Journal of Environmental Management 121 (2013) 96–109

Contents lists available at SciVerse ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

LCA and emergy accounting of aquaculture systems: Towards ecological intensification

Aurélie Wilfart [a,b,*], Jehane Prudhomme [a,b,c], Jean-Paul Blancheton [c,d], Joël Aubin [a,b]

[a] INRA, UMR1069, Sol Agro et hydrosystème Spatialisation, 65 rue de Saint Brieuc, CS 84215, F-35042 Rennes, France
[b] AGROCAMPUS OUEST, UMR1069, Sol Agro et hydrosystème Spatialisation, 65 rue de Saint Brieuc, CS 84215, F-35042 Rennes, France
[c] IFREMER, Station d'Aquaculture Expérimentale, Laboratoire de Recherche Piscicole de Méditerranée, Chemin de Maguelone, F-34250 Palavas-les-flots, France
[d] ECOSYM, UMR5119, Université des sciences et Techniques du Languedoc, Place Eugène Bataillon, CC093, F-34095 Montpellier, France

ARTICLE INFO

Article history:
Received 20 December 2011
Received in revised form
22 January 2013
Accepted 27 January 2013
Available online 24 March 2013

Keywords:
LCA
Emergy accounting
Ecological intensification
Aquaculture

ABSTRACT

An integrated approach is required to optimise fish farming systems by maximising output while minimising their negative environmental impacts. We developed a holistic approach to assess the environmental performances by combining two methods based on energetic and physical flow analysis. Life Cycle Assessment (LCA) is a normalised method that estimates resource use and potential impacts throughout a product's life cycle. Emergy Accounting (EA) refers the amount of energy directly or indirectly required by a product or a service. The combination of these two methods was used to evaluate the environmental impacts of three contrasting fish-farming systems: a farm producing salmon in a recirculating system (RSF), a semi-extensive polyculture pond (PF1) and an extensive polyculture pond (PF2). The RSF system, with a low feed-conversion ratio (FCR = 0.95), had lower environmental impacts per tonne of live fish produced than did the two pond farms, when the effects on climate change, acidification, total cumulative energy demand, land competition and water dependence were considered. However, RSF was clearly disconnected from the surrounding environment and depended highly on external resources (e.g. nutrients, energy). Ponds adequately incorporated renewable natural resources but had higher environmental impacts due to incomplete use of external inputs. This study highlighted key factors necessary for the successful ecological intensification of fish farming, i.e., minimise external inputs, lower the FCR, and increase the use of renewable resources from the surrounding environment. The combination of LCA and EA seems to be a practical approach to address the complexity of optimising biophysical efficiency in aquaculture systems.

1. Introduction

Given a projected world population of 9.2 billion by 2050, the pressure on natural resources (e.g. land, water, biodiversity) will increase. As emphasised by the Food and Farming Report (Foresight, 2011), food production must increase yet be sustainable, despite being grown on a finite surface. The need for new guidance is particularly focused on the challenges of ecosystem and biodiversity preservation, energy supply and climate change. To meet this demand and limit climate-change impacts, agricultural systems must become more efficient and more environmentally friendly. Griffon (2010) highlighted that agriculture is facing four challenges: increasing arable land without decreasing biodiversity or increasing water demand, improving food quality, producing ecosystem services and adapting to climate change. Therefore, it is necessary to design systems which use fewer chemical products, more renewable resources and which make the best use of ecosystem services without impairing their regeneration. Such systems can be called "ecologically intensive" (Griffon, 2010), having a high level of production per ha but using ecological processes as much as possible to optimise natural resource use and develop ecosystem services (Bonny, 2011), as defined by the Millennium Ecosystem Assessment (2005). Systemic approaches are essential to describe and develop new production systems, especially their environmental aspects. This implies taking all system components and their interactions into account, including the supply chain of the product, and assessing them with multiple indicators. Available environmental-assessment methods examine multiple scales (global to local) and offer the benefit of international standards. Nevertheless, their limits promote the integration of those that may be complementary (Pizzigallo et al., 2008) to obtain a multi-scale assessment method and to generate consistent performance indicators based on the same set of input data. We identified two complementary

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[*] Corresponding author. INRA, UMR1069, Sol Agro et hydrosystème Spatialisation, 65 rue de Saint Brieuc, CS 84215, F-35042 Rennes, France. Tel.: +33 2 23485942; fax: +33 2 23485430.

E-mail address: aurelie.wilfart@rennes.inra.fr (A. Wilfart).

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http://dx.doi.org/10.1016/j.jenvman.2013.01.031

Abbreviations

%R	Percentage of renewability
CC	Climate change
EA	Emergy accounting
EIR	Emergy investment ratio
ELR	Environmental loading ratio
ESI	Emergy sustainability index
EYR	Emergy yield ratio
F	Purchased input
FCR	Feed conversion ratio
FU	Functional unit
I	Nature contribution
LCA	Life cycle assessment
LCI	Life cycle inventory
M	Material
N	Non-renewable resource
NPPU	Net primary production use
PF1	Pond farm 1
PF2	Pond farm 2
R	Renewable resource
RSF	Recirculating-system farm
S	Services
TCED	Total cumulative energy demand
Tr	Transformity
UEV	Unit emergy value

approaches to develop a combined methodology for a more complete evaluation of aquaculture systems and to identify perspectives for ecological intensification of fish farming: Life Cycle Assessment (LCA) and Emergy Accounting (EA).

