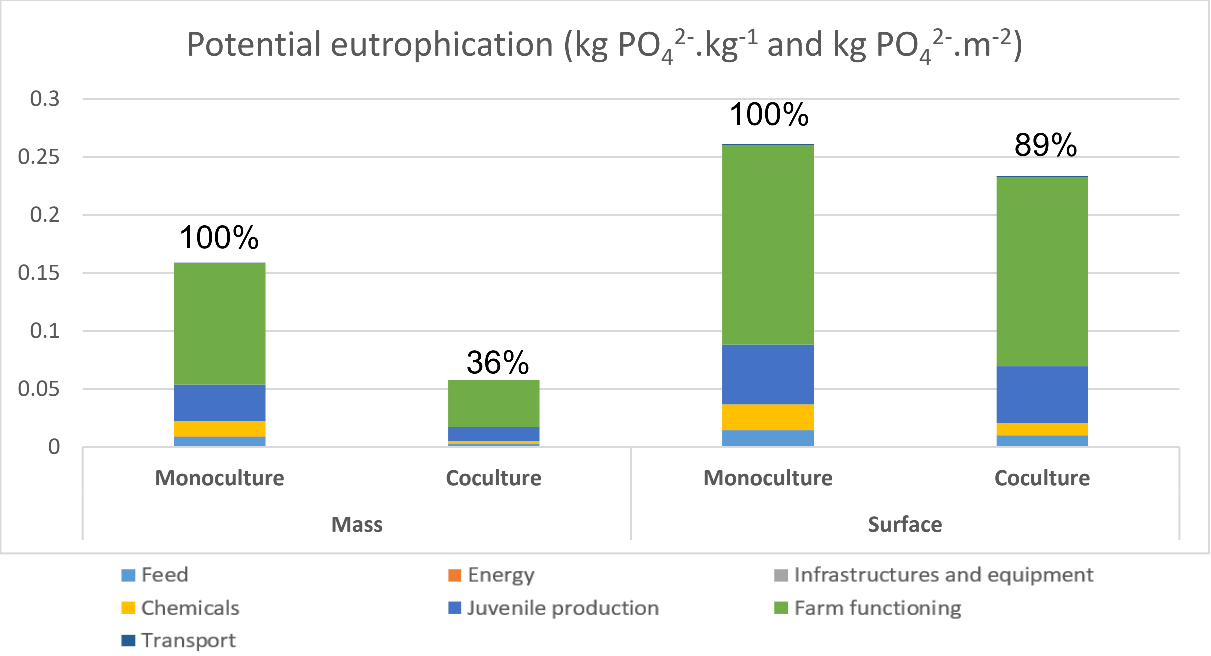

Figure 17: Relative contributions of the system components in the potential eutrophication impact category (kg $PO_4^{2-}.kg^{-1}$ and $PO_4^{2-}.m^{-2}$) for the monoculture of Giant gourami and the coculture of giant gourami and the red azolla in Indonesia with the use of mass of living fresh fish or the use of one square meter of surface as functional unit. Results have been performed by the software SimaPro v.8.

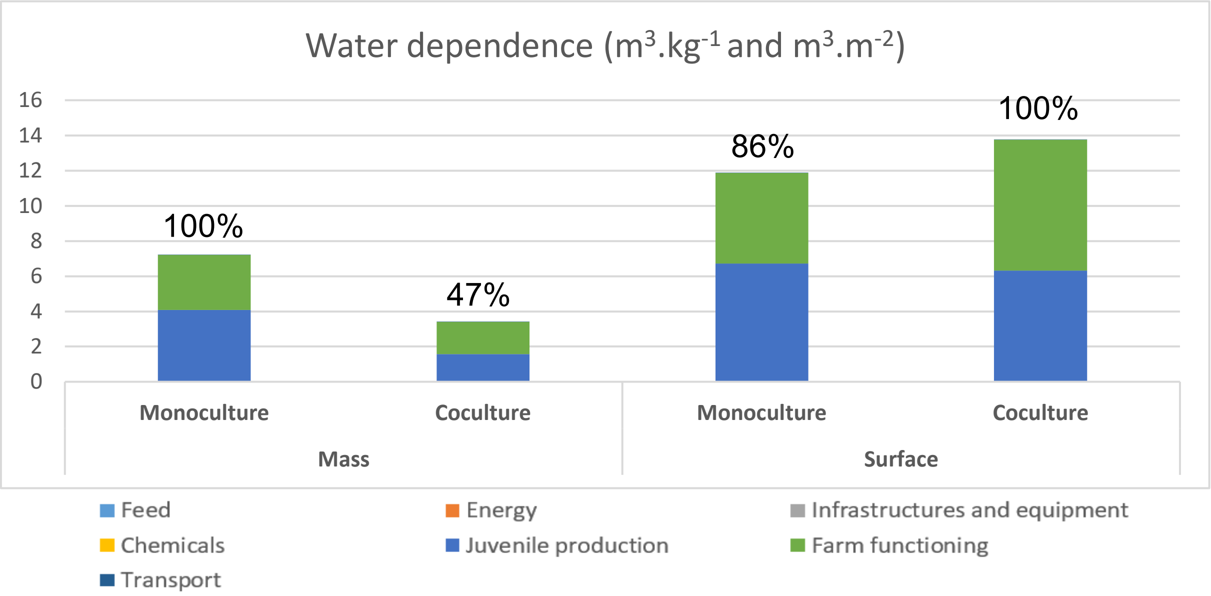

Figure 18: Relative contributions of the system components in the water dependence impact category ($m^3.kg^{-1}$ and $m^3.m^{-2}$) for the monoculture of giant gourami and the coculture of giant gourami and the red azolla in Indonesia with the use of mass of living fresh aquatic products or the use of one square meter of surface as functional unit. Results have been performed by the software SimaPro

Figure 17 presents the potential eutrophication impact and the relative contributions of system components in Indonesia for the monoculture and the coculture. Per kg of fish produced and per m^2 of surface used, the coculture induces the lowest impact. The impact is mainly due to the "farm functioning" with 66% for the monoculture and 70% for the coculture. Follows the juvenile production with 20% for the monoculture and 21% for the coculture; then the "Chemicals" with 8% for the monoculture and 4% for the coculture. Finally, the "feed" contributes to the impact with 6% for the monoculture and 4% for the coculture.

Figure 18 represents the water dependence impact category fot he mono and coculture in Indonesia. We observe contrasting results depending on the choice of functional unit. Indeed, the coculture have the lowest impact per kg of aquatic products with monoculture representing 53% of the coculture impact. On the contrary, the coculture have the highest impact per m^2 of surface used and the monoculture displays 86% of the coculture impact. Concerning the relative contributions, two components are involved in this impact as observed in France and Romania: the "juvenile production" and the "farm functioning". The farm functioning displays a higher contribution for the coculture compared to the monoculture with respectively 54% and 43%. The juvenile production is involved in 57% of the impact of the monoculture and 46% of the impact of the coculture.

