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Life cycle assessment of fish and prawn production: Comparison of monoculture and polyculture freshwater systems in Brazil

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ABSTRACT

This study applied life cycle assessment (LCA) to evaluate and compare environmental impacts of monoculture and polyculture systems in freshwater ponds. Two omnivorous native Brazilian species were used: the fish tambaqui (*Colossoma macropomum*) and the Amazon River prawn (*Macrobrachium amazonicum*). Four semi-intensive aquaculture systems (at an experimental level) were established and studied: monoculture of *C. macropomum* (MM), monoculture of *M. amazonicum* (MA), polyculture in which both species were free in the pond (PF), and polyculture in which *C. macropomum* was reared in a hapa cage and *M. amazonicum* was free in the pond (PH). The MM, PF and PH systems were fed fish feed, while MA was fed shrimp feed. Water was not renewed, but added only to replace losses from evaporation and seepage. Seven impact categories were analyzed: climate change, eutrophication, cumulative energy demand, land occupation, acidification, net primary production use and water dependence. Potential impacts of 1 kg of animal biomass produced by the systems were calculated, as was uncertainty in predictions based on uncertainty in data for the systems. Environmental impacts of each species in the polyculture systems were estimated using system expansion and different allocation approach: mass, energy and economic. PF and MM had the lowest impacts in all impact categories, while MA had the highest. When economic allocation was used, PF had lower impacts than MM per kg of *C. macropomum*. The rearing stage itself was the main contributor to eutrophication, land occupation and water dependence. However, feed was the main contributor to acidification and net primary production use in all systems. Only for PH was feed not the most significant contributor to climate change. Productivity and feed conversation ratio were key factors that defined the most efficient system from an environmental viewpoint. Our study demonstrated the advantage of rearing *M. amazonicum* in a polyculture instead of a monoculture, while no difference was found for *C. macropomum*. Changing the allocation approach revealed that aquaculture of *M. amazonicum* has lower impacts when the species is reared in polyculture systems. Moreover, aquaculture of native species remains in the early stages, and further development of its production chain may decrease its environmental impacts.

1. Introduction

Fed aquaculture is increasingly used to produce high-value fish and crustacean species (FAO, 2014). However, its nutrient efficiency remains moderate, since only 30% of the total nitrogen (N) and phosphorus (P) delivered to the system is recovered in biomass (Boyd and Tucker, 1998). The discharge of enriched effluents from aquaculture sites causes environmental pollution and degradation in the receiving water bodies (Boaventura et al., 1997; Jegatheesan et al., 2011). In addition to the discharge, the spread of diseases and escape of farmed species can affect local biodiversity; these impacts are amplified in the case of non-native species (Diana, 2009; Naylor et al., 2000). Domestication of native species and improvements in aquaculture production systems are important steps to achieve sustainable development, especially from an environmental viewpoint. From this perspective, domestication of native species in Brazil is important because the country is a hotspot of biodiversity

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and has a growing aquaculture sector.

Production by Brazilian aquaculture increased by 8.5% from 2013 to 2014 reaching 561 kt (IBGE, 2014). According to the FAO (2016), it ranked 2nd and 14th in Latin American and global aquaculture production, respectively. Brazil has placed special focus on rearing native species. In particular, the fish *Colossoma macropomum*, the second most produced species in Brazil, is responsible for nearly 25% of all national aquaculture production (IBGE, 2014). Domestication of native Brazilian species, however, remains at an early stage. For instance, the freshwater prawn *Macrobrachium amazonicum* has only small-scale regional production, despite its potential for aquaculture (Moraes-Valenti and Valenti, 2010) and many research studies of its production stages (de Araujo and Valenti, 2007; Maciel and Valenti, 2009).

The focus of this study was to explore the relevance of improving production system efficiency by combining the aquaculture of two species. In polyculture, nutrients not used by one species can be used by the other, and in some cases the presence of one species increases the productivity of the other (Joyni et al., 2011; Wahab et al., 2011). In addition to improvements in nutrient use, the additional product at the end of the cycle provides an economic benefit (Kadir et al., 2007; Whitmarsh et al., 2006). Nevertheless, environmental efficiency of a production system does not rely only on the nutrients retained as biomass; pollutant emissions and fate, and consumption of resources at different stages of the production system, should also be considered.

Life cycle assessment (LCA), an important tool for estimating environmental impacts and identifying their sources (ISO, 2006a, b), has been used to analyze aquaculture production systems around the world (Aubin et al., 2015; Cao et al., 2011; Dekamin et al., 2015; Huysveld et al., 2013; Pelletier and Tyedmers, 2010; Santos et al., 2015). However, to our knowledge, LCA has been applied only once to polyculture systems (Aubin et al., 2015) and rarely to integrated aquaculture and agriculture systems (Efole Ewoukem et al., 2012; Phong et al., 2011), since most LCA studies evaluate monoculture systems. One advantage of LCA is that it allows different products or systems to be compared using the same functional unit. Decisions and assumptions made by LCA practitioners about system boundaries and life cycle inventories, however, may lead to biased comparisons.

