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Role of life cycle assessment in sustainable aquaculture

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Abstract

As an alternative food source to wild fisheries, aquaculture shows a great potential to help meet the growing demand for seafood and animal protein. The expansion of aquaculture has been achieved partly by system intensification, which has drawn vast criticisms of aquaculture for its environmental, social and economic sustainability issues. Life cycle assessment (LCA) has become the leading tool for identifying key environmental impacts of seafood production systems. A LCA evaluates the sustainability of diverse aquaculture systems quantitatively from a cradle-to-grave perspective. It provides a scientific basis for analysing system improvement and the development of certification and eco-labelling criteria. Current efforts focus on integrating local ecological and socio-economic impacts into the LCA framework. A LCA can play an important role in informing decision makers in order to achieve more sustainable seafood production and consumption. This article reviews recent applications of LCA in aquaculture, compares the environmental performance of different aquaculture production systems, explores the potential of including biodiversity issues into LCA analysis and examines the potential of LCA in setting criteria for certification and eco-labelling.

Key words: aquaculture, biodiversity, certification, environmental impact, life cycle assessment, sustainability.

Introduction

As an alternative food source to wild fisheries, aquaculture shows a great potential to meet the growing demand for seafood and to feed the world (Pauly *et al.* 2002). The global production of aquaculture including fish, molluscs, crustaceans and aquatic plants has increased from <700 000 tonnes in 1950 to nearly 70 million tonnes by 2008, accounting for 50% of the world's fish supply (FAO 2010). Most production occurs in Asia, which contributes 89% by volume and 79% by value to world aquaculture production. China is the leading producer, accounting for 48% of the world aquaculture total in 2008 (Bostock *et al.* 2010). Aquaculture has already become the most rapidly increasing food production sector with an average annual growth rate of 6.9% since 1970 (Bostock *et al.* 2010) and will continue to grow at a significant rate (Diana 2009). Modern aquaculture is highly diverse, encompassing a great variety of production systems, technologies and more than 310 different farmed species recorded by FAO in 2008 (Pelletier & Tyedmers 2008; Bostock *et al.* 2010). Freshwater aquaculture is dominated by carp, tilapia and catfish. Coastal aquaculture primarily comprises salmon, shrimp, oyster, scallop and mussels (Bostock *et al.* 2010). Production systems range from traditional low intensity such as extensive and semi-intensive to highly intensive systems with different farming technologies. Closed recirculating and organic systems have emerged as newly developed alternatives to conventional systems.

The expansion of aquaculture has been achieved partly by system intensification, which has drawn criticisms of aquaculture for its environmental, economic and social sustainability. These criticisms include pressure on natural resources such as water, energy and feed, eutrophication caused by effluents, depletion of biodiversity, conversion of sensitive land, introduction of invasive species, genetic alteration of and disease transmission to wild stocks (Diana 2009), as well as food insecurity. Increasing attention to the environmental responsibility of aquaculture underscores the urgent need to understand the environmental footprints of different production systems in order to better manage them to promote more sustainable aquaculture.

Many assessment tools have been developed recently to evaluate the environmental impacts of food production systems, including risk analysis, ecological footprint, energy analysis and life cycle assessment (LCA) (Bartley *et al.* 2007). Life cycle assessment allows the comprehensive assessment of relevant environmental impacts along the whole life cycle of a product. It allows one to compile the relative inputs and outputs in an overall process and to calculate the potential associated impacts based on a functional unit. Those impacts that cannot be measured directly are calculated by models. Life cycle modelling comprises four steps: goal definition and scope, inventory, impact analysis and interpretation (ISO 1998). In the goal definition and scope phase, one should define a system boundary and functional unit for the studied systems. In the inventory phase, inputs and outputs for each life cycle stage are quantified and the inventory results are used to characterize resource depletion and environmental and human health impacts in the impact assessment phase. Life cycle assessment has already become the leading tool for identifying and comparing the environmental impacts of different food production systems (Pelletier & Tyedmers 2008).

Currently, there are few methods to evaluate the sustainability of aquaculture in a quantitative and scientifically sound way (Diana 2009). Life cycle assessment can be used to make such an evaluation in quantifiable terms that are clear indicators of sustainability. In aquaculture, the system boundary is often from cradle to farm gate with the focus on the farm management. Post-farm stages including processing, sale, consumption and waste disposal are less affected by aquaculture practices and thus usually excluded from previous aquacultural LCAs. However, the environmental impacts of post-farm stages, especially distribution to market, may be significant from a cradle-to-grave perspective and need to be included in future studies. Life cycle assessment can highlight the specific processes responsible for major environmental impacts. For example, phosphate in pond effluents is the driving force to eutrophication impact. This can be used to inform environmental problems and to track hotspots that significantly contribute to overall impacts in aquaculture. Life cycle assessment also enables the analysis of system eco-efficiency and can make suggestions for system/activity improvement, as well as predict environmental outcomes if one activity is changed. However, it should be pointed out that LCA has limited applications of methodologies in aquaculture.

