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Mangrove-shrimp farms in Vietnam – comparing organic and conventional systems using life cycle assessment

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ABSTRACT

Interactions between aquaculture and the environment remains a debated issue, especially in areas where the aquaculture sector is still expanding, such as in the Mekong delta in Vietnam. In response to environmental concerns, various eco-certification schemes have been introduced for seafood, aiming to improve production practices. In order to reflect upon the criteria of these certification schemes, life cycle assessment (LCA) was applied to conventional and certified extensive organic mangrove-shrimp farms in the lower Mekong. In total, 21 organic and 20 non-organic farms were included in the study for evaluation of effects on global warming (including emissions from land transformation and occupation), eutrophication and acidification. Monte Carlo simulations and random sampling was applied to aggregate contributing processes into results. The emissions of greenhouse gases per tonne of shrimp produced were substantial for both groups, and almost solely caused by the release of carbon during mangrove land transformation. Differences in the land area needed to support shrimp production explain the discrepancy. Organic farms emitted less CO_2-equivalents (eq.) than the non-organic farms in 75% of the Monte Carlo iterations. Acidification impacts were similar for the two groups, with higher emissions from the non-organic farms in 67% of the iterations. Meanwhile, most mangrove-integrated farms showed a net uptake of eutrophying substances, indicating that both types of mangrove-shrimp production systems are nutrient limited. In order to put the results into perspective, a comparison with intensive and semi-intensive shrimp farms was made. While the extensive mangrove-shrimp farms showed higher emissions of CO_2-eq. per tonne shrimp produced (20 tonnes in average for organic and non-organic farms compared to 10 tonnes from intensive/semi-intensive production), results indicated lower impacts in terms of both acidification and eutrophication. We recommend LCA to be used as a central tool for identifying practices relevant for eco-certification audits, including considerations for land use. However, a better understanding of the consequences of land quality change and linkages to impacts at the ecosystem level e.g. effects on ecosystem services, are needed.

Key words: shrimp, aquaculture, life cycle assessment, organic, eco-certification, Vietnam

1. INTRODUCTION

During the last decade there has been a rapid increase in the number of eco-certification schemes for aquaculture (Washington and Ababouch 2011; Bush et al., 2013). The main objective of these programs has been to incentivise a shift towards more sustainable production methods and ultimately to reduce negative environmental impacts and improve the environmental image of the sector. The demand for organic-certified seafood has been growing, particularly in Europe, but also among the middleclass in low/low-middle income countries (Prein et al., 2010). A number of certification bodies have standards specifically developed for organic shrimp culture (e.g. Naturland (2012) and Soil Association (2011)). In brief, organic standards restrict the use of toxic chemicals (for instance synthetic pesticides), antibiotics and inorganic fertilizers, and also oppose practices that result in negative impacts on the local ecosystem (particularly mangrove forests). There is, however, a growing need to standardize the audits used by different certification bodies, and to promote methods for quantifying the environmental benefits of different certification schemes (Blackman and Rivera, 2010; Jonell et al., 2013)

The present study aims to assess differences in environmental performance between organic and non-organic mangrove-shrimp farms using life cycle assessment (LCA), and to evaluate the potential usefulness of LCA as a tool for determining environmentally favourable practices. The results could be used to advance the requirements of existing aquaculture eco-certification schemes, as well as increase our understanding of the environmental impacts related to mangrove-shrimp farming. This information may be relevant for certification programs, policymakers and organisations working with sustainable seafood awareness campaigns.

1.1 Organic certification of shrimp in Ca Mau, Vietnam

Vietnam is the largest producer of farmed *Penaeus monodon* (giant tiger prawn) in the world, with a production increase of 400% (from 67.5 to 333 thousand tonnes) between 2000 and 2010 (FAO, 2013). Ca Mau stands out as the leading province for shrimp farming, both in terms of area occupied and volume of shrimp produced (Ha et al., 2012) (Fig.1). More than half the provincial surface area is used for aquaculture production, of which shrimp farming is dominant (Omoto, 2012). Despite that large areas of mangrove forest were destroyed in Ca Mau during the Vietnam war (Second Indochina War between 1956 and 1975) (Omoto, 2012), the province still holds about half of the remaining intact mangrove forest in the Mekong delta (Ha et al., 2012). Integrated mangrove-shrimp farms make up around 15% of the shrimp farming area in Ca Mau, but contributes with less than 5% towards total production (Ha et al., 2012). These extensive polyculture systems are regulated by the provincial government to maintain a mangrove forest-to-pond area ratio of at least 40%, and are characterised by no/low feed inputs, no/low fertilization rates, passive water exchange and low production (Ha et al., 2012).

Organic certification of integrated mangrove-shrimp farms was initiated in Ca Mau province in 2001 by the Vietnam Association of Seafood Exporters and Producers (VASEP) in collaboration with the Swiss Import Promotion Program (SIPPO) (Ha et al., 2012). By 2010, around 1 000 integrated mangrove-shrimp farms had been certified by the German organic certification scheme Naturland and audited by the certification body Institute for Market Ecology (IMO) (Ha et al., 2012; Omoto, 2012). The shift from non-certified to organic did not require major changes in farm infrastructure nor production practices since the majority of the farms were not using supplementary feeds or commercial fertilizers, and had a mangrove cover exceeding 50% of the pond area. Thus, a majority of the mangrove-shrimp farms in the area were already complying to the organic aquaculture standards, even before entering the Naturland-program (Ha et al., 2012).

