Use of life cycle assessment (LCA) to compare the environmental impacts of aquaculture and agri-food products

Rattanawan Mungkung[1]
Department of Environmental Science, Faculty of Science, Kasetsart University, Thailand
Shabbir H. Gheewala
The Joint Graduate School of Energy and Environment, King Mongkut's University of Technology, Thailand

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ABSTRACT

This paper aims to explore the potential as well as limitations of using Life Cycle Assessment (LCA) for comparing environmental impacts associated with aquaculture and other agri-food products. LCA has been used to assess environmental impacts, to identify environmentally-friendlier farming systems, to support environmental improvement, to designate benchmarking, and to develop eco-labelling criteria. However, its main limitations are related to specific impact categories attached to aquaculture and agri-food products that are not yet included in the current LCA methodology. The non-inclusion of temporal and geographical differences as well as social and economic aspects are some of the shortcomings of LCA which is primarily an environmental assessment tool. Moreover, LCA results are often different when using different functional units. To overcome these constraints, it is suggested to use the normalization of the nutrients gained per kg of product consumed with the daily nutritional values required. It is concluded that the life cycle approach should be considered in policy development and LCA can be used to provide decision-supporting information to guide sustainable consumption and production of food products.

INTRODUCTION

Food is one of the core elements for sustainable development of our society. Food products are also the most important commodities traded in the world and the food market chains are continually being extended. However, food production systems both from agriculture and aquaculture (including marine fisheries) have been criticised

[1] fscirwm@ku.ac.th

for their high usage of energy and resources as well as generating wastes along their product chains. Trade-off between food productivity and externality costs has raised a great concern over how to make the food production systems sustainable.

In this regard, a life cycle framework provides a clear understanding of the whole production and supply chain. LCA, based on the life cycle approach, has emerged as a scientifically-based and product-oriented environmental impact assessment tool. It is considered as a potential tool to systematically assess and compare the environmental impacts associated with food products as well as to identify ecoefficiency improvement options. Application of LCA is expected to provide a new insight leading to sustainable development of food production systems. The overall aim of this paper is to evaluate LCA in terms of potentials and limitations for supporting environmentally sustainable aquaculture and agriculture.

Overview of LCA methodology

LCA is an environmental assessment tool to quantify potential environmental burdens throughout the entire life cycle of a product or service. The life cycle stages of product include extraction and processing of raw materials (including packaging materials); manufacture; distribution; use/re-use/maintenance; recycling; final disposal and transport in all stages. Assessment is done via compiling relevant inputs and outputs of the product system and calculating the possible associated impacts. The environmental impacts are calculated based on a functional unit which provides a reference to which the inputs and outputs are related. The magnitude of overall environmental impacts can be used to evaluate environmental performance of the product.

The environmental impact categories assessed in LCA can be divided into three main groups: resource depletion, human health impacts and ecosystem consequences. The LCA methodology, as described in ISO 14040 series, comprises four phases: Goal and scope definition; Inventory analysis; Impact assessment; and Interpretation.

To conduct LCA studies, the objectives and intended application of the LCA study, system boundary as well as methodological choices are identified in the goal and scope definition phase. The environmental inputs and outputs associated with the product system are then quantified in the inventory analysis phase, and the results are used to calculate the potential environmental impacts in the impact assessment phase. The results of the inventory and impact assessment phase are analysed in the interpretation phase and recommendations for environmental improvement suggested.