Although LCA has been applied widely in industrial and agricultural products (Roy *et al.* 2009; de Vries & de Boer 2010), LCA-style studies for seafood production systems have been developed for less than a decade. To date, LCA of wild-caught seafood include Swedish cod (Ziegler *et al.* 2003), Danish fish products (Thrane 2004), Spanish tuna (Hospido & Tyedmers 2005) and Norwegian cod (Ellingsen & Aanondsen 2006). Aquacultural LCAs mainly focus on intensive farming systems (Iribarren *et al.* 2010) or species with high economic value, including salmon (Ellingsen & Aanondsen 2006; Ayer & Tyedmers 2009; Pelletier *et al.* 2009), shrimp (Mungkung *et al.* 2006; Cao et al. 2011), rainbow trout (Grönroos *et al.* 2006; Aubin et al. 2009; d'Orbcastel *et al.* 2009), sea bass and turbot (Aubin *et al.* 2009), tilapia (Pelletier & Tyedmers 2010) and mussel (Iribarren *et al.* 2010). There is a growing trend in the use of LCA to study the sustainability of seafood production systems (Pelletier *et al.* 2007).

This article reviews recent applications of LCA in aquaculture, compares the environmental performance of different aquaculture production systems, explores the potential of including biodiversity and socio-economic issues into LCA analysis and examines the potential of LCA to assist in setting criteria for certification and eco-labelling. The goal of the review is to highlight LCA methods and capabilities to inform decision makers, producers, researchers, certification and consumer awareness programmes, and other stakeholders who seek to promote more sustainable seafood production and consumption.

Assessing sustainability of aquaculture by LCA

Twelve aquaculture-based LCA studies were found from peer-reviewed journals or conference proceedings in the past 5 years (accessed on 1 August 2011). To compare LCA results among selected studies, the functional unit was recalculated to be the same on a mass basis for each scenario. Of all the studies reviewed, the impact categories commonly used (Henriksson *et al.* 2012) are presented in Table 1 with detailed characteristics. Among them, global warming, eutrophication, and acidification and energy use have been employed with the highest frequency. Only global warming and ozone depletion have effects on a global scale. Other impact categories manifest regionally on a scale of 100–1000 km or locally to the immediate vicinity (Thrane 2004). However, LCA is still underdeveloped for assessing local ecological impacts such as biodiversity loss, habitat loss, and land use change and socio-economic impacts such as social welfare (Cao *et al.* 2011).

Numerous impact assessment methodologies have been developed, such as CML 2000, Eco-indicater 99 and IMPACT 2002 + (PRé 2008). Each method has a different focus and their own special impact categories that might lead to different results. There is no single methodology that comprehensively covers all environmental issues from seafood production. Differences in system boundaries, functional units and impact assessment methodologies adopted make comparisons of different production systems

Table 1 Impact categories commonly used in aquacultural LCAs (adapted from Owens 1996; Pelletier *et al.* 2007)

Impact category	Characterization factor	Category indicator	Equivalency unit	Interpretation	Spatial	Temporal
Climate change	GWP	CO_2	kg CO_2 eq	Atmosphere absorption of infrared radiation	Global	Decades/Centuries
Eutrophication	EP	PO_4	kg PO_4 eq	Nutrient enrichment	Regional/local	Years
Acidification	AP	SO_2	kg SO_2 eq	Acid deposition	Regional	Years
Energy use	EUP	MJ	MJ	Depletion of non-renewable energy resource	Regional/local	Centuries
Biotic resource depletion	BDP	NPP	kg C	Depletion of renewable resources	Regional/local	Years
Abiotic resource depletion	ADP	Sb	kg Sb eq	Depletion of non-renewable resources	Local	Centuries
Ecotoxicity	Ecotoxicity potential	1,4 DB	kg 1,4 DB eq	Toxic to flora, fauna and humans	Local	Hours/Days/Years
Ozone depletion	ODP	CFC	kg CFC eq	Stratospheric ozone breakdown	Global	Decades/Centuries
Photochemical oxidant	POP	C_2H_4	kg C_2H_4 eq	Photochemical smog	Regional/local	Hours/Days

GWP, global warming potential; EP, eutrophication potential; AP, acidification potential; EUP, energy use potential; BDP, biotic depletion potential; ADP, abiotic resource depletion potential; ODP, ozone depletion potential; POP, photochemical oxidant potential. Category indicators: CO_2, carbon dioxide; PO_4, phosphate; SO_2, sulphur dioxide; MJ, mega Joules; NPP, net primary productivity; Sb, antimony; 1,4 DB, 1,4 dichlorobenzene; CFC, chlorofluorocarbon; C, carbon.

more difficult (Cao *et al.* 2011). In spite of this, comparative studies on different systems or products can still be informative towards more sustainable production techniques or consumption. Such comparative studies are not the same as the so-called 'comparative assertions' disclosed to the public. Although they both require the same functional unit and equivalent methodological considerations, comparative assertions are more rigorous and require external critical review (ISO 1997).