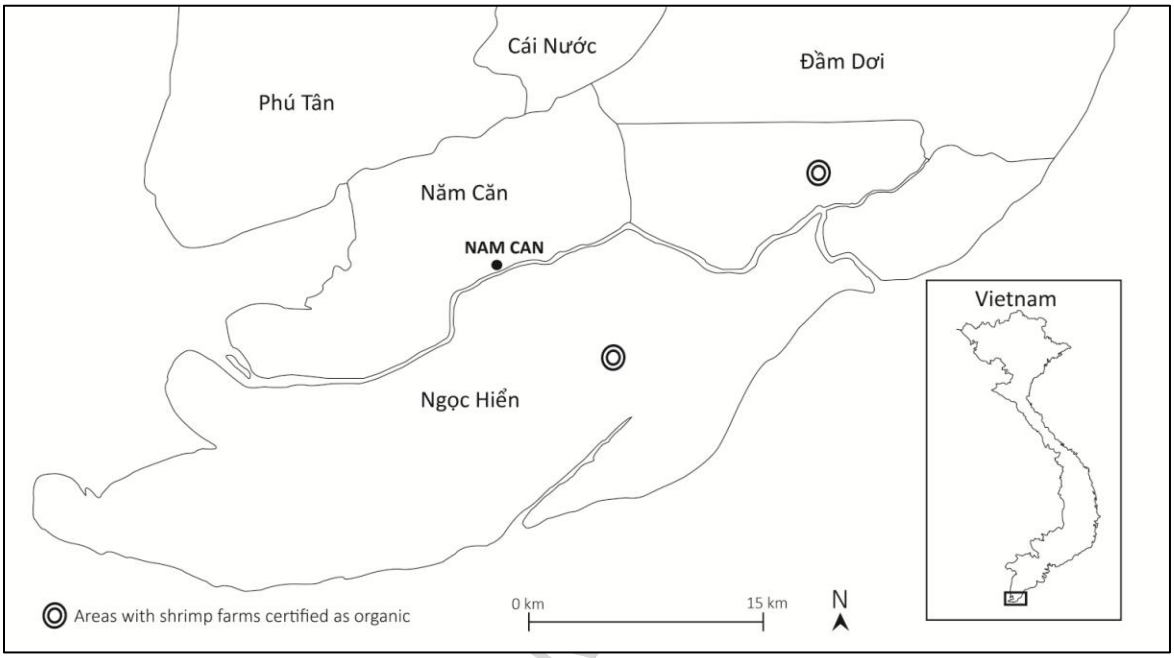

Fig. 1 Map over Ca Mau province in Vietnam. The circles represent areas with Naturland certified farms.

1.2 Study area and system description

Primary data were collected in Ngọc Hiển and Năm Căn district in Ca Mau province, Vietnam (Fig. 1). Two main pond designs were present in the area: mangrove (*Rhizophora apiculata*) integrated farms, and farms with mangrove growing only in proximity to (but not inside) ponds (Clough et al., 2002). In the former system, shrimp were farmed in 3-4 m wide channels dug through the mangrove (Fig. 2). This integrated type of farm was the most common and represents the design of all farms included in this study.

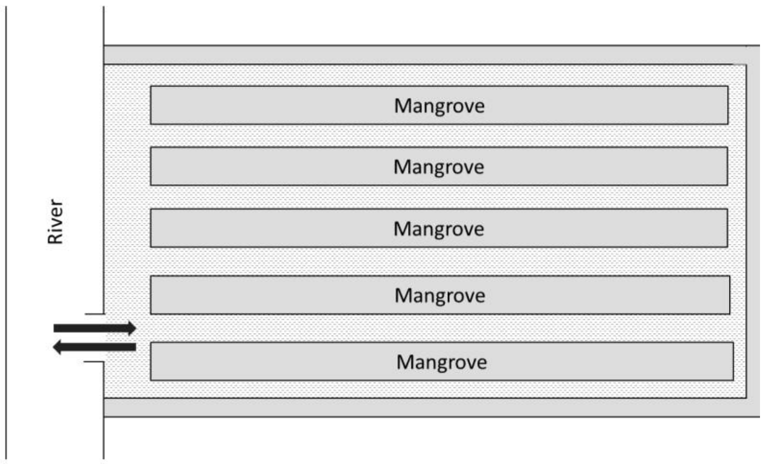

Fig. 2 Mangrove-shrimp farm design. River water enters and leaves the farm through one or two sluice gates, which are opened manually at harvest and during high-tide to let water into the farm. Mangrove trees surround the farm and also occupy the elevations between the channels. Figure adapted from Clough et al. (2002).

Mangrove-shrimp farms in Ca Mau traditionally depend upon wild shrimp species (primarily *Penaeus indicus, Penaeus merguiensis, Metapenaeus ensis* and *Metapenaeus lysianassa*) entering the ponds through a sluice gate during spring tide. Manual stocking of *Penaeus monodon* shrimp is a more recent phenomenon, dating back to around 1990 (Omoto, 2012). At present, ponds are also frequently stocked manually with mud crab (*Scylla serrata*). Stocking of both species occurred all year round and harvesting usually took place during spring tide for three to five days.

1.3 Using Life Cycle Assessment (LCA) to assess impacts from implementation of eco-certification

LCA is a "cradle to grave" tool that aims to assess the environmental impacts of a product throughout its value chain. LCA has been put forward as a potentially important tool for the formulation of eco-certification criteria for wild caught fish (Thrane et al., 2009), aquaculture products (Mungkung et al. 2006), seafood certification, and sustainability schemes in general (Pelletier and Tyedmers, 2008). However, when it comes to investigating differences in environmental impacts between certified and non-certified seafood production systems, few studies have been conducted (e.g. Pelletier and Tyedmers, 2007). Even though a lifecycle perspective is required by the International Organization for Standardization (ISO) 14020 series when setting criteria for eco-certification (Mungkung et al., 2006), present seafood certification programs address a limited number of the environmental impacts covered by LCA (Pelletier and Tyedmers, 2008; Belton et al., 2010). Evaluating the environmental trade-offs of implementing eco-certification schemes is an important step in understanding which impacts certification influence and to which extent.

1.4 Aim of the study

The main objective of this study was to compare two different groups (one certified organic by Naturland, and one non-certified) of mangrove-shrimp farms producing *Penaeus monodon* in Vietnam. Since mangrove-shrimp farms are located in mangrove forests and appropriate larger areas for production compared to more intensive farms, special focus was given to greenhouse gas emissions (GHGs) resulting from land transformation and occupation (Koellner et al., 2012). Besides global warming, the impact categories of eutrophication and acidification were also evaluated. Data for the two groups were collected in Ca Mau province, Vietnam, in 2012. The outcomes were also compared to intensive and semi-intensive farms in order to provide an assessment against more intensive production systems (Henriksson et al., 2014a).

2. METHODS

2.1 Life cycle assessment

The present paper follows the four LCA phases defined in the ISO standard (14044): goal and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation/discussion. The goal and scope defines the ambition of a study, its intended audience, methodological choices and any assumptions made. Based upon this premise, the LCI is modelled. An LCI consists of an assembly of connected unit processes that detail inputs and outputs from activities throughout a production chain. LCI results are attained by aggregating all unit processes entailed within the system boundary (as defined in the goal and scope) and scaling these to a functional unit. If dispersions are considered, an error propagation method is also needed (Heijungs and Lenzen, 2014). Thereafter the LCI results can be classified and characterised towards impact categories in the LCIA phase. Lastly, the results are reflected upon and communicated in the interpretation phase.