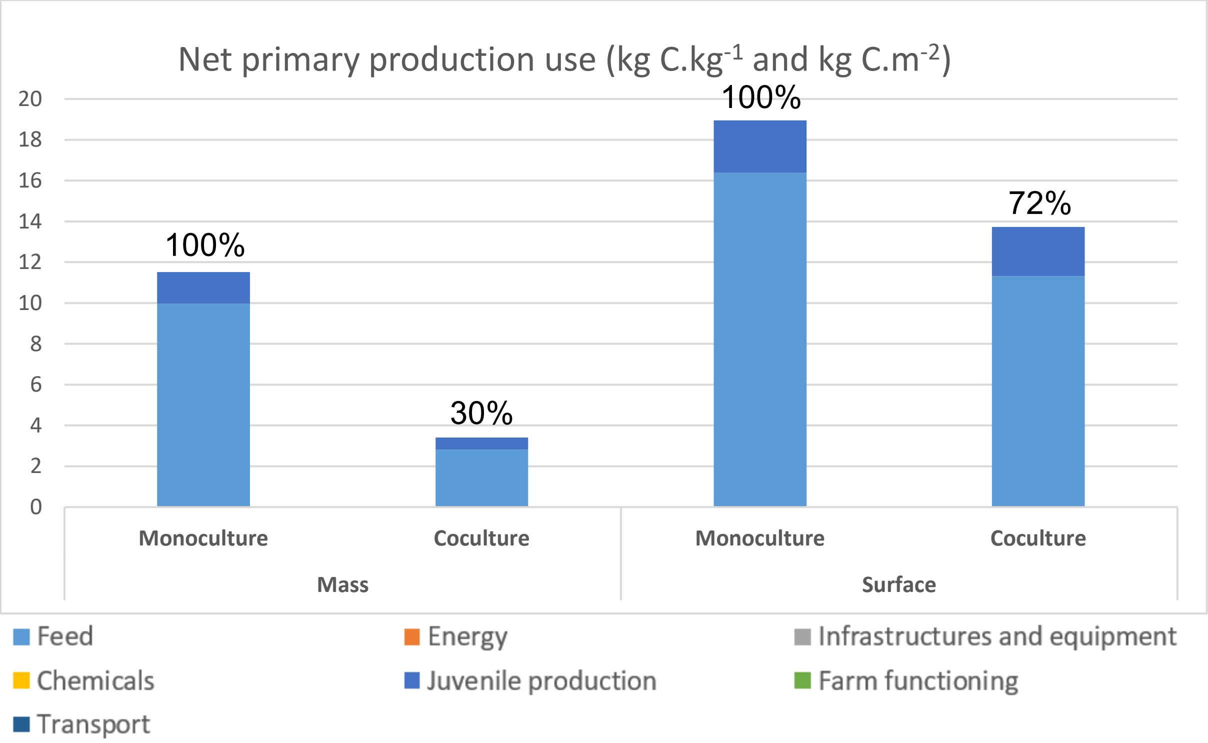

Figure 19: Relative contributions of the system components in the Net Primary Production Use impact category (kgC.kg^{-1} and kgC.m^{-2}) for the monoculture of giant gourami and the coculture of giant gourami and the red azolla in Indonesia with the use of mass of living aquatic products or the use of one square meter of surface as functional unit. Results have been performed by the software SimaPro v.8

Figure 19 shows the Net Primary Production Use impact category for the mono and the coculture in Indonesia. The coculture have the lowest impact for both functional units and display, as well as for the monoculture, two main contributors: the "feed" and the "juvenile production". The "Feed" accounted for 86% of the impact of monoculture and 82% for the coculture. The juvenile production contributes to 14% of the impact of the monoculture and 18% for the coculture. Changes in the functional unit induce changes in the percentage differences. Indeed, the coculture accounts for only 30% of the monoculture impact per kg of aquatic products (Gourami+azolla) while it reaches 72% of the monoculture impact per square meter.

IV- Results (Emergy Accounting)

A- France

Table 4: Aggregate emergy flows of the Extensive, Semi-intensive and Coupled system in France to produce 1kg of aquatic products (fish + co-products). The extensive practices refer to a non-fed polyculture of common carp, perch and roach, the semi-intensive practices to a fed polyculture of common carp, perch and roach and the coupled practices which refers to the same polyculture as the semi-intensive practices but connected to a planted lagoon.

Emergy flows (sej.yr^{-1})	**Extensive**	**Semi-intensive**	**Coupled**
	(sej)	**(sej)**	**(sej)**
Nature contribution (I)	*5,96E+12*	*4,03E+12*	*8,79E+12*
Renewable resources (R)	*1,71E+12*	*1,47E+12*	*2,26E+12*
Non-renewable resources (N)	*4,24E+12*	*2,56E+12*	*6,54E+12*
Feedback from the economy (F)	*1,93E+14*	*1,81E+14*	*2,14E+14*
Total materials (M)	*1,93E+14*	*1,81E+14*	*2,14E+14*
Renewable materials (MR)	*1,84E+13*	*1,76E+13*	*2,07E+13*
Non-renewable materials (MN)	*1,75E+14*	*1,64E+14*	*1,93E+14*
Total services (S)	*2,35E+06*	*2,02E+06*	*2,35E+06*
Renewable services (SR)	*3,06E+05*	*2,62E+05*	*3,06E+05*
Non-renewable services (SN)	*2,05E+06*	*1,75E+06*	*2,05E+06*
Total emergy (Y)	*1,99E+14*	*1,85E+14*	*2,23E+14*
% Nature (I)	3,0%	2,2%	3,9%
% Materials (M)	97,0%	97,8%	96,1%
% Services (S)	0.0%	0,4%	0,4%
% Renewable resource	28,7%	36,5%	25,7%

Table 4 presents the aggregate emergy flows occurring in the extensive (E), semi-intensive (SI) and coupled (C) polyculture in France. The nature contribution (I) differed among systems. It contributed for an average of 3% for E, 2.2% for SI and 3.9% for C of the total emergy. In (I), the relative contribution of renewable resources differed also among practices. Overall the coupled system uses more renewable resources, but it accounted for only 26% of the total nature contribution compared to the extensive and the semi intensive system which display respectively 28.7% and 36.5% of renewable resources from nature. Our systems show an important dependence on materials (M) that represent 97%, 97.8% and 96.1% of the total emergy for the extensive, the semi-intensive and the coupled system. In our cases, the contributions of services (S) are negligible (<1% for the three cases) mostly due to the lack of data on this part of the system especially on economic aspects (materials, equipment, goods prices), services only include the work force (number of days of work).

Table 5: Comparison of the emergy indicators of the Extensive (E), the Semi-intensive (SI) and the Coupled (C) system in France. The extensive practices refer to a non-fed polyculture of common carp, perch and roach, the semi-intensive practices to a fed polyculture of common carp, perch and roach and the coupled practices which refers to the same polyculture as the semi-intensive practices but connected to a planted lagoon.