LCA is a multi-criteria method that estimates the environmental impacts of goods or services. Over the past decade, LCA has been adapted to perform comprehensive evaluations of environmental impacts of agricultural production systems (van der Werf and Petit, 2002). It estimates resource use and potential environmental impacts throughout a product's life cycle, from raw material acquisition to production, use and disposal/recycling at global and regional scales (ISO, 2006). Furthermore, LCA provides criteria for eco-profiling food products and a systematic basis for developing sustainability indicators for them (Beccali et al., 2010). However, LCA of agricultural systems does not consider the provision of ecosystem services or products (Ulgiati et al., 2006) or natural environmental inputs (e.g. solar energy, rain, wind).

EA (Odum, 1996; Bastianoni et al., 2001; Vassallo et al., 2009) is a tool based on Energy Systems Theory (Odum, 1983), which was developed to integrate all system inputs (i.e. resources, services and commodities) using a common unit. It is particularly suitable for evaluating systems at the interface between the "natural" and the "human" spheres (Castellini et al., 2006). Emergy is the amount of energy (in solar-energy equivalents) that is directly or indirectly required to provide a given flow or storage of energy or matter. Emergy accounting provides indicators to evaluate energy quality and efficiency along the life cycle. Therefore, it is particularly suitable for studies in agriculture, in which natural and human contributions interact to obtain final products (Pizzigallo et al., 2008). This highlights the role of ecological inputs, which constitute the basic life support for living beings (Brandt-Williams, 2002).

The PISCEnLIT project ("Ecologically Intensive PISciculture") aims to define and develop approaches for ecological intensification in aquaculture. Within this project, the combination of LCA and EA was applied to analyse three contrasting fish farms in France: a recirculating system highly dependant on external resources; a semi-extensive farm which attempts to minimise inputs while optimising productivity and an extensive farm based only on natural productivity.

2. Methods

2.1. Description of the systems

2.1.1. The recirculating-system farm (RSF)

Located near Veys Bay (Normandy, France), the RSF is composed of one production tank that produces 55 tons of Atlantic salmon (*Salmo salar*) in a 10-month growing period. The recirculation system contains four major compartments: fish tank, biofilter, pump and drum filter. Inlet water is pumped from salty (25 g salts l^{-1}) ground water 15 m deep and passes through a unit in which iron concentration is decreased to 0.01 mg l^{-1}. Recirculated water passes through a drum filter, a biological filter and a CO_2-degassing unit (aeration ring). The water is re-oxygenated using pure oxygen before returning to the rearing unit, where a water velocity of 25 cm s^{-1} is maintained. Finally, outlet water (with a mean of 1 m^3 water per kg feed distributed) is released into surrounding natural wetlands, where it is purified (e.g., due to N and P uptake by plants) before reaching the sea. Particles trapped by the drum filter are collected with freshwater rinses, stocked in a sedimentation tank and then used as fertiliser on a nearby 250-ha cereal farm.

The tank is initially stocked with 50 g salmon smolts imported from Scotland. The diet is specially formulated for the farm, with a high percentage (77%) of fishery-based ingredients and no vegetable oil. It is distributed continuously by an automatic feeder. The feed conversion ratio (FCR, mass of distributed feed divided by fish body-mass gain) from smolt to commercial size (4–5 kg per fish) is 0.95. The rearing unit is continuously lighted to negate the effects of circadian rhythm on growth. At the end of the rearing period, fish are pumped out of the rearing unit, sorted according to size and slaughtered. Major characteristics of the farm are given in Table 1.

2.1.2. The extensive pond farm (PF1)

This "system of ponds" (as defined by Balvay, 1980) is located in Lorraine (France) and produces fish for human consumption and pond restocking (for recreational fishing). The total water surface area of its 8 ponds is 96 ha. The farm produces 35 t of fish per year, composed of common carp (*Cyprinus carpio*), tench (*Tinca tinca*), roach (*Rutilus rutilus*), perch (*Perca fluviatis*), sander (*Stizostedion lucioperca*) and pike (*Esox lucius*) (5.25, 3.50, 17.5, 1.75, 1.75, and 5.25 t yr^{-1}, respectively). One hundred thousand newly-hatched commercial larvae and 10 t of fingerlings produced naturally at the farm are released at the beginning of the production cycle. The ponds are fed with cereal grains (mainly wheat) distributed from July to September. Every 5 years, 500 kg ha^{-1} of lime are added to the ponds after draining. Major characteristics of the farm are given in Table 1.

2.1.3. The semi-extensive pond farm (PF2)

This farm, located in Lorraine (France), produces fish of high organoleptic quality. The total area of its five ponds is 12 ha. Each year, three ponds are completely drained to control production. Its annual production is 3.3 t of common carp, tench, roach, perch and pike (2, 0.55, 0.40, 0.22, and 0.15 t per year, respectively). Half of the fingerlings are produced naturally on the farm, and the remainder