LCA applications in aquaculture and agri-food products

The concepts of LCA have been widely applied mainly to industrial products (Baumann, 1996; Berkhout and Howes, 1997). Its application to food products, though recent, is rather promising. The general purpose of LCA in food products is basically to identify the problem areas and possible options for environmental improvement. Comparative LCA studies have been used to evaluate different production systems or choice of management strategies to identify the most environmentally-preferred system or option (Basset-Mens and van der Werf, 2003; Cederberg and Mattsson, 2000; Hospiso, *et al.*, 2006; Mungkung, 2005; Papatryphon *et al.*, 2004; Papatryphon *et al.*, 2003; Thrane, 2006; Ziegler *et al.*, 2001). LCA results have been used as basic information to support consumer decisions (Jungbluth, Tietje and Scholz, 2000) as well as in development of eco-labeling criteria to inform consumers of the environmental characteristics of products that will be in demand in the near future (Mungkung, Udo de Haes and Clift, 2006). The studies also illustrate the inherent limitation, of current LCA methodology in terms of impact categories assessed (land use and biodiversity are not well-characterized as discussed in the sections below) and choice of methodology used (Cederberg and Darelius, 2002a; Harald and Svein Aanond, 2006). Overall, LCA is seen as a useful tool for environmental assessment covering both global and local impacts but its potential for application to support policy-making is still under discussion.

Potential use of LCA in comparing aquaculture and agri-food products

LCA can be used to compare the environmental performance of different food products. For doing that, however, the following methodological issues should be considered and the comparison as well as interpretation should be done with care.

Associated environmental impacts

Aquaculture interacts with agriculture production systems by sharing some common resources and environmental impacts, e.g. land use, emissions to water and soil, toxicity and some related to fisheries such as use of wild-caught fish for fishmeal processing which is a major component of agriculture and aquaculture feeds. It can be seen that such interactive production systems are inter-related but a definitive impact assessment method is yet to be identified.

System boundary

The definition of system boundary plays a very important role in the assessment of environmental impacts associated with inputs and outputs. The LCA results are highly dependent on the product system defined. In principle, it should cover all life cycle stages from raw materials acquisition to final waste disposal. The system boundary is often limited by data and financial resources availability, or reduced to cover only the major life cycle stages i.e. cutting off the stages contributing to impacts less than 5-10 percent. For example, construction of infrastructure is often excluded for LCA studies because their contribution to the overall environmental burden of the product may be less than 5 percent due to their long lifespan. However, what is included and excluded from the study must be clearly defined.

Functional unit

The functional unit is the quantification of function that the product system delivers, and is used as a basis for calculating the potential impacts. The definition of functional unit is especially critical in comparative LCA studies. The functional unit used for fisheries and aquaculture products is normally potential impacts per kilogram or tonnes, whilst per ha is used to compare the land productivity of different agriculture products. However, different units can lead to different results as highlighted by Halberg *et al.* (2005). For example, for the eutrophication potential, red label pig production system performs better than organic agricultural practices when the comparison is based on per ton of pig produced. However, this result is reversed when the same comparison is done per hectare.

Results from several case studies are summarized in Table 1. Based on the energy use per kg of product produced, fisheries seems to be the most energy intensive production system followed by aquaculture and agriculture. This is because of the high energy consumption during fishing. However, the energy consumed depends on the type of gear, fishing method, and intensity of fishing activities. The energy use per kg mixed fish caught can be much lower than the fishing for one target species, as shown in the case study of Danish fish products (Thrane, 2006). Intensive shrimp and trout aquaculture consumed energy nearly at the same level. It is likely that agriculture products use less energy than fisheries and aquaculture. Among different types of agriculture products, chicken is the most energy intensive followed by beef and pork. Bread production consumed slightly lower energy than pork. However, the results are not the same when comparing the environmental impacts based on the land used for production. Trawling for cod was the most land intensive due to the nature of trawling which requires sweeping through the sea bottom (in terms of impacted seafloor area per

TABLE 1
Environmental impacts comparison of different products based on energy consumption and land use per kilogram of product