Emergy indicators	**Coupled**	**Semi-intensive**	**Extensive**
Transformity (SeJ/kg)	*2,2E+14*	*1,9E+14*	*2,0E+14*
Transformity (SeJ/J)	*3,3E+07*	*2,7E+07*	*2,9E+07*
% Renewability	*10,29*	*10,30*	*10,08*
Emergy Yield Ratio (EYR)	*1,04*	*1,02*	*1,03*
Emergy Investment Ratio (EIR)	*6,56*	*7,56*	*7,19*
Environmental Loading Ratio (ELR)	*8,72*	*8,71*	*8,92*

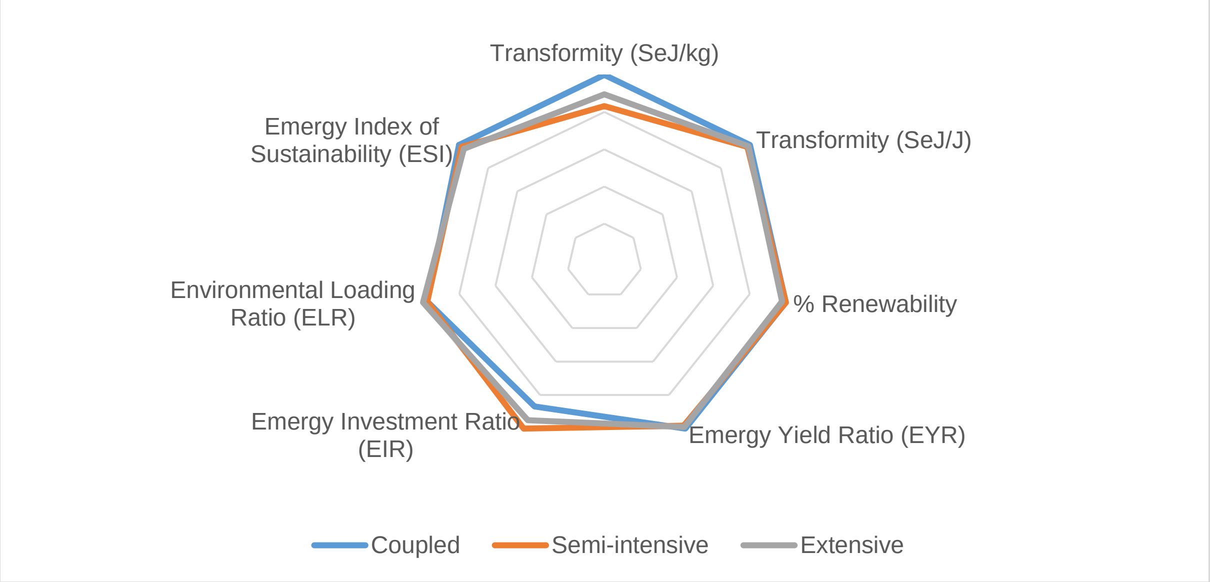

Figure 20: Comparison of the emergy indicators for the Extensive, the Semi-intensive and the Coupled system in France. The system refers to the polyculture of common carp, roach and perch. For each emergy indicators, the highest value is set as 100% and others are compared to it.

Table 5 and figure 20 show the comparison of emergy indicators between the three system in France. We choose to present two values of transformities, one that is bounded to the production of biomass (sej.kg-1 of fish) and one that refers to the gross energy content of fish and which is expressed in sej per joules (i.e. based on the energy content of fish). According to the definition of the transformity, the lower the value is more the system is efficient. The Coupled system have the highest transformity whether it is expressed in sej per kg or in sej per joules (respectively 2.2E+14 and 3.3E+07). Follows the Extensive system with 2.0E+14 sej.kg^{-1} and 2.9E+07 sej.j^{-1} and the semi-intensive system with 1.9E+14 sej.kg^{-1} and 2.7E+07 sej.j^{-1}. The three systems present around 10% of renewability with the lowest percentage for the extensive system (10.08%) followed by the coupled (10.29%) and the semi-intensive (10.30%) system. The difference between systems came mainly from the use of feed displaying 12% of renewable resources and thus enhancing the percentage of renewability of the Coupled and the Semi-intensive system. Indeed, the addition of feed will diminish the influence of lower renewable components of the system in the final percentage of renewability. The Emergy Yield Ratio traduces the ability of the system to exploit natural contributions by investing external economic resources (Wilfart et al., 2013). Similar values are observed in our cases with 1.04 for the Coupled system, 1.02 for the semi-intensive and 1.03 for the extensive system. The Emergy Investment Ratio permit to evaluate whether a process is a suitable transformer of invested external emergy (Brown & Ulgiati, 2004). For the coupled system, 6.56 sej of economic resource were necessary for each sej of natural resources used followed by the extensive system with an EIR of 7.19 and the semi-intensive system with an EIR of 7.56. High value of EIR demonstrate that the system rely more on purchased resources and low value of EIR indicate that the system uses local emergy sources more efficiently (Wilfart et al., 2013). The Emergy Loading Ratio refers to the ratio between non-renewable resources and renewable resources. Despite low levels of technologies, all systems present ELR between 2 and 10 (8.72, 8.71, 8.92 respectively for C, SI and E) demonstrating a moderate environmental impact. The Emergy Sustainability Index (ESI) is the ratio between EYR and ELR. It gives a measure of sustainability but here this index does not discriminate our systems according to their practices.

B- Romania

Table 6: Aggregate emergy flows of the traditional and IMTA system in Romania in 2016 and 2017 to produce 1 kg of products and co-products. Traditional systems refer to a fed (cereal's mixture) polyculture of common carp, bighead carp, silver carp, grass carp and crucian carp in earthen pond and IMTA practices refers to a fed monoculture of common carp connected to a non-fed polyculture of common carp, bighead carp, silver carp, grass carp and crucian carp. Both practices are performed with the same water surface.

Emergy flows (sej.yr^{-1})	**2016**		**2017**	
	Traditional	**IMTA**	**Traditional**	**IMTA**
Nature contribution (I)	*2,06E+13*	*2,45E+13*	*3,29E+13*	*7,28E+13*
Renewable resources (R)	*1,87E+11*	*2,23E+11*	*1,60E+12*	*1,05E+12*
Non-renewable resources (N)	*2,04E+13*	*2,43E+13*	*3,13E+13*	*7,17E+13*
Feedback from the economy (F)	*3,39E+16*	*1,61E+16*	*6,37E+14*	*3,51E+14*
Total materials (M)	*3,39E+16*	*1,61E+16*	*5,30E+14*	*3,51E+14*
Renewable materials (MR)	*6,52E+15*	*3,01E+15*	*7,00E+13*	*4,67E+13*
Non-renewable materials (MN)	*2,73E+16*	*1,31E+16*	*4,60E+14*	*3,05E+14*
Total services (S)	*1,74E+05*	*2,07E+05*	*1,06E+14*	*6,30E+04*
Renewable services (SR)	*2,26E+04*	*2,69E+04*	*6,33E+04*	*1,27E+05*
Non-renewable services (SN)	*1,51E+05*	*1,80E+05*	*4,24E+05*	*8,48E+05*
Total emergy (Y)	*3,39E+16*	*1,61E+16*	*1,05E+15*	*8,54E+14*
% Nature (I)	0.1%	0.2%	3.1%	8.5%
% Materials (M)	99,9%	99,8%	60,4%	41,2%
% Services (S)	0,0%	0,0%	10,1%	35,7%
% Renewable resource	0,9%	0,9%	4,9%	1,4%

Table 6 presents the aggregate emergy flows occurring in the different systems in Romania. In both years, we saw differences in nature contribution between practices. In 2016, nature accounted for 0.1% of the total emergy (Y) under traditional practices and 0.2% under IMTA practices. In 2017, nature accounted for 3.1% under traditional practices and for 8.5% under IMTA practices. In (I), percentage of renewable resources does change according to the practices. It accounts for only 0.9% for the traditional and the IMTA system in 2016 and respectively for 4.9% and 1.4% in 2017. On the contrary, we observed percentage differences between 2016 and 2017 concerning the material needs. Our systems relied entirely on materials in 2016 (almost 100%) and show no significant differences between traditional and IMTA practices. However, we saw differences in 2017 on the use of materials. IMTA practices rely less on materials than traditional practices (41.2% vs 60.4% for the traditional practices). Again, due to the lack of data on economic aspects of the system, we did not highlight the importance of services on Emergy except in 2017 that is explained by the difference in work force (10 times higher in 2017 compared to 2016).