2.2 Goal and scope definition

This comparative study aimed to evaluate the differences between two production systems of *P. monodon* in Vietnam. Given that certified and non-certified shrimp generally are distributed and consumed in identical ways, this attributional LCA study only considered the systems from cradle to farm-gate. The system boundary covered the same upstream processes as considered by Henriksson et al. (2014a), including energy provision, extraction of raw materials, upgrading of materials, agriculture, capture fisheries, hatcheries, cultivation of shrimp and harvest (Fig. 3). Infrastructure was excluded from the present study as earlier work has demonstrated it has negligible influence on the lifecycle impacts considered herein for aquaculture production (Ayer and Tyedmers, 2009; Henriksson et al., 2012). Land use and land use change (LULUC) were evaluated solely for the cultivation phase and feed production (excluding land used for hatcheries), as these were deemed most relevant for the evaluated production systems. For methodology for inclusion of LULUC related to feed production, see section 2.5, 'Comparison with intensive and semi-intensive shrimp farms'. The functional unit of this study was 1 000 kg of live weight shrimp at farm-gate. Data on feed production, transportation, and electricity production in Vietnam were sourced from Henriksson et al. (2014a), while additional LCI data were obtained from the ecoinvent v2.2 database (ecoinvent.ch).

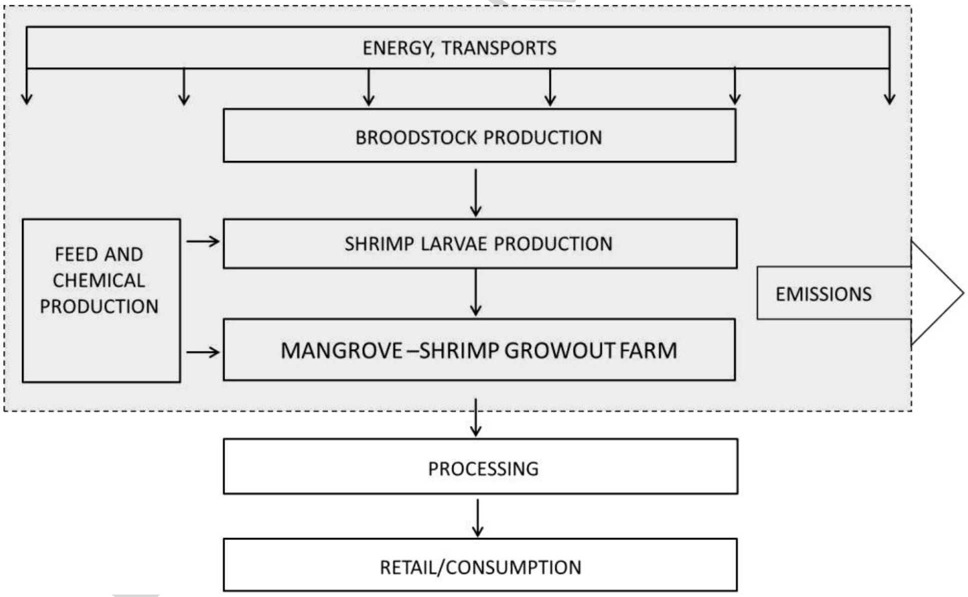

Fig. 3 Flowchart of the general cradle to retail lifecycle of shrimp farmed in mangrove-shrimp farms. The shaded area represents the system boundary of the present study.

From previous LCAs of aquaculture systems, the three most commonly implemented impact categories were evaluated in the present study (Henriksson et al., 2012), namely eutrophication (Eut.) (kg PO_4-eq.), acidification (Acd.) (kg SO_2-eq.), and global warming (GW) (kg CO_2-eq.). Eco-toxicity and human toxicity are impact categories that also would have been highly relevant to the present study since one of the main characteristics of organic aquaculture is restrictive use of hazardous chemicals. However, due to incomplete inventory data and a lack of characterisation factors for some of the agents most relevant to the present study, no toxicity impacts were quantified. Similarly, for biodiversity impacts, limited guidelines and limited characterisation factors results in such large uncertainty that few conclusions would be viable. Instead, we will address these impacts only in text.

The LCIA method applied was the midpoint CML-baseline method (Guinée et al., 2002), and the software used was CMLCA (v. 5.2; www.cmlca.eu) developed by R. Heijungs, Leiden University. To test the fit of data to distributions, EasyFit software (mathwave.com/products/easyfit.html) was employed, selecting for the most suitable out-of-four available distributions (uniform, triangular, normal and lognormal).

2.3 Allocation

Allocation is the subdivision of environmental burdens among several products originating from the same process (e.g. fish meal and oil), or among processes relying on the same product (e.g. frying oil used as fuel). Different bases can be used as numerators when conducting allocation, of which weight, gross energy content or monetary value are most commonly used in aquaculture studies (Henriksson et al., 2012). While a rough hierarchal system for selecting a procedure for allocation is presented in the ISO 14044 standard, the final choice often falls back upon the practitioner's worldview. As mangrove-shrimp farms are polyculture systems, allocation is highly relevant. In the present study partitioning based upon monetary value was adopted. While the use of economic allocation is the least preferred method according to ISO 14044, it was appropriate for this analysis as the production of shrimp is largely profit motivated (Joffre and Schmitt, 2010), rather than nutritionally motivated (e.g. Ellingsen et al., 2009). Economic allocation was consistently carried out to the furthest extent possible with regards to premade allocation decisions in the ecoinvent database. A sensitivity analysis was, however, conducted using mass allocation (ISO, 2006; Henriksson et al., 2012).

2.4 Life cycle inventory data collection

2.4.1 Primary data collection

Primary data on organic and conventional mangrove-shrimp farming practices were collected in Ca Mau province, Vietnam, in November 2012 through semi-structured on-site interviews with mangrove-shrimp farmers. In total, 21 farms certified as organic and 20 non-certified farms were included in the study for which data on pond size, share of mangrove in ponds, production and price of all species groups, scheduling over the year, use of chemicals and fertilizer, amount of shrimp larvae used, distance to hatcheries and historical land use were collected. The data on farming practices and yearly production represents an average of 2011 and 2012.