Species	Energy use (MJ/kg)	Land use (m^2/kg)	Reference
Swedish wild-caught cod	95.0	1 711.0	Zielger (2001)
Norwegian wild-caught cod	67.5	1 075.0	Ellingsen and Aanondsen (2006)
Norwegian farmed salmon	66.0	6.0	Ellingsen and Aanondsen (2006)
French trout (very large trout)	65.1	NA	Papatryphon *et al.* (2003)
Norwegian chicken	55.0	12.5	Ellingsen and Aanondsen (2006)
Norwegian lobster	52.3	NA	Thrane (2006)
French trout (large trout)	49.5	NA	Papatryphon *et al.* (2003)
Thai shrimp	45.6	2.2	Mungkung (2005)
Swedish beef	40.0	33.0	Cederberg Darelius (2002)
French trout (portion trout)	36.2	NA	Papatryphon *et al.* (2003)
French pig (Agriculture Biologique)	22.2	9.8	Basset-Mens and van der Werf (2003)
Swedish pig	22.0	15.0	Cederberg and Darelius (2002b)
Icelandic cod	18.5	NA	Eyjólfsdóttir *et al.* (2003)
French pig (Label Rouge)	17.9	6.3	Basset-Mens and van der Werf (2003)
French pig (Good Agricultural Practice)	15.9	5.4	Basset-Mens and van der Werf (2003)
German bread	15.8	1.5	Brashkay *et al.* (2003)
Danish flatfish	7.4	NA	Thrane (2006)
Danish shrimp	7.4	NA	Thrane (2006)
Danish prawn	6.6	NA	Thrane (2006)
Danish mussel	2.5	NA	Thrane (2006)

trawled cod) whilst aquaculture and agriculture use much less land. However, it must be noted that the production of fish meal in aquaculture and agriculture feeds did not include the land use impacts associated with fishing. Intensive shrimp farming showed a very low amount of land required, whilst beef, pork and chicken required more land due to fodder consumption of the livestock and the yield of the fodder crops. The area used for producing bread is mainly related to the land required for cultivating wheat and was thus the lowest.

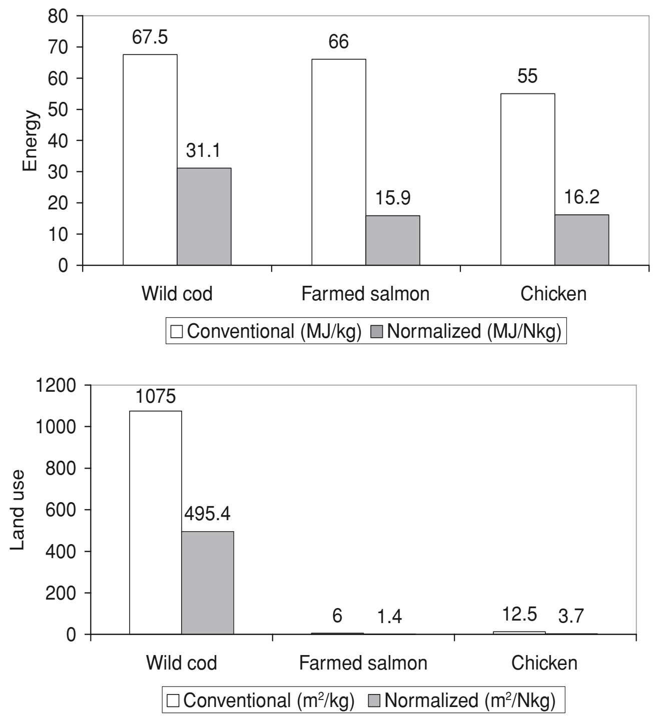
However, it may be misleading to compare different foods on a "per kg" basis. The functional unit is a quantification of the function that the product system delivers. As the main function of food is to provide nutrients, it is proposed to use the nutritional values gained from 1 kg of food products (based on the USDA Nutrient Database: http://www.nal.usda.gov/fnic/foodcomp/search last accessed in April 2006) as the basis for comparison rather than directly 1 kg of food or even 1 kg of protein. The proposed method is to normalize the nutrients gained by the daily nutrients required called "normalization factor". The normalization factor can then be used to evaluate the "normalized impact indicator" as shown in the equation below. The normalized results will be on a "per Nkg" basis rather than "per kg" where "Nkg" stands for the mass of nutrients gained from consuming 1 kg of food.

$$\text{Normalization factor} = \sum_{i=1}^{n} \frac{\text{nutrient gained}}{\text{daily nutrient required}}$$

$$\text{Normalized impact indicator} = \frac{\text{impactindicator value}}{\text{normalization factor}}$$