Table 7: Comparisons of the emergy indicators of the traditional and IMTA system in Romania. Traditional systems refer to a fed (cereal's mixture) polyculture of common carp, bighead carp, silver carp, grass carp and crucian carp in earthen pond and IMTA practices refers to a fed monoculture of common carp connected to a non-fed polyculture of common carp, bighead carp, silver carp, grass carp and crucian carp. Both practices are performed with the same water surface.

Emergy indicators	**2016**		**2017**	
	Traditional	**IMTA**	**Traditional**	**IMTA**
Transformity (SeJ/kg)	*3,4E+16*	*1,6E+16*	*5,6E+14*	*4,2E+14*
Transformity (SeJ/J)	*5,1E+09*	*2,4E+09*	*8,8E+07*	*6,6E+07*
% Renewability	*19,25*	*18,71*	*12,72*	*11,25*
Emergy Yield Ratio (EYR)	*1,00*	*1,00*	*1,22*	*1,21*
Emergy Investment Ratio (EIR)	*4,18*	*4,30*	*5,51*	*2,55*
Environmental Loading Ratio (ELR)	*4,20*	*4,35*	*8,35*	*7,89*
Emergy Index of Sustainability (ESI)	*0,24*	*0,23*	*0,15*	*0,15*

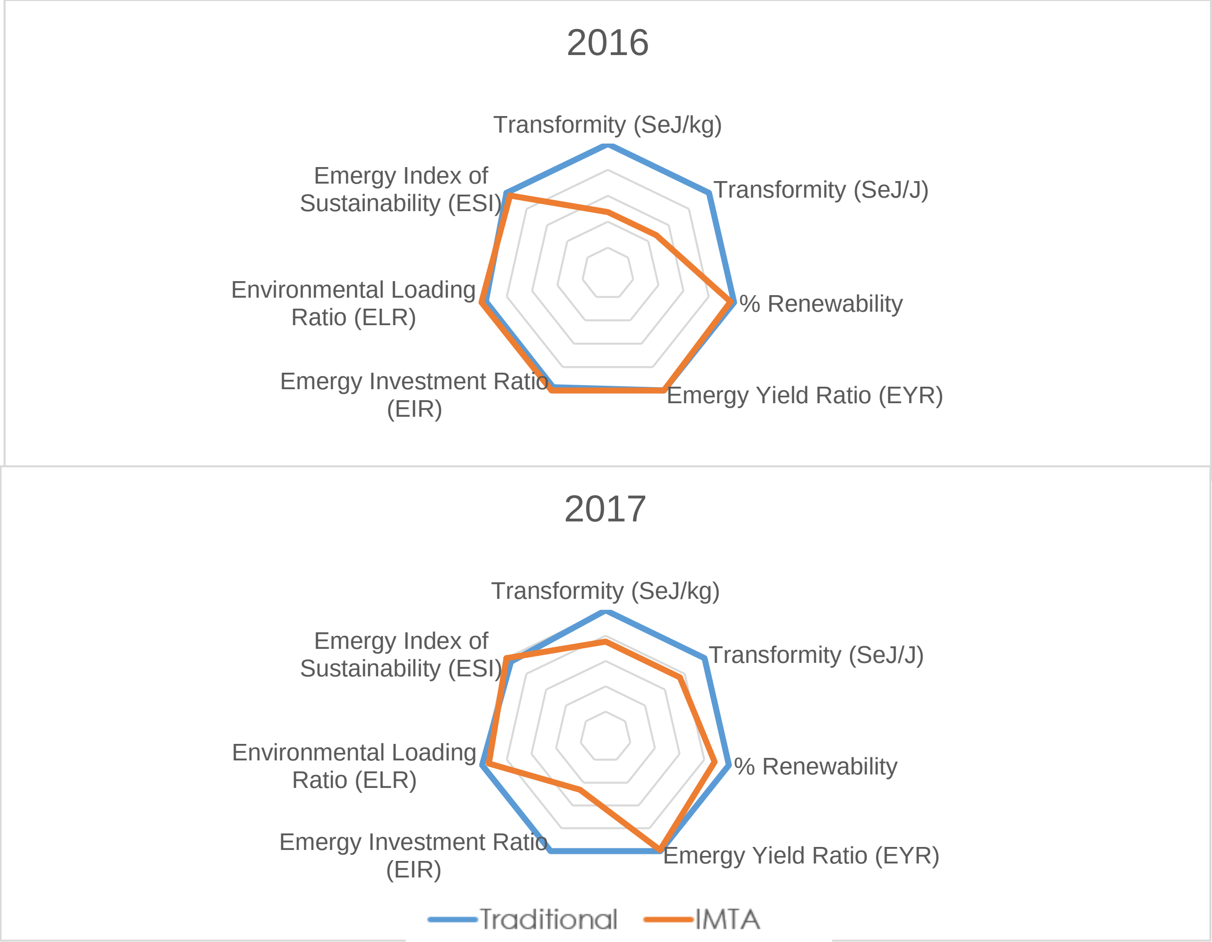

Figure 21*:* Comparison of the emergy indicators for the traditional and the IMTA system in Romania in 2016 and 2017. The system refers to the polyculture of common carp, bighead carp, silver carp, grass carp and crucian carp in earthen pond. For each emergy indicators, the highest value for each indicator is set as 100% and others is compared to it.

Table 7 and figure 21 present the comparison of emergy indicators between the use of traditional and IMTA practices in 2016 and in 2017. In both years, the IMTA practices display the lowest value of transformity in both sej per kg and sej per J. IMTA systems present also the lowest value of percentage of renewability with 18.71% vs 19.25% in 2016 and with 11.25% vs 12.72% in 2017. Like France, differences between systems came mainly from the use of feed displaying here 20% of renewability. An increased use of feed will thus increase the percentage of renewability as the mean percentage of renewable resources without feed is lower than 20%. Concerning the Emergy Yield Ratio, no differences can be observed between the two practices in both years. In 2016, systems show an EYR of 1.00, which is consistent with the percentage of materials in total emergy (almost 100%). In 2017, systems present higher values of EYR (1.21 and 1.22) which is also consistent with the fact that the systems in 2017 rely more on natural resources than those in 2016. Contrasting results are observed between the two years concerning the Emergy Investment Ratio. Indeed, 4.18 sej of economic resources are needed under traditional practices in 2016 for the exploitation of 1sej of natural resource used while 4.30 sej are needed under IMTA practices against 4.18 under traditional practices. On the contrary, in 2017, less sej of economic resources are needed for each sej of natural resource used under IMTA practices compared to traditional practices (5.51 vs 2.55). As a result, IMTA practices show contrasting result but appear to rely less on purchased resources compared to traditional practices especially in 2017. We can explain the absence of effect of IMTA practices compared to traditional practices on EIR in 2016 by the absence of difference in the percentages of renewability. The ELR follow the same pattern with higher value under IMTA practices in 2016 (4.35 vs 4.25) and under traditional practices in 2017 (8.35 vs 7.89), however according to the literature every system here display moderate environmental impact (value comprised between 2 and 10). Concerning the ESI, it does not differ along with practices but the system in 2016 display higher value than those of 2017 (0.23-0.24 vs 0.15).