2.4.2 Shrimp post-larvae

Shrimp post-larvae (PL) were produced locally and/or in more distant provinces. The larvae purchased from local hatcheries were transported by small motor powered riverboats (which constituted the most common way of transportation as roads are scarce in the area), whereas the larvae from distant hatcheries were transported first by truck (on average 740 km one way) and subsequently by boat (estimated 30 min) to the farms. The number of transport occasions was approximated based upon stocking events per year. The speed of the small riverboats was estimated to be 20 km h^{-1} and the fuel consumption 0.3 L diesel/km (Bui et al., 2013). The inventory data for emissions related to the combustion of diesel in transport of larvae were retrieved from Waldron et al., (2006).

2.4.3 Input of fish killing plant

The majority of farms used a small amount of *Derris scandens*, a plant containing the active substance rotenone, to manage unwanted finfish in the ponds. Farming of *Derris sp.* was not included in the present inventory and given the low quantities used, the ecotoxicological effects are most likely negligible.

2.4.4 Sediment removal

Data on the type and amount of fuel used for machines removing sediments from the ponds were obtained from five farms. The majority of farms used either propane (also known as liquefied petroleum gas or LPG) or diesel. The average amount of diesel and propane used for sediment removal was 201 L ha^{-1} and 35 L ha^{-1}, respectively. It was assumed that all farms utilizing machines for sediment removal used 50% propane and 50% diesel.

2.4.5 Emissions of nutrients from grow-out farm

An estimate of the nutrient balance in the ponds (input and output of nitrogen and phosphorous) was conducted according to the pond dynamic model presented by Funge-Smith and Briggs (1998). The nutrients in stocked shrimp and crab larvae were considered negligible, and were therefore not included in the nutrient budgets of the ponds. All crustacean species (crab and shrimp, wild and stocked) were assumed to have the same N- and P-content (3.2% N and 0.33% P per wet weight unit) (Funge-Smith and Briggs, 1998). The majority of farms also harvested a small amount of fish every year (entering the ponds through the sluice gates and surviving the rotenone treatment) primarily for home consumption. Due to the small quantities of fish harvested, their effect on the nutrient balance was assumed to be negligible and fish were thus excluded from the calculations. The N- and P-content of the trash fish used as feed in one of the farms was sourced from Muangkeow et al. (2007).

2.4.6 Secondary data and background data

The inventory data for feed production, input and emissions from shrimp hatcheries, transports (boat and lorry) in Vietnam, operation of the sediment removing machine, production and transportation of lime and fertilizer were retrieved from Henriksson et al. (2014a) and supported by ecoinvent v2.2 processes. Emissions of CO_2 originating from the application of lime were calculated according to de Klein et al. (2006). Inventory data for harvesting of artemia (for shrimp larvae feed) in the US was retrieved from Mungkung (2005).

2.5 Land use and carbon footprint

The land-use and land-use change (LULUC) approach in the present study was limited to evaluate the climate impacts in the form of CO_2 emissions related to mangrove deforestation, occupation of former mangrove land and feed production. Inclusion of other potential effects of land transformation, such as impacts on biodiversity, nutrient cycling and effects on other key ecosystem services were not considered. The methodology adapted was developed by Müller-Wenk and Brandão (2010) and a brief description of the model and the assumptions made are outlined in the Appendix (Fig. A.1). For more detailed information, see Müller-Wenk and Brandão (2010). Land-use related CO_2 emissions from feed production were included by calculating the carbon footprint of land transformation for soy and cassava production (the two main terrestrial ingredients in Vietnamese shrimp feed) according to the method suggested by Müller-Wenk and Brandão (2010).

2.5.1 Sensitivity analysis for mangrove LULUC

In order to evaluate the sensitivity from modifications of the data used in the model and the given uncertainty of data, six sensitivity analyses for land transformation and climate impacts were conducted (Table 1). The baseline model assumed that 245 t C ha^{-1} reacts with oxygen and is released as CO_2 at land transformation. The occupation time was set at 50 years, the mean backflow of carbon at relaxation to 4.9 t C year^{-1} and the cut off time for the Bern carbon cycle to 500 years (for more information on assumptions and choices made, see Appendix). In Model 1, the carbon lost was set to 102 tonnes C ha^{-1}, and in Model 2 to 406 tonnes C ha^{-1}. Both figures were gathered from Pendleton et al. (2012) (as the Baseline figure), with model 1 representing 25% carbon loss at land transformation, and model 2 representing 100% carbon loss at land transformation together with sediment down to 1 m depth. Model 3 represents an alternative assumption for the lifespan of mangrove-shrimp farms, expecting the farm to be in operation for 100 years instead of 50 years (the Baseline scenario). In model 4, the mean carbon backflow at relaxation was changed from 4.9 tonnes C year^{-1} to 2.45 t C year^{-1} (the value used by Müller-Wenk and Brandão, 2010). In model 5, lost carbon sequestration (data derived from Mcleod et al., 2011) was included as an emission of CO_2, while model 6 has an altered cut-off time for the Bern carbon cycle from 500 years to 100 years.

Table 1. Six sensitivity analyses conducted to estimate the sensitivity of the model assessing the net carbon fluxes from mangrove land transformation and occupation.

Model	Description	Carbon released at transformation (tonne C)	Occupation time (years)	Mean carbon backflow at relaxation (t C year^{-1})	Lost carbon sequestration (t C year-1)	Bern carbon cycle, cut off time
	Baseline	**242**	**50**	**4.9**	**-**	**500**
1	25 % carbon loss	**102**	50	4.9	-	500
2	100% carbon loss	**406**	50	4.9	-	500
3	Occupation 100 years	242	**100**	4.9	-	500
4	50% of C-backflow	242	50	**2.45**	-	500
5	Inclusion of lost C uptake	242	50	4.9	**2.26**	500
6	100 years cut off time, Bern carbon cycle	242	50	4.9	-	**100**

2.6 Comparison with intensive and semi-intensive shrimp farms

In order to investigate how the environmental impact profile of the two groups of mangrove-shrimp farms compare to more intensive shrimp aquaculture in Vietnam, a comparison with data from Henriksson et al. (2014a) was conducted. The primary data for this study originated from 20 intensive *P. monodon* farms and 60 semi-intensive *P. monodon* farms, collected in 2011 in Vietnam as part of the SEAT project. Modelling and methodological choices were largely identical with the present study. To estimate the CO_2 emissions from land-use from these farms, the total pond areas were assumed to have been converted mangrove. While most intensive farms are constructed in areas other than coastal wetlands (Lewis et al., 2003), we chose a conservative approach to avoid underestimating the emissions of carbon dioxide from LULUC. For more information on methodological choices and assumptions, see Appendix.