Intensive, semi-intensive and extensive systems

Aquaculture can be classified mainly by stocking density, feeding management and capital investment. There is a trend towards growing more aquatic crops per unit area in recent years. Extensive systems have been replaced gradually by semi-intensive and intensive systems with higher unit production. Aquaculture mostly takes place in both semi-intensive and intensive systems in developing countries, while it remains intensive in developed countries (Diana 2009). Semi-intensive aquaculture is considered a way of remedying environmental problems associated with intensive farming systems. But does semi-intensive aquaculture at a lower level of intensity using more natural systems truly result in a significant reduction in environmental impacts, especially taking its lower productivity into account? If yes, semi-intensive aquaculture should be promoted to conserve biodiversity and environment. There are very limited published data on the comparison of extensive, semi-intensive and intensive systems.

The most common types of shrimp farms in China are semi-intensive and intensive. Semi-intensive shrimp farming is often different from other traditionally defined semi-intensive aquaculture such as tilapia farming that relies only on natural food. With much higher yields, semi-intensive shrimp farming feeds on both commercial feed and fertilizer-based natural food. Criticism of intensification of shrimp farming systems has been focused on high material and energy inputs, and more effluent discharge, which might largely increase environmental burdens. Our published work indicates that, although with higher unit production, intensive shrimp farming systems have almost double the environmental impacts than semi-intensive farming in all the studied impact categories (Table 2) (Cao *et al.* 2011). This is due to higher electricity use, feed inputs and concentrations of nutrients in effluents. With a lower land footprint, intensive systems might outperform semi-intensive systems in land modification (Cao *et al.* 2011). Semi-intensive shrimp aquaculture is environmentally preferable to intensive farming systems in China (Cao *et al.* 2011). By a comparison of two Chinese shrimp farming systems with a Spanish extensive mussel farming system (Iribarren *et al.* 2010), the extensive mussel system outperformed the other two systems in acidification, eutrophication and global warming per tonne produced. This is probably because mussel culture requires much lower feed inputs than shrimp culture. The result is probably not true for all extensive farming systems due to their lower unit yield. Energy and feed dependence are usually positively correlated with

Table 2 Environmental impacts of 1 tonne of live-weight fish produced

Species	System	Location	Acd. (kg SO_2 eq)	Eut. (kg PO_4 eq)	GW (kg CO_2 eq)	CEU (GJ)	BRU (kg C)	Reference
Shrimp	Intensive	China	43.9	63	5280	61.5	60 700	Cao *et al.* (2011)
	Semi-intensive		19.4	32.3	2750	34.2	36 800	
Mussel	Extensive	Spain	4.72	0.4	472	–	–	Iribarren *et al.* (2010)

Acd., acidification; Eut., eutrophication; GW, global warming; CEU, cumulative energy use; BRU, biotic resource use.

system intensity (Pelletier & Tyedmers 2007). Aquatic plants such as seaweed culture at a lower intensity usually require the least material and energy inputs. They would be much less environmentally damaging compared with fish aquaculture.

Open flow-through and closed recirculating systems

The majority of fish farms, especially in the developing countries, are outdoor flow-through systems that discharge effluents directly to receiving water bodies without treatment. A number of environmental impacts have been recognized. The impacts include: eutrophication and change of fauna in the receiving water bodies; escapement of aquatic crops and their potential ecological and genetic alteration; transfer or spread of disease and parasites to wild stocks; release of chemical hazards to receiving waters (Diana 2009). Research is ongoing to develop alternatives with an emphasis on closed recirculating systems that may reduce or eliminate the impacts associated with open systems. By isolating the culture environment from the surrounding ecosystem, closed recirculating systems are designed to grow fish at high densities with zero discharge of effluents. Water is treated to remove toxic wastes and then reused. Reusing water gives farmers better control over the environment, and reduces water consumption and effluent discharge (Bostock *et al.* 2010). Notable advantages of recirculating systems also include fewer fish escapes and improved waste management.