Figure 1 demonstrates the results of using the new functional unit proposed in some previous case studies. The case study of wild cod, farmed salmon and chicken (Ellingsen and Aanondsen, 2006) show a similar trend with the new functional unit – wild cod has the worst environmental performance in terms of energy use and land requirement, for both conventional as well as normalized units. However, the factors indicate relative magnitude of impacts are rather different – the land use impact of wild cod is 179 and 86 times of farmed salmon and chicken respectively in terms of conventional units, whilst it is 342 and 134 times in terms of normalized units. Similarly, the energy use impact of cod is 1 and 1.2 times of farmed salmon and chicken respectively in terms of conventional units, whilst it is 2 and 1.9 times in terms of normalized units. It is interesting to note that farmed salmon performs worse than chicken for energy use in terms of conventional units but is slightly better in terms of normalized units. It should also be noted here that all the nutrients are assumed to be equally important in the normalization scheme. Still, the authors consider the normalization by using nutrients gained to be more rational than directly calculating impacts per kg of food or protein.

FIGURE 1
Comparison of environmental impacts of wild cod, farmed salmon and chicken using conventional and normalized indicator values (data from Ellingsen and Aanondsen, 2006 and excluding costs of producing feed)



Inventory data required

Collecting primary data is not always feasible. Thus, LCA practitioners often use secondary data from databases embedded in commercially available LCA software. The sources of inventory data used in LCA must be clearly stated so as to understand uncertainties attached to the results. This is linked to interpretation as well as conclusions from LCA studies. It is worth noting here that the databases of food products – covering fish, crops, dairy, livestock, fruits and vegetables – have been developed.[2]

Environmental impacts assessed

Efforts have been made to develop methodologies for evaluating land use impacts, seafloor effects, use of anti-fouling agents, depletion of biotic resources, and losses of biodiversity in LCA. Land-use is a very significant parameter for assessing agriculture and aquaculture systems. However, there has been no consensus regarding its characterization in LCA. Several methodologies have been proposed but there is lack of single definition due to lack of adequate impact indicators and scarcity of data (Antón, Castells and Montero, 2005). A simple way of characterizing it is by using land occupation – the area of land occupied for a certain time period, expressed as area □ time (e.g. m^2×year) per functional unit (Guinée *et al.*, 2002). This however, does not take into account the change in soil quality. A semi-quantitative way of taking land use change into account is to consider land transformation from type A to type B, expressed as land area (e.g. m^2). The land could be classified into five types, viz., I, natural systems; II, modified systems; III, cultivated systems; IV, constructed

[2] Data and references can be found at http://www.lcafood.dk/.

systems; V, degraded systems (Heijungs *et al.*, 1992). The obvious shortcoming of this classification is that all agriculture and aquaculture would fall under type III without scope for differentiation. Several more sophisticated methods have been developed to account for soil degradation, loss of biodiversity and productivity. Soil degradation is characterized in terms of its physical, chemical and biological properties (Mattsson, Cederberg and Blix, 2000, Wegener *et al.*, 1996a, Wegener *et al.*, 1996b) whereas biodiversity and productivity indicators are based on loss of life support (net primary productivity) and diversity of species (Antón *et al.*, 2005, Goedkoop and Spriensma, 2000, Koellner, 2000; Weidema and Lindeijer, 2001). Even indicators based on ecosystem thermodynamics are being developed (Wagendorp *et al.*, 2006). Thus, it is clear that a good indicator should include area of occupied surface, time of activity and change in soil quality. However, as stated earlier there is no consensus on a single indicator. Also, the data to support the computation of change in soil quality is not readily available. This issue needs to be researched further to develop a set of rigorous, but relatively easy to compute indicators which could be standardized internationally. Geographic Information System (GIS) has recently been introduced for tracking fishing vessels to assess the impacted area of seafloor (Nilsson and Ziegler, 2006). There is however still a need for further research on these issues.