2.7 Uncertainty and sensitivity analysis

With the aim of exploring the potential effects of variability and uncertainty in the dataset, overall dispersions were defined for unit process data according to Henriksson et al. (2014b). The unit processes were aggregated into LCI results using Monte Carlo simulations (1 000 iterations) in CMLCA. Alongside the quantification of overall dispersions for inventory data, sensitivity analyses were conducted for the static choices of CO_2 emissions resulting from LULUC and allocation method.

3. RESULTS

3.1 Unit process data

Characteristics of inputs and outputs to and from the 41 mangrove-shrimp farms are presented in Table 2. The data were typically not normally distributed, hence median values (and ranges) are presented (arithmetic means were used in CMLCA as it is the expected central value). Farms certified as organic generally had a larger share of mangrove in the ponds (50-78% for organic and 10-60% for non-organic), used less PL per tonne shrimp produced, and had a somewhat higher productivity than the non-certified farms (360 kg ha^{-1} compared to 229 kg ha^{-1} for the non-organic farms).

Table 2 Farm-level inputs and outputs for production of 1000 kg live weight *Penaeus monodon* from organic and non-organic mangrove-shrimp farms in Vietnam, 2012.

	Organic (*n*=21)			Non-organic (*n*=20)		
	Median	Range	CV	Median	Range	CV
INPUTS						
Land use mangrove (ha)	2.8	0.7-27.6	1.3	4.4	2.0-14.6	0.7
Post Larvae (PL) (kpcs)	486	178-1455	0.6	901	378-7958	1.1
Transport PL, boat (vkm)	26	5-197	1.2	33	5-200	0.9
Transport PL, truck (tkm)	8.3	0-150	1.4	104.5	0-712	1.1
$CaCO_3$ (kg)	0.00	0-1852	2.0	0.00	0-500	2.9
Fertilizer NPK (kg)	0.00	0-595	4.6	0.00	0.00	-
Fertilizer P_2O_5 (kg)	0.00	0-1852	4.6	0.00	0.00	-
Zeolite (kg)	0.00	0-240	4.6	0.00	0-790	1.8
Feed (kg)	0.00	0.00	-	0.00	0-421	4.5
Artemia (kg)	0.00	0-0.4	4.6	0.00	0.00	-
Trash fish (kg)	0.00	0-2222	4.6	0.00	0.00	-
OUTPUTS						
N (kg, total)	-70	-468-299	-1.6	-78	-157-(-47)	-0.38
P (kg, total)	-7	-48-364	8.9	-8	-16-(-5)	-0.36

The average yearly income (million VND $year^{-1}$) and production (kg $year^{-1}$) of the mangrove-shrimp farms are presented in Table 3. These figures are not corrected for production area, but provide an overview of the mass relations between the species farmed, as well as economic importance (allocation basis) of the three species groups produced. The majority of the farms were not using any input to the ponds except for shrimp PL and crab larvae. A greater number of non-organic than organic farms used zeolite for reduction of ammonium concentrations in ponds (6 non-organic, 1 organic). Limestone ($CaCO_3$) was applied regularly by six organic and three non-organic farmers, whereas commercial fertilizers were used in only two organic farms. Feeds were similarly used by only two organic farmers and one non-organic farmer (trash fish, commercial feed and artemia for stocked PL).

Table 3. Total yearly income (million VND $year^{-1}$) and production (kg $year^{-1}$) of shrimp, wild shrimp and crab production. Since data on income for all species as well as for production of crab and wild species was not collected for all farms, the number of farms (*n*) differs from the overall sample. The average share of incomes from aquaculture respective share of total production is presented in brackets. 1 USD = 21000 VND at the time of the study.

	Income (million VND $year^{-1}$) (average share of total income from aquaculture)	Production (kg $year^{-1}$) (average share of total prod.)
P.monodon (shrimp) (*n*=40, 41)	165 (55%)	735 (39%)
Wild shrimp (*n*=35, 37)	44 (15%)	705 (37%)
Crab (*n*=36, 37)	92 (30%)	446 (24%)

3.2 Life Cycle Impact Assessment

The impact assessment results are presented in Figure 4. The non-organic farms showed higher greenhouse gas (GHG) emissions, as well as acidifying emissions. Though the majority of organic farmers did not apply feed or fertilizer to the ponds (Table 2), the overall emission of nitrogen and phosphorous (causing eutrophication) from the organic group was higher compared with the non-organic group.