Studies by Aubin *et al.* (2009), Ayer and Tyedmers (2009), d'Orbcastel *et al.* (2009) and Pelletier and Tyedmers (2010) employed LCA to compare the environmental performance of open and closed recirculating systems. They investigated how the life cycle environmental impacts would change if open systems shifted to closed recirculating systems (Table 3). Overall, the closed recirculating

Table 3 Environmental impacts of 1 tonne of live-weight fish produced

Species	System	Location	Acd. (kg SO_2 eq)	Eut. (kg PO_4 eq)	GW (kg CO_2 eq)	CEU (GJ)	BRU (kg C)	ABD (kg Sb eq)	HT (kg 1,4 DB eq)	MT (kg 1,4 DB eq)	Reference
Salmon	Bag	Canada	18	31.9	2250	37.3	–	12.1	639	822 000	Ayer and Tyedmers (2009)
	Flow through tank	Canada	33.3	31	5410	132	–	–	–	–	
	Net pen	Canada	17.9	35.3	2070	26.9	–	–	–	–	
Catfish	Flow through pond	Vietnam	48.1	65	8930	13.2			4280	251 000	Bosma *et al.* (2011)
Tilapia	Net-Pen	Indonesia	20.2	47.8	1520	18.2	2760	38.1	2580	384 0000	Pelletier and Tyedmers (2010)
	Flow through pond	Indonesia	23.8	45.7	2100	26.5	2700	–	–	–	
Trout	Flow through tank	France	13.4	28.5	2020	34.9	28 000	13.9	840	574 000	Aubin *et al.* (2009); d'Orbcastel *et al.* (2009)
	Flow-through raceway	France	19.2	65.9	2750	78.2	62 200	–	–	–	
	Recirculating tank	France	13.1	21.1	2040	63.2	28 100	–	–	–	
Sea bass	Sea cage	Greece	25.3	109	3600	54.7	71 400	–	–	–	Aubin *et al.* (2009)
Arctic char	Recirculating tank	Canada	63.4	11.6	10 300	233	–	72.5	54 400	6 510 000	Ayer and Tyedmers (2009)
Turbot	Recirculating tank	France	48.3	77	6020	291	60 900	–	–	–	Aubin *et al.* (2009)

Acd., acidification; Eut., eutrophication; GW, global warming; CEU, cumulative energy use; ABD, abiotic depletion; HT, human toxicity; MT, marine toxicity.

systems outperformed the open systems in eutrophication emission and biodiversity conservation, but all other environmental impact categories such as global warming and energy use were substantially worse. This was due to the greater energy and material requirements for the recirculating system and lower unit production. The study on catfish produced in flow-through ponds showed abnormally high global warming potential, beyond that estimated for many recirculating systems. This was due to the rice products used in the feed that can result in emissions of high global warming potential gases during rice cultivation (Bosma *et al.* 2011). Relatively high capital costs would be another barrier for closed recirculating systems to be widely employed and promoted.

Conventional and organic systems

A growing number of consumers place emphasis on seafood safety issues, animal welfare and environmental concerns. Organic aquaculture is becoming increasingly important as consumers become more environmentally aware and demand more secure seafood. Organic aquaculture is considered as one of the most promising alternatives for reducing environmental burdens associated with intensive farming (EU 2007). It is defined as an overall system of farm management and food production that combines best environmental practices, a high level of biodiversity, preservation of natural resources, application of high animal welfare standards and a production method in line with the preference of certain consumers for products produced using natural substances and processes (EU 2007). Organic aquaculture is often described as superior to conventional farming in that it relies largely on internal resources and thus consumes fewer external materials and energy. Prohibition on the use of man-made artificial chemicals in organic farming markedly reduces ecotoxicity potentials and also conserves biodiversity. Organic products usually have great market opportunities and stable prices in export markets. Despite the rapid growth of organic agriculture production, organic aquaculture is newly developed and still in its early stage (Mente *et al.* 2011). This is due to the diversification of cultured species, obstacles to implementing some organic practices such as complete chemical prohibition and fishmeal substitution, as well as a lack of unified certification standards and criteria (Mente *et al.* 2011). Moreover, some organic farming systems have a lower yield and the requirement to adopt organic practices such as using organic feed ingredients may reduce farm eco-efficiency and cause more environmental problems (Pelletier & Tyedmers 2007). The question arises whether organic farming is really less environmentally damaging once lower yields and all the changes in practices are considered. Life cycle assessment can be used to answer this question and to provide a basis for certification and eco-labelling of aquaculture to indicate environmentally preferable products and systems.

