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Life Cycle Assessment for environmentally sustainable aquaculture management: a case study of combined aquaculture systems for carp and tilapia

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ABSTRACT

Life Cycle Assessment (LCA) was applied to evaluate the potential environmental impacts associated with two-net cage aquaculture systems of common carp (*Cyprinus carpio carpio*) and tilapia (*Oreochromis niloticus*) in the Cirata reservoir, Indonesia. The studied system included fingerling production in hatcheries, fish rearing in cages, and transport of fry and feed as well as that of harvested fish to markets. The environmental impact indicators were calculated based on the annual production in 2006–2007 using the CML2 Baseline 2000 method, and expressed per tonne of fresh fish delivered to the market. The rearing performances and the environmental efficiency of the system were highly dependent on the lake water quality. Therefore the location of the cages and associated practices influenced the environmental impacts. Feed was identified as the major contributor to land occupation, primary production use, acidification, climate change, energy use and water dependence. Those impacts were mainly linked to the production of fishmeal followed by the production of crop-based feed materials and the production of electricity for feed processing. Eutrophication was mainly the consequence of the fish growing stage and linked closely to nutrient loading from cages. Better feeding practices to reduce feed conversion ratio (FCR), as well as improvement of feed composition by using less fishmeal and more local plant-based materials along with improving energy efficiency of feed production processing should be implemented to improve the environmental profiles of carp and tilapia production. The reduction of FCR from 2.1 to 1.7 could decrease eutrophication by about 22%. However, it is of first priority to reduce the number of cages in order to improve the water quality of the reservoir. The comparison of Cirata reservoir fish culture to other sources of animal protein revealed that it generated average energy use but high eutrophication level. LCA was demonstrated to be a useful tool for decision-making when targeting improved environmental sustainability of cage aquaculture.

1. Introduction

Indonesia is the 4th aquaculture producer in the world, with 1.7 M tonnes in 2008, and the production increase reaches 10% per year (FAO, 2010). Fish is a major source of animal protein for the population and cultivated fish (mostly carps, tilapias, pangas and gouramis) are highly appreciated because of their freshness, as they are generally sold alive on local markets.

Floating net cage aquaculture of common carp (*Cyprinus carpio carpio*) was implemented on the 6200 ha Cirata reservoir (Citarum River, West Java, Indonesia) in 1988, following the construction of a dam for hydroelectricity production. The cultured species were selected due to a high market demand for carp and its considerable economic value, using technology from previous experiences in other areas in Indonesia. Over the years, a two-net cage aquaculture

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system in which carps are stocked in the upper net and tilapias (*Oreochromis niloticus*) in the lower net, was adopted in an attempt to maximize feed utilization and reduce nutrient loading from cages into the reservoir. The rationale of this carp-tilapia polyculture system is to use the waste output (uneaten feed and fish faeces) from carp and fouling induced by nutrient emissions as feed for tilapia, which also provides supplementary income. Tilapias also help to facilitate water circulation in the cages by grazing on biofouling developing on the nets. Nevertheless, due to their lower market price tilapia are considered as a co-product in this system.

The two-net cage aquaculture system has become a common aquaculture practice since 1995, supplying a local livelihood and good investment for income. However, the rapid adoption of the Cirata reservoir as a new aquatic resource for fish production has resulted in the establishment of a massive number of cages. Due to the higher profit gained from cage aquaculture as well as a lower investment requirement compared to pond production, the number of cages has strongly increased from 25,558 cages in 1996 (Costa-Pierce, 1998) to 39,300 cages in 2005 (Abery et al., 2005). Previous studies reported the carrying capacity of the lake based on its capacity for self-purification to be around 10,600 cages (Costa-Pierce, 1998) and 18,500 cages (Murniyati et al., 2006), whereas it was estimated around 20,300 cages based on empirical results of maximum productivity per cage (Abery et al., 2005). However, after 2003, the number of cages in activity (>38,000) was about twice the estimated carrying capacity of the reservoir. This high cage density has led to a declining productivity per cage, from 3.5 to 7.0 to less than 1.2–1.5 tons per cage per year (Prihadi, 2003). The average weight of harvested carps also decreased from 1000 to 350–500 g, as reported by cage operators surveyed. Water quality analyses from twelve sampling stations across the reservoir found the concentrations of sulphate, hydrogen sulphide, ammonia, nitrite, phosphate and organic matter exceeding water quality standards for aquaculture (Murniyati et al., 2006). In addition, an increased susceptibility to disease and rate of mortality was observed in the reservoir (Bondad-Reantaso, 2004).