C- Indonesia

Table 8: Aggregate emergy flows of the traditional and IMTA system in Romania in 2016 and 2017 for 1 kg of products and co-products. The coculture refers to the culture of the giant gourami fed with artificial feed along with the red azolla plants in the same pond in separated compartment with the red azolla plants harvested frequently and used as supplementary feed. The monoculture refers to the culture of giant gourami supplied with artificial feed. Each system comprises the culture of the giant taro plants on the banks of the pond.

Emergy flows (sej.yr^{-1})	**Coculture**	**Monoculture**
Nature contribution (I)	*3,31E+12*	*2,21E+12*
Renewable resources (R)	*1,33E+11*	*1,26E+11*
Non-renewable resources (N)	*3,18E+12*	*2,08E+12*
Feedback from the economy (F)	*9,45E+15*	*9,59E+15*
Total materials (M)	*9,45E+15*	*9,59E+15*
Renewable materials (MR)	*4,75E+14*	*4,88E+14*
Non-renewable materials (MN)	*8,97E+15*	*9,10E+15*
Total services (S)	*2,12E+05*	*3,44E+05*
Renewable services (SR)	*2,75E+04*	*4,47E+04*
Non-renewable services (SN)	*1,84E+05*	*2,99E+05*
Total emergy (Y)	*9,45E+15*	*9,59E+15*
Nature contribution (I)	0,04%	0,02%
Total materials (M)	99,96%	99,98%
Total services (S)	0,00%	0,00%
% renewable resource use	4,03%	5,72%

Table 8 presents the aggregate emergy flows occurring in the mono and the coculture in Indonesia. The coculture rely more on natural resources (0.04% vs 0.02%) even if this percentage remain negligible in the total emergy Y and thus demonstrating that our systems mainly rely on another source of emergy. In (I), the percentages of renewable resources used differ among practices with 4.03% for the coculture and 5.72% for the monoculture. Again, we can explain this difference by a small percentage of renewable resources in the components of the systems compared to the one of the feeds that is used in higher quantity in the monoculture.

The mono and coculture rely almost entirely on purchased materials (~100%) and services relying solely on working force do not represent an important part of our systems and account for around 0% of the total emergy Y.

Table 9: Comparisons of the emergy indicators of the coculture of giant gourami along with the red azolla and the monoculture of giant gourami in Indonesia. The coculture refers to the culture of the giant gourami fed with artificial feed along with the red azolla plants in the same pond in separated compartment with the red azolla plants harvested frequently and used as supplementary feed. The monoculture refers to the culture of giant gourami supplied with artificial feed. Each system comprises the culture of the giant taro plants on the banks of the pond.

Emergy indicators	Coculture	Monoculture
Transformity (SeJ/kg)	*3,7E+15*	*9,60E+15*
Transformity (SeJ/J)	*2,8E+08*	*1,50E+09*
% Renewability	*5,02*	*5,09*
Emergy Yield Ratio (EYR)	*1,00*	*1,00*
Emergy Investment Ratio (EIR)	*18.78*	*18,57*
Environmental Loading Ratio (ELR)	*18.91*	*18,65*
Emergy Index of Sustainability (ESI)	*0,05*	*0,05*

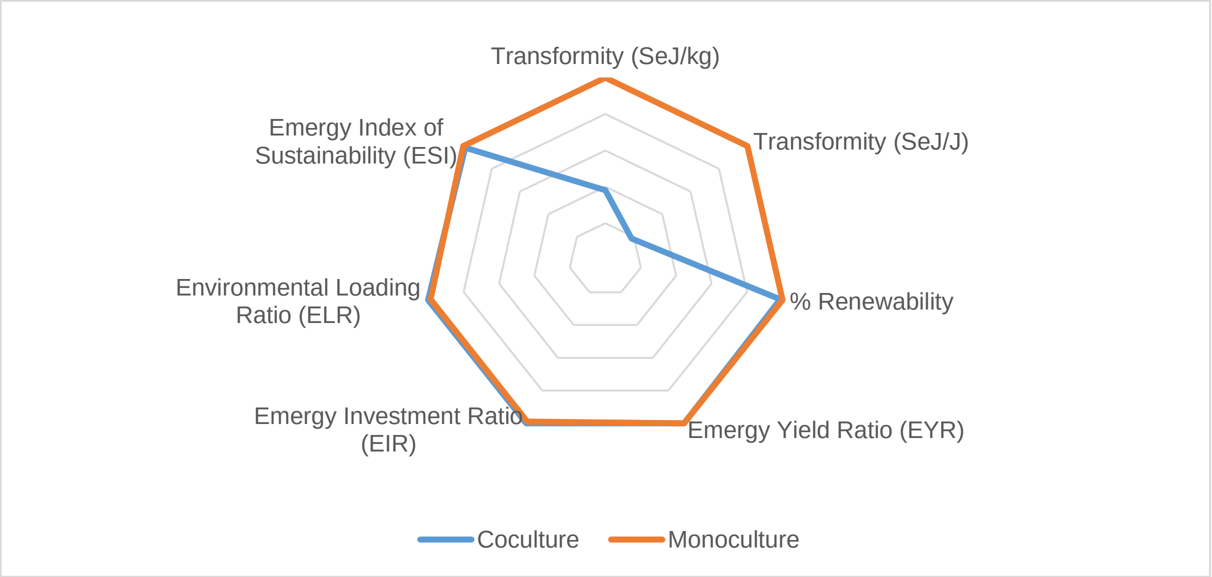

Figure 22: Comparison of the emergy indicators for the traditional and the IMTA system in Romania in (A) 2016 and (B) 2017. For each emergy indicators, the highest value for each indicator is set as 100% and others is compared to it.