Mungkung (2005)conducted an LCA study for shrimp farming in Thailand and compared the life cycle impacts of conventional intensive methods with organic as well as other transitional systems (Table 4). Organic shrimp farms in Thailand were characterized by operation at a lower stocking density with the best available organic inputs and the complete elimination of man-made artificial chemicals and antibiotics. Conventional intensive systems were managed at a high stocking rate and high inputs aiming for high productivity. Overall, the conventional intensive farm showed the highest impacts per tonne produced for all impact categories, except for eutrophication that was highest for the organic farm. The significantly higher impacts from conventional intensive farms were caused by high energy inputs, feed use and chemical use. The organic system in her study was identified as the more environmentally sustainable practice.

Pelletier and Tyedmers (2007) studied organic salmon farming and concluded that the use of organic crop ingredients and fisheries by-products did not reduce the

Table 4 Life cycle impacts of 1 tonne of conventional and organic products

Product	System/ specification	Acd. (kg SO_2 eq)	Eut. (kg PO_4 eq)	GW (kg CO_2 eq)	ABD (kg Sb eq)	MT (kg 1,4 DB eq)	BRU (kg C)	CEU (GJ)	Reference
Shrimp	Conventional	18.5	10.6	5210	91.3	475 000	–	–	Mungkung (2005)
	Organic	3.77	11.5	901	19.5	61 300	–	–	
Salmon feed	Conventional	12.6	5.3	1400	–	60 700	10 600	18.1	Pelletier and Tyedmers (2007)
	Partial-organic	11.8	4.9	1250	–	61 100	10 600	17.1	
	All-organic	24.6	6.7	1810	–	63 300	45 100	26.9	
	All-organic with substitutions*	6.9	2.3	690	–	47 600	6300	9.86	

Acd., acidification; Eut., eutrophication; GW, global warming; ABD, abiotic depletion; MT, marine toxicity; BRU, biotic resource use; CEU, cumulative energy use.

*Fish based ingredients are substituted with plant based ingredients.

environmental impacts of feed production for all impact categories considered in their study. They indicated that compliance with current organic standards in salmon farming would rather result in markedly higher environmental burdens with respect to energy use, global warming, ecotoxicity, acidification, eutrophication and biotic resource use. They suggested that the substitution of animal-derived ingredients with plant-based ingredients in fish feed could probably solve this dilemma. It also depends on what plant ingredients are used for substitution. Some highly processed plant ingredients such as wheat flour may be as environmental damaging as fish-derived ingredients or even result in more environmental burdens in some impact categories such as eutrophication. This is due to the use of concentrated fertilizer during cultivation and intensive energy and water use during processing. Genetically modified (GMO) soybeans are competing with conventional soybeans to replace animal-derived ingredients in the fish feed in some countries. Organic aquaculture prohibits the use of any GMO ingredients. The substitution of animal-derived ingredients with plant ingredients should be further evaluated. More research and case studies are needed to test whether the substitution satisfies the nutritional requirements of fish and does not harm fish growth. Some species with high economic value such as shrimp and salmon require a higher protein level in the feed. Substitution of animal-based protein with plant protein may result in a lower growth rate. Pelletier and Tyedmers (2007) also pointed out that impacts on land use would be greater in organic systems due to lower yields. Optimizing organic farming to achieve higher yields could solve this problem.

Monoculture and polyculture systems

As one of the integrated systems, polyculture has been developed as an alternative model to counter the problems such as disease vulnerability and low feed efficiency caused by monoculture. Polyculture systems have higher levels of biodiversity and usually gain more economic profits. But is polyculture superior to monoculture in terms of environmental sustainability?

Based on a published LCA study on polyculture (Baruthio *et al.* 2009), the potential impacts per tonne of all products from polyculture with freshwater prawn as the main species, prawn from polyculture and marine shrimp from monoculture were compared (Table 5). The results showed that polyculture performed better in terms of global warming and energy use, but not in terms of acidification and eutrophication compared with shrimp monoculture. By economic allocation (a proportion of the impacts are allocated to each polyculture species based on its market value), the impacts per tonne of prawn from polyculture were higher than per tonne of monocultured shrimp. The comparative results indicated that the polyculture system was less environmentally sustainable than monoculture in this case.

Geographical comparisons

Ongoing efforts have been devoted to manage the environmental performance of food production from local through regional and global scales. A global-scale comparison of farmed salmon and shrimp using LCA is presented in Table 6. The environmental burdens associated with salmon and shrimp farming in different countries were evaluated. For farmed salmon, Pelletier *et al.* (2009) found that impacts were lowest per unit production for Norwegian production in most impact categories, and highest for the UK. This was mainly due to differences in feed composition and the feed utilization rate among regions. The greater biotic resource use in Norway and the UK resulted from higher inclusion rates of fish-based inputs such as fishmeals and oils derived from high trophic level species. The US farmed shrimp had highest impacts on acidification, global warming and energy use, but it had lowest impact on eutrophication. This was due to US shrimps being produced in a closed indoor system that used more materials and energy, while effluent water was treated and reused. Sometimes, different electricity generating files among regions might be another pivotal environmental performance driver. The electricity generating mix of many developing countries such as China and India is still coal-dominated (Deng & Wang 2003). If the electricity mix