Life cycle impact assessment method

There are different impact assessment methods available, based on different principles and measurements resulting in different set of impact categories. Which method should be used for each case study depends upon the type of information required for further application as well as the specific impacts associated with the product being studied. As a result, the detailed comparison of foods products from different LCA studies can be done only if the same impact assessment methodology is used (Baumann and Tillman, 2004).

DISCUSSION

LCA applies a systems perspective yielding a more comprehensive and realistic environmental assessment of products. Providing the magnitude of environmental impacts in each life cycle stage in quantitative terms, the key life cycle stages, significant issues and main impact contributors can be identified. The environmental information provided by LCA can thus assist in deriving possible options for environmental improvement. LCA studies are used for comparing the environmental performance (i.e. friendliness) of different production systems as well as to set the indicators for benchmarking. LCA is also useful for identifying the key environmental criteria that can be used as ecolabelling criteria. In addition, it has also been used as a policy-support tool in assessing environmental sustainability of different production systems or management options.

However, one could argue that LCA results are practically applied only for environmental certifications or ecolabelling to indicate the environmentally-friendlier product but not practical for policy implications. This is because they do not provide the absolute values of impacts or incorporate the safety margin to support policy development in terms of regulations. Another particular concern among policy makers is related to how to compare the severity across different environmental impact categories. Nevertheless, the LCA results can still provide information regarding the better management option and could be used for supporting strategic policy development in terms of planning. The magnitude of several impacts can be combined into single score by applying the weighting factors according to the level of importance of each impact category in a specific context. However, it is rather subjective, depending on the valuation choice. Some of the weighting methodologies currently in use are based on willingness-to-pay, damage costs and panel approach (Heijungs *et al.*, 1992). The choice of methodology is based on the value-systems of the users and will thus yield different results.

The LCA method is still under development and the methodology to assess some potential environmental impacts are still not conclusively determined. Such impacts include biotic depletion, impacts of land use, biodiversity loss and unknown chemical toxicity. Moreover, LCA is not site specific; thus the severity of impacts from different locations cannot be distinguished. The LCA procedure, particularly the inventory step, is rather resource intensive and time consuming – which can be the constraints for LCA implementation. LCA only focuses on environmental aspects, but does not include social and economic dimensions. Therefore, the LCA results must be applied in conjunction with other tools for decision making.

CONCLUSIONS AND RECOMMENDATIONS

- The life cycle framework presents a systematic approach of analyzing the environmental impacts of a product along its entire life cycle and should be taken into consideration in policy development.
- LCA has been used to identify problematic areas and options for environmental improvement and compare the environmental performance of different food production systems.
- For agriculture, different cultivation practices should be compared to identify the better environmental performance system; impacts of land use in terms of soil quality degradation should be further investigated.
- For fisheries, different fishing gears and methods should be compared based on energy use per kg caught and identify the environmentally-preferred fishing gear and method; population dynamics of aquatic resources should be applied to evaluate their potential of renewability i.e. sustainability of production capacity.
- For aquaculture, as well as for agriculture and capture fisheries, different production systems should be compared to identify the most environmentally friendly practices. The sustainable use of resources, particularly, the interactions with other production systems should receive attention.
- LCA has been shown to be applicable for comparing aquaculture and agri-food products based on a novel normalization scheme based on nutrients gained from food products.
- The main limitations of LCA applications are related to specific impact categories associated with aquaculture and agri-food products that are not yet included in the current LCA methodology. Thus, how to include all associated impacts in LCA to obtain a more realistic assessment of environmental impacts should be further investigated for the practicality and credibility of using LCA. Such impacts are: land use impacts, chemical toxicity, seafloor effects and biodiversity losses.
- Interactive effects of agriculture, aquaculture and fisheries on ecosystem services – which are not known yet – should receive attention.
- Sustainability of production capacity from agriculture, aquaculture and fisheries should be managed in an integrated manner, due to the requirements of same resources and interaction among sectors.
- Information on environmental impacts associated with the production of aquaculture and agriculture products will be in demand for eco-labeling to support purchasing decisions for both sustainable production and consumption. Thus this area should be further researched.

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