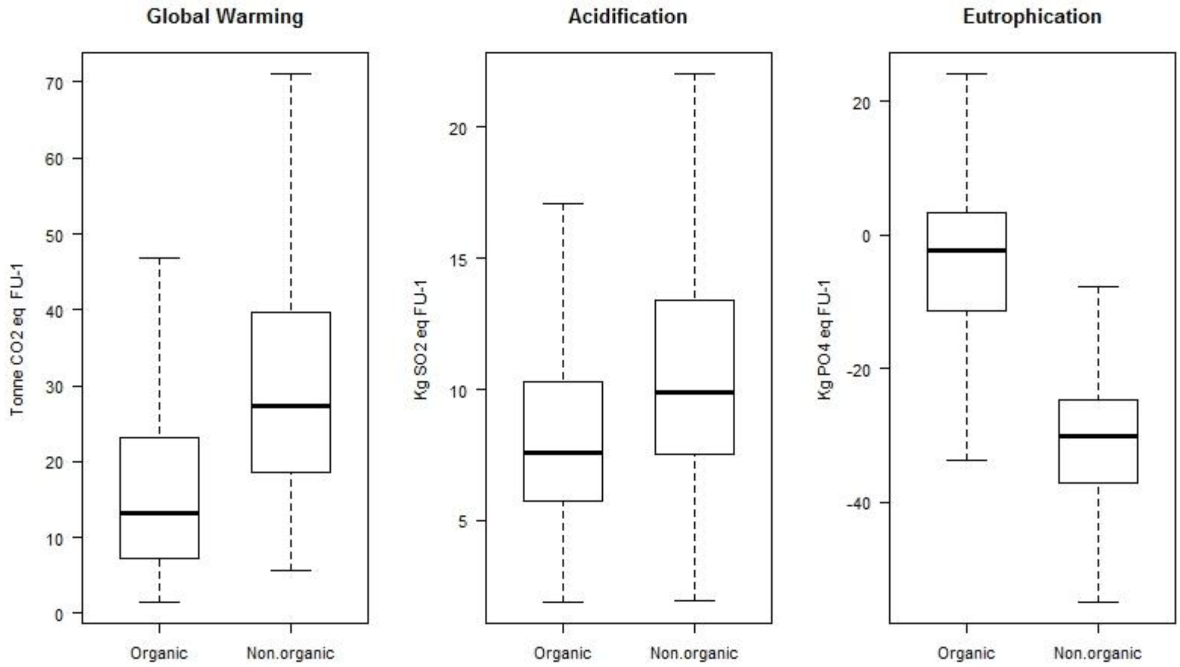

Fig.4. Comparative cradle to farm-gate impacts for organic and non-organic mangrove-shrimp farms in Vietnam producing one tonne of *P. monodon* shrimp. The figure illustrates the outcomes of the Monte Carlo simulation (1 000 iterations). The box-whisker plots indicate the median (horizontal line in boxes) alongside the first (Q_1) and third (Q_3) quartile (50% of the sample illustrated by the box), as well as the minimum and maximum values (excluding outliers, i.e. figures larger than Q_3 + 1.5*IQR or smaller than Q_1 - 1.5*IQR) represented by the whiskers. *n*=41.

The results from the LCIA are presented in Table 4 as baseline results (the product of the central value of the unit process data), and as measures of central tendency (median, mean and geometrical mean) from the Monte Carlo samples (1 000 iterations). The Monte Carlo results for global warming were closer to lognormal distribution than other distributions and consequently the median and geometrical mean can be considered the most accurate estimates of the central value. The results for acidification were also skewed to the right and therefore median and geometrical mean is recommended here as well. For eutrophication, baseline, median and mean results are considered accurate.

Table 4. The results from the Monte Carlo analysis (1 000 iterations) presented as baseline results (based on average unit process data for 21 organic and 20 non-organic farms), median, mean and geometrical mean. The geometrical mean cannot be obtained for negative figures and is therefore not presented for eutrophication.

		Baseline	Median	Mean	Geometrical mean
GW (tonne CO_2-eq. FU^{-1})	Organic	19.8	13.1	19.4	13.3
	Non-organic	31.3	27.3	32.0	27.4
Acd. (kg SO_2-eq. FU^{-1})	Organic	9.14	7.6	9.5	8.1
	Non-organic	11.2	9.9	11.2	10.1
Eut. (kg PO_4-eq. FU^{-1})	Organic	1.44	-2.4	-2.2	Non applicable
	Non-organic	-31.6	-30.3	-31.5	Non applicable

3.2.1 Global warming

Farms certified as organic showed lower emissions of GHGs compared with the non-certified farms in 75% of the 1 000 Monte Carlo iterations. Mangrove deforestation (land transformation and occupation) accounted for 94% of the GHG emissions for both groups. The second most important activity contributing to emissions of GHGs was diesel burned when removing sediments (also at the grow-out stage), accounting for 3% and 2% of the emissions for the organic and non-organic farms respectively.

3.2.2 Acidification

Non-organic farms showed higher emissions of acidifying substances than organic farms in 67% of the Monte Carlo runs. Most of the emissions (44% for organic farms and 43% for non-organic farms) originated from diesel used when removing pond sediments. For the non-organic farms, manufacturing of zeolite used in the shrimp grow-out phase was the second largest source of acidifying emissions (11%), while for the organic farms, production of fertilizer used to increase productivity in the ponds was the second most important contributor (19%).

3.2.3 Eutrophication

Most farms, both organic and non-organic, showed net uptake of eutrophying substances (N and P) indicating that they functioned as a nutrient sink. Application of fertilizer and/or feed among some organic farms, however, resulted in higher eutrophication impacts compared with the non-organic farms in 89% of the Monte Carlo runs. The production phase causing the largest emissions of PO_4-eq. was application of fertilizers for the organic farms (12.9 kg PO_4-eq. FU^{-1}) and NO_x emissions from burning of diesel in sediment removing machinery for the non-organic farms (1.26 kg PO_4-eq. FU^{-1}).

3.3 Sensitivity analyses

3.3.1 Land use and carbon footprint

The outcomes of the sensitivity analysis on the influence from mangrove LULUC on global warming are presented in Fig. 5. The results for model 1, where the amount of carbon released during land transformation was changed from 242 tonne ha^{-1} to 102 tonne ha^{-1}, showed a reduction of CO_2-eq. emissions with 64%, from 25.5 tonne FU^{-1} (Baseline model, average for all farms) to 9.3 tonne FU-^{1}. In model 2 the carbon amount released at transformation was adjusted upwards to 406 tonne ha^{-1} leading to overall GHG emissions of 47.7 tonne CO_2-eq. FU^{-1}. When applying an occupation time of 100 years instead of 50 years (model 3), the potential climate change impact was reduced with 16% from the Baseline model, to 21.5 tonne CO_2-eq. FU^{-1}. In model 4, the carbon backflow at relaxation was set to 2.45 tonne $year^{-1}$, leading to an increase of CO_2-eq. emissions by 32% to 33.7 tonne CO_2 FU^{-1}. When including lost carbon sequestration in the model (2.6 tonne ha^{-1} $year^{-1}$), the GHG emissions increased with 23% to 31.5 CO_2-eq. FU^{-1} (model 5). In model 6, the cut off time for the Bern carbon cycle was set to 100 years instead of 500 years in the baseline model leading to a substantial increase of 100% to 51.1 tonne CO_2-eq. FU^{-1}.