To quantify life cycle inventories, most aquaculture LCA studies in the literature used data from commercial units (Dekamin et al., 2015; Jerbi et al., 2012; Pelletier and Tyedmers, 2010), while some relied on questionnaires (Aubin et al., 2015; Bosma et al., 2011) and others designed hypothetical farms based on literature data (Santos et al., 2015). In this study, we performed LCA with data collected during an experiment. The small scale of the experimental units allows better control of system inputs and outputs, and facilitates replication of production scenarios to better understand the influence of controlled factors on system performance.

To determine nutrient fate, the modeling approach designed in this study included emissions to the water and soil, commonly considered in aquaculture LCAs, and added emissions to the air. Although studies have identified gas emissions from aquaculture systems (Gross et al., 2000; Lorenzen et al., 1997), only a few have discussed their importance, especially that of methane, in LCA impact categories in aquaculture systems (Aubin et al., 2015; Phong et al., 2011).

Henriksson et al. (2012) highlight the poor data quality in certain aquaculture LCA studies. Different approaches, such as determining uncertainty, have been developed to increase the level of confidence in LCA inventories (Ciroth et al., 2013; Henriksson et al., 2014); however, uncertainty in input data is often ignored in published studies. Moreover, approaches for allocating environmental impacts of multi-output systems remain under debate. In our study, robustness of the results is considered using estimates of the uncertainty in and their sensitivity to different approaches for allocating impacts among species produced by polyculture systems. The overall aim of this study is to compare the environmental performance of monoculture and polyculture of *C. macropomum* and *M. amazonicum,* based on experimental results, to highlight challenges of developing multi-species aquaculture.

2. Material and methods

Environmental impacts of the aquaculture rearing systems were estimated using LCA in accordance with ISO standards (ISO, 2006a, b).

2.1. Goal and scope

The goal of this LCA study was to estimate and compare environmental impacts of polyculture and monoculture rearing systems of two native Brazilian species. The functional unit was 1 kg of animal biomass (liveweight), and fish and prawn were considered a single output in polyculture systems. This study is based on experimental results designed to compare the efficiency of *M. amazonicum* and *C. macropomum* monocultures and polycultures. When allocation was applied to the polyculture systems, outputs were 1 kg of fish or prawn separately (see section 2.5 Coproduct handling approaches).

The system boundaries used in this study were from "cradle to farm gate" (Fig. 1). The inputs considered for the farm production stage were feed, stocking animals, equipment, infrastructure (ponds and buildings), transport, electricity and water. Emissions to the soil, water and air from the experimental ponds were included. A similar approach was applied to the previous stages of fish fry and prawn post-larvae (pl) production.

2.2. Experimental aquaculture systems

The experiment was conducted at the Freshwater Prawn Sector of the Aquaculture Center of UNESP (CAUNESP) in Jaboticabal, São Paulo, Brazil (21°15′18″S; 48°19′19″W). Twelve earthen ponds with an area of 110–170 m^2 and depth of 0.85–1.19 m were used during 170 days in the warm season (November 2013 to April 2014). No liming, fertilization or water renewals were performed. Water was added to replace loss from evaporation and seepage. Aeration was provided to all ponds from the third month onwards from 1:30–5:30 a.m. in periods of 60:30 min (on:off); in total, propeller aerators were used for 399 h.

Four systems with three replicates each were tested: I) monoculture of *C. macropomum* (MM), II) monoculture of *M. amazonicum* (MA), III) polyculture of *C. macropomum* and *M. amazonicum* in which both species were free in the pond (PF) and IV) polyculture of *C. macropomum* and *M. amazonicum* in which the fish were reared inside a hapa (4 m^3 net cages) and the prawn were free in the pond (PH). Hapas are net cages, supported by wood, metal or bamboo poles, commonly used to separate individuals of different species or size in the same pond. The PH system was created to keep fish from eating prawns. In the polyculture systems (PH and PF), prawn pl were stocked one week before fish fry were stocked. Since the prawn pl were produced in the experimental CAUNESP hatchery in Jaboticabal, no transport was required. The fish fry came from a commercial farm located in Presidente Figueiredo, Amazonas, Brazil, and the delivery included transport by air and road. Initial mean prawn pl weight and stocking density were 0.038 g and 30 pl m^{-2}, respectively, in the MA, PF and PH systems. Initial mean fish fry weight was 1.77 g, and the stocking density was 3 fry$\cdot m^{-2}$ in the MM and PF systems.