Table 5 Environmental impacts of 1 tonne of live-weight fish produced

Species	System	Location	Acd. (kg SO_2 eq)	Eut. (kg PO_4 eq)	GW (kg CO_2 eq)	CEU (GJ)	Reference
Shrimp	Monoculture	China	32	48	4020	48	Cao *et al.* (2011)
Mixed products*	Polyculture	Philippines	34	129	3550	46	Baruthio *et al.* (2009)
Prawn†	Polyculture	Philippines	48	172	5110	67	

Acd., acidification; Eut., eutrophication; GW, global warming; CEU, cumulative energy use.

*Mixed products include prawn, tilapia, milkfish and crab from polyculture.

†Environmental impacts of prawn from polyculture are allocated based on its economic value.

Table 6 Environmental impacts of 1 tonne of live-weight fish produced intensively

Species	Location	Acd. (kg SO_2 eq)	Eut. (kg PO_4 eq)	GW (kg CO_2 eq)	CEU (GJ)	BRU (kg C)	Reference
Salmon	Norway	17.1	41.0	1790	26.2	111 000	Pelletier *et al.* (2009)
	UK	29.7	62.7	3270	47.9	137 000	
	Chile	20.4	51.3	2300	33.2	56 600	
	Canada	28.1	74.9	2370	31.2	18 400	
Shrimp	China	43.9	63	5280	61.5	60 700	Cao *et al.* (2011)
	USA	50.6	1.5	5910	99	–	Sun (2009)
	Thailand	18.5	10.6	5210	–	–	Mungkung (2005)

Acd., acidification; Eut., eutrophication; GW, global warming; CEU, cumulative energy use; BRU, biotic resource use.

could be changed toward less carbon intensive energy production such as hydro, natural gas or nuclear power, the impact on global warming would be reduced significantly.

Life cycle comparison of agri-food and seafood products

Seafood is an alternative protein source to agricultural livestock products. The unique medium of aquaculture also presents new challenges for LCA. It is interesting to use well studied agri-food products for bench-marking when assessing the environmental impacts of seafood products. A comparison of the environmental performance of agriculture and aquaculture products would also be in demand for certification and eco-labelling to guide purchasing decisions for more sustainable consumption. Several studies have been conducted to rank the environmental performance of different agri- and aqua- food products (Ellingsen & Aanondsen 2006; Williams *et al.* 2006; Mungkong & Gheewala 2007; Ellingsen *et al.* 2009; Cao *et al.* 2011).

The results from several recent studies are summarized and compared on a weight-basis in Table 7. Average values are used for products from the same region. Based on the current listing, agri-food products, except chicken, are usually more CO_2-intensive and performed worse in acidification and eutrophication than seafood products from both capture fisheries and aquaculture. Beef is the most CO_2-intensive due to the greenhouse gas emissions from animals and manure. Beef also has the highest impacts in acidification and eutrophication. Beef production also uses more land than aquaculture-based seafood. Wild-caught seafood, followed by farmed seafood, is more energy-intensive than agri-food. The acidification potential of wild-caught fish is comparable to that of farmed fish. Wild-caught seafood has the lowest eutrophication potential compared with farmed fish or agri-food. This was probably due to zero wastewater discharge and no supplementary commercial feed in capture fisheries. Wild-caught fish is more land intensive than farmed fish or agri-food. The land intensity for wild-caught fish is driven by trawling and the area of the seafloor per

Table 7 Environmental impacts of 1 tonne of agri-food and seafood products

Product	Location	GW (kg CO_2 eq)	Acd. (kg SO_2 eq)	Eut. (kg PO_4 eq)	CEU (GJ)	Land (1000 m^2)	Reference
Beef	UK	25 300	708	257	40.7	38.5	Williams *et al.* (2006)
Pork	UK	6360	395	100	16.7	7.4	
Chicken	UK	4570	173	49	12	6.4	
Farmed shrimp*	Asia	5250	31	37	54	2.2	Mungkung (2005); Cao *et al.* (2011)
Farmed salmon*	Europe	2450	22.4	51.7	43.3	6	Ellingsen and Aanondsen (2006); Pelletier *et al.* (2009)
Farmed trout*	France	2270	15.2	38.5	58.8	–	Aubin *et al.* (2009); d'Orbcastel *et al.* (2009)
Wild-caught cod*	Europe	3000	–	–	81.3	1390	Ellingsen and Aanondsen (2006); Mungkong and Gheewala (2007)
Wild-caught tuna	Spain	1800	24	3.7	–	–	Hospido and Tyedmers (2005)

GW, global warming; Acd., acidification; Eut., eutrophication; CEU, cumulative energy use.