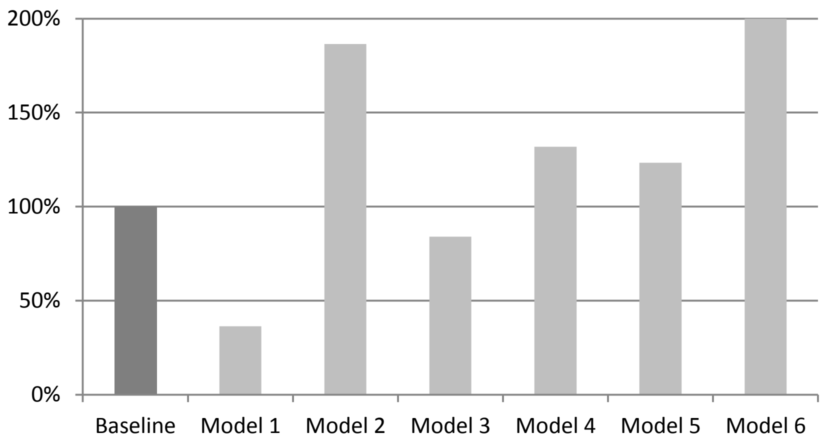

Fig. 5 The figure presents the results of the sensitivity analysis aiming to assess the model uncertainty caused by methodological choices and assumptions for calculation of CO_2 emissions from LULUC. The average global warming potential for all farms (organic and non-organic, n=41) at six scenarios for estimation of the carbon footprint originating from mangrove land transformation and occupation is presented. The data modifications in relation to the baseline scenario are written in brackets after the model number. **Baseline**: 242 tonne C Released at Transformation (CRT), occupation time (OT) 50 years, mean carbon Backflow at Relaxation (BR) 4.9 tonne year^{-1}, Lost Carbon Sequestration (LCS) 0 tonne, Bern Carbon cycle cut off Time (BCT) 500 years , **Model 1**: (CRT 102 tonne) **Model 2**: (CRT 406 tonne), **Model 3**: (OT 100 years), **Model 4**: (BR 2.45 tonne), **Model 5**: (LCS 2.26 tonne) and **Model 6**: (BCT 100 years).

3.3.2 Allocation

Mass allocation was performed as an alternative to economic allocation in order to assess the influence of allocation method used. The results showed a reduction of environmental impacts allocated to the functional unit with an average of 28% (27% for organic farms and 30% for non-organic farms), mainly explained by the large differences in price and mass of shrimps and crabs at farm-gate. For more information on how a shift to mass allocation influenced the three impact categories, see Table A.1. The relationship between total production and economic value of the different species groups produced is presented in Table 3.

3.4 Comparison with intensive/semi-intensive shrimp farms

Adding CO_2-emissions from LULUC to the LCA of the semi-intensive and intensive farms resulted in an increase of 4 tonne CO_2 eq. FU^{-1}. Soy and cassava farming contributed with 1.9 tonne and 0.3 tonne CO_2 FU^{-1}, respectively, while land use of the grow-out system gave an additional 1.8 CO_2 FU^{-1}. The median emission of GHGs for the intensive and semi-intensive *P.monodon* farms was 9.6 tonne CO_2-eq. per tonne shrimp produced (based on Monte Carlo, 1 000 iterations), representing 48% of the estimated emissions from the mangrove-shrimp farms (median for organic and non-organic mangrove -shrimp farms, Monte Carlo 1 000 iterations) (Table 5). For acidification and eutrophication, however, the more intensive production systems showed substantially higher emissions than the mangrove-shrimp farms, 36.5 kg SO_2-eq FU^{-1} and 96.7 kg PO_4-eq. FU^{1} (Table 5 and Fig. A.2). Grow-out farming accounted for on average 76% of the emissions of PO_4-eq. Emissions from agriculture related to feed production (24%), capture fisheries for feed (20%), the aquaculture grow-out system (14%) and transportations (14%) were the most important processes contributing to acidification for the intensive/semi-intensive shrimp farms. For global warming, emissions from agriculture related to feed production (including LULUC) (29%) and mangrove deforestation for establishment of the grow-out system (18%) were the highest contributing processes.

Table 5. Life cycle assessment results for mangrove-shrimp farms (*n*=41, Monte Carlo, 1 000 iterations) and semi-intensive and intensive shrimp farms in Vietnam including LULUC (*n*=20+60, Monte Carlo, 1 000 iterations). The figures presented represent the median values as well as the 1st and 3rd quartile and the 1st and 9th decile for the Monte Carlo iterations.

		Median	1st quartile	3rd quartile	1st decile	9th decile
GW (tonne CO_2-eq. FU^{-1})	Semi-intensive/Intensive	9.6	8.8	10.7	8.1	11.9
	Mangrove-shrimp	20	11.7	33.2	6.4	50.7
Acd. (kg SO_2-eq. FU^{-1})	Semi-intensive/Intensive	36.5	30.8	43.625	26.6	51.9
	Mangrove-shrimp	8.7	6.56	12	5.1	16.7
Eut. (kg PO_4-eq. FU^{-1})	Semi-intensive/Intensive	96.7	86.6	107	79.5	116
	Mangrove-shrimp	-22.2	-32.4	-2.4	-41.7	5.8

4. DISCUSSION

Vietnam has experienced a rapid expansion of shrimp farming during the last decades, and development is predicted to continue (VASEP, 2013). Paralleled with an intensification wave sweeping over the country, largely driven by an increased production of *P. vannamei* shrimp due to its higher disease resistance compared with *P. monodon*, the Vietnamese government is promoting an up-scaling of mangrove-shrimp farming certified as organic (Ha et al., 2012). The present research, however, indicates that extensive mangrove-shrimp farming can result in substantial GHG emissions as a result of mangrove LULUC. Deforestation might also have impacts on local biodiversity and resilience, as mangroves are associated with many important ecosystem services (Rönnbäck, 1999). Meanwhile, the economic incentives for the farmers to partially conserve the mangrove forest may contribute to a better overall management in the longer term. A better insight into the trade-offs between environmental and social consequences related to the preservation of these important mangrove habitats are therefore needed before any production system can be advocated over another, and lifecycle thinking should be central in the process.

4.1 Added knowledge from LCA results

The primary data on farm practices indicated some differences between organic and non-organic mangrove-shrimp farms. The greater mangrove coverage in the certified farms (50% of the area compared with approximately 40% for non-certified farms) was especially important from an LCA standpoint. Also, the lower stocking densities and higher yield of shrimp in the organic group made them seem favourable. Many production practices were, however, rather stochastic in both groups, including the use of fertilizers and feeds. Noteworthy is that some organic farms used commercial fertilizers or non-certified feeds, going against the certification standard criteria (Naturland, 2012). These specific farms might not be representative of organic shrimp aquaculture in general, but rather illustrative of a pattern of non-compliance with organic standards, also observed by Hatanaka (2010). Overall, the LCA results indicated higher GHG emissions from non-certified farms than farms certified as organic. This discrepancy could be explained by differences in land management, as more than 90% of the GHG emissions were related to CO_2 emissions from LULUC, and non-certified farmers tended to have a lower productivity in the ponds. Meanwhile, the intensive and semi-intensive systems performed better with regards to global warming than both of the mangrove-shrimp systems. With regards to acidification, the non-organic farms exhibited somewhat larger emissions (34%) but a few farms in both groups dominated the outcomes. Similarly, most mangrove-shrimp farms displayed a net uptake of substances potentially causing eutrophication, with the exception of a few farmers using alternative practices. The rationale behind these results is that the majority of farms did not apply fertilizer or feed but still maintained sizable harvests, indicating the possibility of production being nutrient limited.