Table 9 and figure 22 present the comparison of emergy indicators between the coculture of giant gourami along with the red azolla and the monoculture of giant gourami in Indonesia in hypothetical farms based on the survey of several farms. The coculture and the monoculture display different values of transformity (in sej per kg and in sej per J) with higher value for the monoculture compared to the monoculture. Moreover, this difference is increased with the use of the transformity in sej per J. Using the red azolla as feed and as co-products [2]increase the total production (Giant gourami + red azolla) compared to the monoculture that produce only giant gourami and use more feed in proportion. Both systems display low level of renewable resources compared to previously with percentages around 5% (5.02% and 5.09% for the co and the monoculture). The coculture and the monoculture have an EYR of 1 which is consistent with the dependence of our system on purchased materials (almost 100%). Concerning the EIR, the coculture display similar value of EIR (18.78 and 18.57) which means that for each sej of natural resource use the coculture and the monoculture need ~19 sej of economic resources. The coculture display also similar value for the ELR with 18.91 for the coculture and 18.65 for the monoculture, which means that both systems display high environmental impact. The values of EIR and ELR were here very high compared to the literature, which can be explained by the lack of data on several homemade processes and the fact that farmers rely on important quantity of fertilizers (mixture of rice bran and poultry manure) and artificial feed with 30% of combined fishmeal and fish oil. Consequently, the ESI of the monoculture and the coculture are very low (0.05 ad 0.03, respectively).

V- Discussion

A wide range of studies demonstrate that feed is a key driver for climate change, acidification, energy demand and the net primary production use while farming process is a key driver of eutrophication and water dependence (Aubin *et al.*, 2009, 2006; Bohnes *et al.*, 2018; d'Orbcastel *et al.*, 2009; Wilfart *et al.*, 2013). In fact, feed can also be considered as a key driver for eutrophication as pollutant wastes of fish are also linked to the type of feed with nitrogen and phosphorus emissions from uneaten feed and fish faeces. This result is consistent with the potential eutrophication of water linked to the "extensive" production in France (figure 9) Indeed, this practice do not use feed but rely solely on the natural production of the pond and it appears that the potential eutrophication is negative under such circumstances reinforcing the idea that feed is a key driver of this impact. Thus, FCR may be a major cause of this result. In our cases, IMTA practices lead to lower apparent FCRs compared to "classical" ones except for the French case. Consequently, it appears that adding a planted lagoon will not enhance the apparent FCR of fish. Indeed, we can state that the FCR of feed is the same between treatments (the formulated feed is entirely consumed) but the presence of other food sources can explain the apparent FCR in each treatment. The planted lagoon can induce the sequestration of nutrients, which consequently are not available to fish juveniles reducing their overall growth performance compared to the semi-intensive treatment. Conversely, separating the pond into two compartments (Romanian and Indonesian case) with one dedicated to the fish production and the other one that is supposed to benefit from the waste emissions of the first reduces the apparent FCR of fish and therefore reduces local impacts such as the potential eutrophication of surrounding water and acidification. IMTA practices in Romania seems even to induce a decrease in the potential eutrophication of water compared to the initial status of the pond (before fish stocking). Different levels of eutrophication have been observed through the entire study as well as the relative contribution of "feed" and "farm functioning". This is mostly due to the quality and quantity of feed used. Indeed, feed impacts mainly stem from the production of the raw materials and specifically through the use of fishmeal and fish oil because of intensive fuel use of fisheries vessels or low efficiency of processing plants (Fréon *et al.*, 2017). In addition, the impacts related to the consumption of feed (carried by the "farm functioning" category) are also related to the quality and quantity of feed. Feed are formulated in a way to minimize the FCR with increased digestibility and/or appetency and therefore are likely to induce less pollutants waste emissions compared to "less processed feed" such as cereal's mixture for example. Indeed, we observe this trend through our study cases for instance with Romania which have a homemade processed feed and an FCR of up to 3.94 (traditional practices in 2017) and thus display a high contribution of "farm functioning" per kg as well as per m^2. In Romania, farmers used cereal's mixture homemade processed (1/3 wheat, 1/3 corn, 1/3 sunflower in 2016 and 60% sunflower and 40% corn in 2017) while France and Indonesia used formulated feed with 16% and 23% of fishmeal and fish oil, respectively. Nevertheless, investigating the influence of the quality of feed is quite complicated here as the same mass balance model for fish digestibility have been used for all systems, the impact linked to the quality of feed are thus only observed through the FCR values and the relative contribution of "farm functioning". Specific values of digestibility for each feed and its related species must be assessed to identify accurately the amount of waste pollutants emissions in the mass balance calculation.

The feed is also deeply involved in the Net Primary Production Use (NPPU) impact as it has been demonstrated as one of the main components of this impact (Aubin *et al.*, 2009, 2006; d'Orbcastel *et al.*, 2009). This is consistent with our results demonstrating that mainly two components are involved in the NPPU: the juvenile production and the production of feed. In fact, the nature of feed strongly influence this impact and especially the use of marine-based ingredients with high value of NPPU (Papatryphon *et al.*, 2004). This can explain higher value of NPPU for France and Indonesia (between 2 and 20 $kgC.kg^{-1}$) compared to Romania. Indeed, Indonesia displays the highest percentage of marine-based ingredients (23%) followed by France (16%) and Romania (0%) and this trend is visible through the NPPU impact values for the different system. In fact, IMTA practices lead to a decrease in the use of feed probably by a better use of feed by the system and therefore a decrease in needed quantity to fishes.

The relevance of feed in the aquaculture overall impact is well known by stakeholders and potential solutions are still under study. For instance, other way of producing feed are explored especially with the use of insects or plants but the risk is to generate environmental burden shifting. In other words this type of feed induce also several impacts which may be different from classical feed with for instance an increase in the land use and aquatic eutrophication or climate change impacts (e.g. agricultural processes, toxic impacts with the use of pesticides or high protein diets for insects) (Le Feon *et al.*, 2018). In this context, it appears mandatory to perform comprehensive studies to assess the environmental trade-offs between crop-based and marine-based ingredients for instance with coverage of a large spectrum of environmental impacts to detect burden shifting (Bohnes & Laurent, 2019).

Concerning global impact such as the potential global warming, IMTA practices display contrasted results according to the nature of the practices investigated. Indeed, in France we investigated the addition of a planted lagoon connected to the fishpond. Thus, in this case we increased the water surface needed by the farm enhancing the fixation of CO_2 and the emission of CH_4 that are demonstrated with the contribution of the "farm functioning" in the total climate change impact which is higher compared to the semi-intensive practices (figure 9). However, we may underestimate the influence of the lagoon due to the lack of data on its production. In Romania and in Indonesia, we investigated the separation of the pond into two compartments thus the water surface needed is the same for both practices (traditional/IMTA and monoculture/coculture). The addition of a Chinese carp polyculture bounded to the production pond reduce the overall impact but the absence of differences in the relative contribution makes any conclusion complicated. It may be partially explained by the better yield under IMTA practices (except for 2016) which is consistent with the fact that IMTA practices in 2016 present higher impact than traditional practices per kilogramme but not per surface. In fact, we observed that only contributions of feed diminish under IMTA practices even in 2016 and this is mostly due to the decrease in feed utilization and a better use of it. For the Indonesian case, the red Azolla were cultured for mainly animal feed uses (for the giant gourami) and selling purposes. Consequently, the addition of Azolla reduces also the amount of feed use and enhance its utilization as it has been demonstrated above in Romania.

The water dependence is an impact category designed specifically for aquaculture environmental impact assessment. It corresponds to the water flowing into the production system and can reflect the intensiveness of the production (Aubin *et al.*, 2009). In our study cases, IMTA systems use less water than traditional system to produce 1 kilogramme of product (except for Romania for the same reasons as above) but usually consume more water per square meter. In other words, our IMTA system water needs are higher than those of traditional system but IMTA use more efficiently water for rearing fishes.