*Average value is presented.

trawled fish is accounted for in these studies (Mungkong & Gheewala 2007). It should be noted that the land use impacts related to the production of fishmeal used in aqua- and agri-feed are not considered in these studies (Mungkong & Gheewala 2007). For farmed fish and agro-food products, only the land areas used for producing fish/husbandry animals and feed are accounted for in the land use impacts. By only considering land used for the extraction and production of fuel energy in fisheries and for the production of feed raw materials in aquaculture, van den Burg *et al.* (2011) had a different conclusion that wild-caught fish had lower land use impacts than farmed fish.

However, due to differences in data sourcing, system boundaries, functional units, allocation procedures, impact assessment and interpretation methods, and other methodological nuances, comparisons between LCA studies could be subjective and should be made with caution (Mungkong & Gheewala 2007; Cao *et al.* 2011; Heller & Keoleian 2011; Henriksson *et al.* 2012). A detailed discussion of these methodological differences that can significantly influence the outcomes of LCA studies can be found in Henriksson *et al.* (2012). In comparative LCA studies, the selection of an appropriate functional unit is most important. Since the main function of seafood is to provide nutrients, Mungkong and Gheewala (2007) proposed to compare different products based on the nutritional values gained per kg of products, rather than directly compare them on a weight- or protein-basis. Comparison of the different food products with different value chains will be very complicated. Thus, it is necessary to develop a standardized impact assessment methodology to gain a true basis for comparison in the future studies (Ellingsen *et al.* 2009).

Modelling biodiversity loss in LCA

Biodiversity loss is perhaps currently the most serious environmental problem. Global biodiversity is suffering a sharp decline and continuing at an alarming rate (Curran *et al.* 2011). The major causes of aquatic biodiversity loss are invasive species, habitat loss, pollution and overfishing for fishmeal species associated with aquaculture (Diana 2009). Current aquaculture systems now have mostly negative impacts on aquatic biodiversity. None of them is truly sustainable from a biodiversity perspective (Diana 2009). Impacts arise from resource consumption, land modification and waste generation. Diana (2009) listed the five most important effects of aquaculture on biodiversity, including escapement of aquatic crops and their invasive potentials, effluent effects on water quality, conversion of sensitive land, inefficient resource use, and the spread of diseases and parasites. Therefore, it is essential to assess biodiversity loss caused by aquaculture and to examine the opportunities for better protection of aquatic biodiversity. Biodiversity should be included as one of the most important impact indicators of sustainability.

Five direct drivers of biodiversity loss have been identified by the Millennium Ecosystem Assessment in 2005 (MA 2005). They are habitat change, climate change, invasive species, pollution and overexploitation of wild populations. Although the development and inclusion of biodiversity in LCA has been ongoing for more than a decade, many methodologies in LCA are still in their infancy (Curran *et al.* 2011). To date, three of five drivers of biodiversity loss have been treated in LCA to some degree, including habitat change, climate change and pollution. They have been developed into impact categories of land use, water use, global warming, eutrophication, acidification and ecotoxicity. However, land use (m^2) in LCA does not characterize the impacts on biodiversity. A new method for evaluating the impacts on biodiversity from land use in agricultural LCA has been proposed with a focus on species richness (Schmidt 2008). Similarly, mean species abundance and sensitivity to erosion were adopted to identify land-use changes in catfish farming (Bosma *et al.* 2009). Two drivers including invasive species and overexploitation are still completely missing in the LCA framework (Curran *et al.* 2011). A number of complete or ongoing studies are attempting to include them quantitatively on the functional unit basis or qualitatively into an expanded LCA framework (Pelletier *et al.* 2007; Jeanneret 2008; Alkemade *et al.* 2009). Many novel impact categories have been developed but not yet scrutinized. Pelletier *et al.* (2007) also suggested that impact categories in agricultural LCAs can provide a basis for impact category development for seafood. To characterize meaningfully biodiversity in LCA, Curran *et al.* (2011) offered two recommendations for future research: First, the methodological shortcomings should be addressed; then, data representative of distribution of global biodiversity and its pressures should be acquired. Integrating the missing drivers and impact factors of biodiversity could further enhance the credibility of sustainability assessment in LCA (Curran *et al.* 2011).