In this context, this paper explores the environmental implications of cage aquaculture in the Cirata reservoir, through a system analysis of input production (supporting production systems), fish production (main production system), and transport activities (transport of inputs and intermediate products in all stages) associated with the whole supply chain in order to identify areas for environmental sustainability improvement.

2. Methodology

Life Cycle Assessment (LCA) was applied to evaluate the environmental consequences of the two-net cage aquaculture production system developed in the reservoirs of West Java. Previous studies have demonstrated the potential uses of LCA in aquaculture management (Papatryphon et al., 2004; Mungkung et al., 2005; Mungkung, 2005; Aubin et al., 2006; Ellingsen and Aanondsen, 2006; Mungkung and Gheewala, 2007; Aubin et al., 2009; Ayer et al., 2007; Pelletier and Tyedmers, 2007; Pelletier et al., 2009; Pelletier and Tyedmers, 2010). LCA standardized methodology is described in the International Organization for Standardization (ISO) standards (ISO, 2006a; ISO, 2006b) and each phase of methodology adopted in this LCA study is explained hereafter.

2.1. System boundary

The system evaluated in this study covers the supply chain from hatchery (fingerling production) to farm (fish rearing in cages) and transport of fry and feed as well as that of harvested fish to local markets. The functional unit was one tonne of fresh fish delivered to the market. Downstream life cycle stages (i.e. consumption and post-consumption, waste management) were not considered, as they are not relevant for aquaculture management decisions. Based on the defined system boundary, the required inventory data included the main inputs (energy and resources) and outputs (wastes and pollutants) in hatchery, cage and transport of live fish to local market by using boats and small trucks. The inventory data requirement also extended to the supporting production systems of the following inputs and outputs: energy resource extraction, energy production, feed ingredients' production, chemicals' production and infrastructure materials' production (Fig. 1). Transport in all stages was also covered.

2.2. Inventory data collection

The inventory data for this study were conducted on an annual production basis from 2005 to 2007 by interviewing cage fish-farmers representative of typical production practices of different farm sizes. The data collection has been conducted in two stages. The first stage was a general survey on thirty farms, based on a random sampling within farms of varying technical, social and economic performances. The second stage consisted in a detailed survey on five farms, to validate the previous data and complete inventories especially on facilities and feed origins. All the collected data were validated by local experts from the Indonesian Department of Marine Affairs and Fisheries. Inventory data for carp fingerling production were gathered by collecting the data from three hatcheries located between 150 and 200 km from the reservoir. All hatcheries used broodstock from the same district; the associated inventory data of broodstock production were obtained through an interview with a representative fish farmer specialised in carp broodstock production. For tilapia fingerlings production, the inventory data were collected by interviewing a tilapia hatchery owner at 80 km from the reservoir. The production of tilapia fry and juveniles was conducted in ponds using natural productivity enhanced by chicken manure fertilisation, and the addition of rice bran or rice meal (homemade enrichment, Table 1). The inventory data for chicken manure production was provided by a study on chicken production in France and Brazil (Da Silva et al. 2010), and adapted to local context by specific data (density, growth, feed conversion) from a chicken grower who sells chicken manure. Environmental impacts associated with products from chicken production (chicken meat and chicken manure) were allocated according to their economic values, estimated by their annual average prices. Commercial pelleted feeds are used for rearing carp broodstock (Feed 1), and for grow-out of both carp fingerlings in the hatcheries and fish in the cages (Feeds 2–4). Their chemical and ingredients compositions (Table 1) were determined on the commercial labels completed by interviews of a feed company nutritionist and the manager of a feed mill. The feed formulations were then validated by nutritional value according to Guillaume et al. (1999). This data was complemented by detailed information from a local feed producer, including the energy use for feed production. The inventory data for local fishmeal production was collected from a local fishery processing plant dedicated to frozen fish (for export), surimi and fishmeal (Palembang, Sumatra Island). Fishmeal was produced from discarded fish from the freezing and surimi activities. Heat energy from wood wastes was used for fishmeal processing. Environmental impacts associated with products from trawling fisheries (exported fish, surimi raw material fish, and trash fish) were allocated according to their economic values. Data for world market crop-based ingredients were considered according to Boissy et al. (2011). The inventory data for Indonesian electricity production were obtained from Widiyanto et al. (2003).