The EA method is a method based on global ecological considerations, which put the emphasis on renewable and non-renewable aspects of sustainability; it gives the opportunity to assess hidden environmental costs and intrinsic sustainability. In this study, IMTA practices display similar percentages of renewability and Emergy Yield Ratio compared to traditional practices that is explained be the lack of differences between practices, particularly in terms of infrastructures and equipment (table 6, 8, 10). However, IMTA practices does present different Emergy Loading and Investment Ratio (ELR and EIR) compared to classical practices. The Emergy Loading Ratio can be considered as a measure of the environmental impact and demonstrate here that IMTA practices lead to a decrease in overall impact which is consistent with the LCA results. Moreover, EA demonstrated that IMTA practices lead to a better use of resources with lower EIR compared to "traditional" practices except in 2016 in Romania that can be mainly explained by the low yield and the water surface for the latter. Indeed, IMTA system in Romania in 2016 display lower yield and higher water surface compared to traditional practices increasing the impact per kg of fish produced and consequently the EIR which represent the ability of the system to use local resources. However, EA mainly discriminate IMTA systems by their ability to use local and natural resources and despite LCA results for France and the lack of data on the planted lagoon the EA results show a better ability of the coupled system to use resources compared to "classical" practices (lowest EIR). Thus, it demonstrates the relevance of performing Emergy Accounting to assess IMTA systems and to highlight underlying natural processes favoured by IMTA practices. Moreover, IMTA systems display lower transformities compared to traditional system that means that less energy is necessary to produce 1 kilogramme of product or 1 joule. Thus, the EA methodology is particularly suitable for IMTA systems as one of the main aims underlying those systems is to better use resources and to fit better with the carrying capacity of its environment. Moreover, this methodology is suitable with the inclusion of ecosystem services through the Emergy Loading Ratio which are not consider by LCA (Brown & Ulgiati, 2004).

LCA and Emergy accounting procedures are based on the same two first steps which are the definition of the goal and scope of the study as well as the system boundaries and to create an inventory of input/output data (Wilfart *et al.*, 2013). In fact, Emergy accounting (EA) includes also the energy flows from nature and permit to provide indicators such as transformities based on life-cycle inventories. Moreover, units used in the life-cycle inventories (kg, t, j, ha, etc.) can be supported by the Emergy accounting methodology. In fact, the combination of the two methods permit to the practitioners a broader view of the benefits and impacts of a system on its environment (Wilfart *et al.*, 2013).

The use of biomass as functional unit present several issues. It mostly benefits to farms that present important yield. In fact, when mass based LCA is performed it calculates each impact to produce one unit of biomass (kg, t, etc.). As a result, it appears relevant to compare systems with the same stocking density differing only by their type (recirculated, inland-based farms, marine sea cages, etc…) and their practices. Thus, the definition of the objectives of the system is a critical step, as it will orientate the consecutive steps. Depending on the problematic under study, it is mandatory to disentangle whether the system is performed to produce fish biomass, to provide calories or to use the landscape for instance. Each functional unit will provide answer to their own linked issues. Production with important yields will benefit from the use of biomass as functional unit and production with low yields will be disadvantaged. We observe this trend with the French case between the semi-intensive and the extensive practices. As the extensive practices present the lowest stocking density and yield, it leads to the highest impact per kg of fish produced. However, when using the surface of the fish farm as functional unit it appears that the extensive practices have the lowest impact per m^2 and the semi-intensive the highest. For instance, in France, it may be relevant to assess environmental impact by using the surface as functional unit, particularly for productions made by multi-asset operators trying to use their surface more efficiently and in the most environmentally friendly way. The use of calories as functional unit may be also relevant when comparing species assemblages to highlight the benefit of producing multiple species with different quantity of calories per kilogramme or even compare two monocultures of two different species. The relevance of the functional unit is even more important for studying IMTA systems as their statements lay on rearing multiple species in integrated compartments and in the most environmentally friendly way thus involving multiple objectives ranging from biomass production, nutrient recycling, and provision of ecosystem services to the use of surface. Consequently, the decisions and assumptions made by LCA practitioners about system boundaries and life cycle inventories may lead to biased comparisons and misunderstanding of the impacts and benefits linked to the production.

The inclusion of post farming stages such as processing, distribution, consumption and end-of-life are extremely scarce (Abdou *et al.*, 2017). It can be explained by the lack of available data for modelling such stages as seafood farmers usually in contact with LCA practitioners often know a little about processes occurring after farm gate and about the distribution webs. In our study cases, the main aim was to provide evidences and solutions to producers for the development of environmentally friendly and robust aquaculture using IMTA systems. However, to better apprehend consequences of IMTA practices and to draw the most accurate picture of this kind of systems it will be relevant to includes post farm processes (Henriksson *et al.*, 2012). Such analysis induces documentation and the creation of data on processes and objects involved in these steps. Specific processes occurring in aquaculture are problematic as their potential high complexity in term of number of components and variety of materials increase the difficulty of modelling for LCA practitioners (e.g. water filtration in recirculated system). Moreover, the accessibility of precise description of processes can be limited because of industrial secret leading to withholding information.

VI- Conclusion:

This study tried to highlight the relative importance of management practices in the environmental impact of integrated multi-trophic aquaculture (IMTA) for three different systems by using two complementary environmental assessment methods. Overall, IMTA practices lead to lower environmental impact especially for local impact such as the potential eutrophication of water compared to classical practices (semi-intensive in France, traditional practices in Romania and the monoculture in Indonesia). Feed is one of the main causes of environmental impacts through its production and its use. A wide range of studies explored other way of producing feed with the use of insects or plants. It appears through our results that IMTA practices solely can lead to a better use of resources and can reduce the overall impact of the production. However, to fully comprehend the consequences of IMTA practices, further studies need to be performed on species interactions and trophic exchange in the food web. Moreover, IMTA covers a broad spectrum of practices based on the complementarity of productive compartments and applies to many groups of species inhabiting different ecological niches. The combination of the life cycle assessment and the emergy accounting methodology permit a global approach of the environmental impact by the inclusion of all processes involved in the life cycle of a product as well as the contribution of nature in the production and the system ability to fit with its environment. For future studies, it would be relevant to complete such analysis with more social and economic aspects to go towards more sustainable practices.