Using LCA for certification and eco-labelling

Certification and eco-labelling systems for aquaculture are used to identify sustainable seafood products based on their relative environmental performance. They are a form of sustainability measurement that integrates environmental concerns into the aquaculture sector. Certification and eco-labelling intend to prevent misleading advertising, provide producers with market-based incentives and direct consumers towards more sustainable food consumption. Three types of labelling schemes have been defined in the ISO 14020 family (ISO 2000): Type I is a multi-attribute label developed by a third party; Type II is a single-attribute label developed by the producer; Type III is an eco-label is based on a full life-cycle assessment.

At present, certified and eco-labelled food products represent one of the fast growing food markets, with a growth rate at 20–25% per annum (Pelletier & Tyedmers 2008). The rapid development of diverse certification and eco-labelling systems underscores the need to standardize criteria to provide producers with clear guidelines and reduce consumers' confusion (Pelletier & Tyedmers 2008). There are now many certification initiatives and consumer awareness programmes focusing on food safety, animal welfare, environmental protection and social risk assessment standards. However, few of them are life-cycle based and fully cover all relevant environmental issues. Developing robust measures of sustainability and its assessment tools have been highlighted by the World Wildlife Fund (WWF) aquaculture dialogues (Bostock *et al.* 2010). Life cycle assessment is one of the key approaches that can provide a relatively comprehensive measure of the sustainability in the seafood sector to inform certification and eco-labelling criteria. It helps to identify key environmental impacts in the product life cycle that can be used as certification or eco-labelling criteria (Mungkung *et al.* 2006). Mungkung *et al.* (2006) identified abiotic depletion, global warming and eutrophication as key environmental impacts for shrimp aquaculture that could be covered by eco-labelling criteria. Other important impacts including depletion of wild broodstock, impacts of trawling for fishmeal species on marine biodiversity, the choice of suitable farm sites, disease spread and release of invasive species could not be quantified by traditional LCA. They can be included as 'hurdle criteria' and qualitatively described in the expanded LCA (Mungkung *et al.* 2006).

The use of LCA for setting certification and eco-labelling criteria is still very much limited, since socio-economic impact categories are still under development in the LCA framework. Some economic and social indicators at each life cycle stage were proposed for assessing the sustainability of agri-food systems (Heller & Keoleian 2003), which could be also utilized for assessing seafood production systems. Those indicators include land conversion rate, farm profitability, average wages, health benefits, quality of life and worker satisfaction (Heller & Keoleian 2003). However, methodologies for the integration of social and economic sustainability through a life cycle approach are still in their early stages. There are increasing efforts working on the integration of social and economic aspects into the LCA framework (Kruse *et al.* 2009). For instance, life cycle costing has often been employed to address economic issues. Guidelines for social life cycle assessment have also been developed to address social issues (UNEP/SETAC 2009). However, practical applications of social life cycle assessment are currently very limited. Future development and refinement of those economic and social sustainability indicators are needed.

Conclusion

An increasing number of LCA studies of aquaculture have been published. This indicates that LCA is an appropriate means and will become a mainstream tool to evaluate global and local environmental impacts of seafood production systems. As a systematic approach, LCA can evaluate the sustainability of aquaculture systems quantitatively from a cradle-to-grave perspective. By assessing system performance, it presents a useful basis for system improvement in terms of environmental sustainability and the development of certification or eco-labelling criteria. However, existing LCA methods are not capable of quantifying local ecological and socio-economic impacts, which limits its ability and future application. More efforts should be given to adapt the tool for aquaculture applications, as well as integration of current missing (such as biodiversity) or immature (such as socio-economic) impact indicators for more comprehensive evaluations of system/product sustainability. Overall, LCA is a useful tool and has great potential in assisting decision-making for more sustainable seafood production and consumption.

Comparative LCA studies indicate that farming systems with relatively lower intensity using more natural systems are more environmentally preferable. Semi-intensive farming outperforms intensive farming systems. Closed recirculating systems outperform open systems in eutrophication emission and biodiversity reservation but all other environmental impact categories such as global warming and energy use are substantially worse. Polyculture appears not superior to monoculture in terms of environmental sustainability. All current seafood production systems generate environmental burdens and thus environmental sustainability is measured in relative terms. Organic farming with low intensity seems to be a promising system if animal-derived ingredients are substituted with proper plant-based ingredients in the feed. By comparing captured and farmed seafood with agri-food products, agri-food products, except chicken, are usually more CO_2-intensive and perform worse in acidification and eutrophication than seafood products. Beef is the most CO_2-intensive and generates the highest impacts in acidification and eutrophication. Wild-caught seafood is more energy-intensive than farmed seafood and agri-food. More comparative studies are needed to benchmark different aquaculture production systems and their seafood products to promote more sustainable production and consumption. These comparative studies will require the development of a more appropriate functional unit(s) and a more comprehensive set of life-cycle based impact indicators.

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