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ENVIRONMENTAL IMPACT ASSESSMENT OF FRESHWATER POLYCULTURE: BALANCE BETWEEN PRODUCTIVITY AND RESOURCES MOBILIZATION

This study tried to highlight the relative importance of management practices in the environmental impact of integrated multi-trophic aquaculture (IMTA) for three different type of system in France, Romania and Indonesia by using two complementary environmental assessment methods: The Life Cycle Assessment and Emergy Accounting. IMTA practices are based on the combination of complementary species with different trophic and living habits enhancing the ability of the system to use resources (feed and other food sources). The results demonstrate that IMTA practices induce a decrease in the overall impact; particularly local impacts such as the potential eutrophication of water through a better use of resources especially the feed. Independently of the practices used, feed remain the major contributor to the environmental impact of an aquaculture production. In Romania we demonstrated that adding a Chinese carps polyculture bounded to a fed common carp monoculture reduce the overall impact compared to conventional fed Chinese carp polyculture through a better resource use. In France, we investigated the addition of a planted lagoon to the fishpond. Results showed that this practice reduced the impact per square meter but the lack of data on plant production might lead to an underestimation of the benefits of the lagoon. In Indonesia, we investigated the coculture of the giant gourami and the red azolla. According to our results, the coculture allows the reduction of feed use and a decreased potential eutrophication. The combination of the life cycle assessment and the emergy accounting methodology permit a global approach of the environmental impact by the inclusion of all processes involved in the life cycle of a product as well as the contribution of nature in the production and the ability of the system to fit with its environment. For future studies, it would be relevant to complete such analysis with more social and economic aspects to go towards more sustainable practices.

EVALUATION ENVIRONNEMENTALE DE POLYCULTURE D’EAU DOUCE : EQUILIBRE ENTRE PRODUCTIVITE ET MOBILISATION DES RESSOURCES

Cette étude a tenté de montrer l’importance relative des pratiques de gestion en aquaculture sur les impacts environnementaux associés à des systèmes d’aquaculture trophique intégré (AMTI) en France, Roumanie et Indonésie en utilisant deux méthodes complémentaires d’analyse environnementale : l’Analyse de Cycle de Vie et l’Emergy. Les pratiques AMTI sont des pratiques basées sur la combinaison d’espèces complémentaires par leurs habitudes alimentaires et leurs niches écologiques dans le but d’améliorer la capacité du système à utiliser la ressource (Aliment ou tout autre source de nourriture). Les résultats ont montré que ces pratiques induisent une diminution de l’impact total, et plus particulièrement des impacts locaux tels que le potentiel d’eutrophisation notamment au travers d’une meilleure utilisation des ressources et plus spécifiquement de l’aliment par rapport à des pratiques conventionnelles. Indépendamment des pratiques utilisées, l’aliment reste un des contributeurs majeurs aux impacts environnementaux liés aux productions aquacoles. En Roumanie, nous avons pu montrer que l’ajout d’une polyculture de carpes chinoises non nourris à une monoculture de carpe commune nourrie entraine la diminution des impacts par une meilleure utilisation des ressources comparé à une polyculture de carpes chinoises nourries. En France, nous nous sommes intéressés à l’ajout d’une lagune planté à une polyculture de carpe commune, perche et gardon nourris. Les résultats ont montré une réduction des impacts au mètre carré mais le manque de données sur la production de plantes de la lagune peut mener à une sous-estimation des bénéfices liés à celle-ci. En Indonésie, nous avons étudié la coculture du Gourami géant avec l’Azolla fausse-fougère. Les résultats ont montré que la coculture permet d’abord la réduction de l’utilisation de nourriture artificielle remplacée en partie par l’Azolla mais également une réduction du potentiel d’eutrophisation. La combinaison de l’analyse de cycle de vie et de l’emergy permet une approche globale des impacts environnementaux en incluant tous les procédés impliqués dans le cycle de vie d’un produit ainsi que la contribution de la nature et la capacité du système à s’intégrer dans son environnement. Pour des études futures, il serait intéressant de compléter ce type d’analyse avec des aspects socio-économique dans le but de développer des pratiques toujours plus durables.

Annexe 1

Feed formulations and origin

Table 1: Proportions and origin of the ingredients of the feed used in the polyculture of common carp, perch and roach in France under coupled and intensive practices.

Ingredients	Proportions	Origin
Wheat flour	34 %	France
Soybean meal 48	25 %	Brasil
Rape meal	17 %	France
Fish meal	10 %	Perou
Fish meal	6 %	Perou
Soybean meal 50	4 %	Brasil
Monocalcium Phosphate	2 %	France
Lysine / Methionine	1 %	France
Additif Premix	1 %	France

Table 2: Proportions and origin of the ingredients of the feed used in the polyculture of common carp, bighead carp, grass carp, silver carp and crucian carp under traditional and IMTA practices in 2016.

Ingredients	Proportions	Origin
Wheat flour	33%	Local
Corn meal	33%	Local
Sunflower meal	33%	Local

Table 3: Proportions and origin of the ingredients of the feed used in the polyculture of common carp, bighead carp, grass carp, silver carp and crucian carp under traditional and IMTA practices in 2017.

Ingredients	Proportions	Origin
Corn meal	40%	Local
Sunflower meal	60%	Local

Table 4: Proportions and origin of the ingredients of the feed used in the mono- and coculture of the giant gourami along with the red azolla in Indonesia.

Ingredients	Proportions	Origin
Fish meal	10.0%	Chili
Fish meal	11.0%	East Java
Soybean meal 48	15.0%	Argentina
Meat and bone meal	10.0%	Australia
Wheat bran	20.5%	Australia
Rice bran	25.0%	West Java
Fish oil	2.0%	East Java
Plant oil (palm)	2.5%	West Java
Choline chloride	0.5%	China
Premix vitamin	2.0%	China
Premix mineral	1.2%	China
BHT	0.3%	Central Java

Annexe 2

Compositions of the aquatic products and feeds used in the mass balance

Table 1: Compositions of the aquatic products in Indonesia for the mono- and the coculture used in the mass balance calculation. Percentages are based on the dry weight.

Composition	Stocked fish	Harvested fish (monoculture)	Harvested fish (coculture)	Red azolla
Protein	54.2%	60.29%	58.41%	20.29%
Lipids	13.7%	23.40%	25.09%	1.76%
Carbohydrates	9.7%	0.91%	1.08%	50.89%
Ash	15.7%	14.61%	14.67%	11.49%
Fiber	6.0%	0.80%	0.76%	15.58%
Phosphorous	0.2%	0.16%	0.20%	0.02%
Humidity	70.8%	68.63%	68.70%	92.06%

Table 2: Percentages of protein, phosphorous and dry matter of the species for the polyculture of common carp, roach and perch in France in 2017 and for the polyculture of common carp, bighead carp, silver carp, grass carp and crucian carp in Romania in 2016 and in 2017.

Species	Protein (%FW)	Phosphorous (%FW)	Dry matter (%)
Common carp	13.9%	0.48%	26.78%
Grass carp	16.3%	0.61%	25.80%
Silver carp	16.3%	0.61%	25.80%
Bighead carp	17.0%	0.91%	22.48%
Crucian carp	16.3%	0.61%	22.48%
Roach	17.7%	0.92%	22.48%
Perch	17.0%	1.02%	22.48%

Table 3: Composition of the feeds used in the polyculture of common carp, perch and roach in France, in the polyculture of common carp, bighead carp, silver carp, grass carp and crucian carp in Romania and in the mon- and coculture of the giant gourami along with the red azolla in Indonesia.

Composition	Feed France	Feed Romania	Feed Indonesia
Protein	34.7%	19.10%	32.72%
Lipids	8.6%	2.33%	5.29%
Carbohydrates	21.9%	49.46%	47.29%
Ash	15.29%	18.88%	10.01%
Fiber	7.76%	5.20%	4.70%
Phosphorous	1.48%	0.70%	1.35%
Humidity	10.33%	11.33%	7.95%