Though the results from the present study indicated that there are differences in global warming impacts between certified and non-certified mangrove-shrimp farms, an important question is whether this was due to the implementation of eco-certification, or if simply only the best performing farms were selected for certification. The majority of farmers visited during the collection of primary data stated that they did not make any substantial production changes in order to get certified. Certified farmers likely performed according to the standard criteria of Naturland prior to certification (see also Ha et al., 2012). However, some farmers expressed that they benefited from training sessions on aquaculture practices and organic farming techniques offered by the processing company as a mandatory component of the certification program. Even though yields and some other differences existed between the two groups, it is uncertain to which extent implementation of organic eco-certification of mangrove-shrimp farms in Ca Mau has contributed to a shift towards or maintaining of more sustainable production practices.

4.2 Carbon dioxide emissions from mangrove-deforestation

To our knowledge, the present study is the first one investigating the environmental impacts of mangrove-integrated shrimp farming from an LCA-perspective. Moreover, inclusion of CO_2-emissions from mangrove deforestation is a new approach in LCA studies for shrimp. The sensitivity analysis performed showed that the contribution from LULUC towards global warming is greatly affected by the assumptions made and the method used. The model where the carbon emitted at transformation was set at 102 tonne C, representing 25% of the estimated carbon content in the sediment (1 m depth) and in the vegetation, resulted in the lowest CO_2 emissions. According to Pendleton et al. (2012), the low end of 25% would apply if most land uses are "relatively light-handed and retain, bury, or merely redistribute most near-surface carbon". Construction of shrimp aquaculture ponds (with an average maximum depth of approximately 1 m) can hardly be considered as light handed and instead most likely cause a larger share of the carbon stored in the sediment and the vegetation to be released. Ong (1993) estimated that as much as 750 tonnes of carbon ha^{-1} bound in sediments and 150 tonne ha^{-1} from vegetation may be released to the atmosphere when mangrove forest is transformed to aquaculture ponds. More recent estimates on carbon emissions resulting from transformation of mangrove forest (Donato et al., 2011) are in the range of emissions used for the calculations in this study (Pendleton et al., 2012) (approximately 100-400 tonne C ha^{-1}). When the occupation time was assumed to be 100 years instead of 50 years used in the Baseline model the emissions of CO_2-eq. FU^{-1} was 16% lower compared with an occupation time of 50 years. Given that the farms in Ca Mau have been in operation for approximately 30 years and that mangrove-shrimp farming can be considered relatively resistant to disease outbreaks in comparison with more intensive farming systems (Bush et al., 2010), it can be expected that 100 years is a more probable life-span. Nonetheless, the outcomes from all sensitivity tests (including the most conservative model) showed substantial emissions of CO_2 from mangrove land use and land use change.

Five types of production systems for *P. monodon* can be distinguished in Vietnam; semi-intensive/intensive farming, improved extensive (input of small amounts of feed and PL), rice-shrimp rotation and integrated mangrove-shrimp farming (Phan et al., 2011). While intensive/semi-intensive systems show the highest growth rate in utilized land area (9% in 2010), improved extensive and extensive farming still accounts for the greater share of the land allocated to shrimp aquaculture in the Mekong delta (Phan et al., 2011). Whether extensive organic farming may constitute a more environmentally sustainable model for future food production has been widely discussed (e.g. Seufert et al., 2012). The low productivity of mangrove-shrimp farms together with substantial release of carbon during land transformation argues against these practices. Meanwhile, intensive and semi-intensive farms showed higher emissions of both eutrophying and acidifying substances. Moreover, the real benefits of organic production is the reduction of chemicals in production, which remains an issue in aquaculture production (Rico et al., 2013). Particularly, the application of antibiotics is of great concern, a practice that still persists for a small number of Vietnamese shrimp farmers (Rico et al., 2013). Avoiding inorganic fertilizers and pesticides is also environmentally beneficial. Increasing production in these extensive systems by amending nutrients from organic sources, such as manure or even sediments from pangasius farms, may boost production and require less mangrove area. This is important since many of the ecosystem services provided by mangrove forest (e.g. their function as fish and shrimp nurseries and carbon sinks) may be negatively affected by the fragmentation of the landscape caused by construction of ponds. However, the fact that mangrove integrated shrimp farming may ensure the conservation of mangrove, even though fragmented, should not be neglected.

4.3 Life Cycle Assessment as a tool to evaluate effects of implementation of eco-certification – opportunities and limitations

Until now, few LCA studies have been conducted comparing the environmental performance of farms certified as organic and non-certified farms. Moreover, it has been stressed that a life cycle perspective is lacking in certification standards for seafood and that a more holistic approach is needed if eco-certification is to effectively reduce negative environmental impacts and improve the aquaculture sector as a whole. This study demonstrates that LCA may be used to assess different environmental impacts of integrated shrimp farming from a lifecycle perspective. However, the magnitude of dispersions underpinning LCA results indicates limited accuracy even for relatively assertive impact categories. Other impact categories such as biodiversity loss and ecosystem services may therefore make little sense due to their dynamic nature and site-specific impacts (the latter also applies to, for example, eutrophication effects). Trends in toxicity may also be hard to decipher when the added uncertainty of characterisation factors is considered. Moreover, additional efforts are needed towards providing more accessible and consistent ways for accounting of LULUC. Such guidelines should also consider the influence of LULUC on other impact categories, such as eutrophication. Moreover, other lifecycle impacts not included in the present study are the positive or negative social and economic impacts of mangrove-shrimp farming (e.g. increased incomes for shrimp farmers or lost functionality of the mangrove ecosystem potentially affecting people not involved in the shrimp aquaculture sector). Developments within the field of life cycle sustainability assessments (LCSA) (Zamagni, 2012) would therefore be highly welcomed into future studies similar to the presented. We believe the resources needed to conduct a detailed LCA (time and capital) are also often underestimated and generally too extensive for farm-level certification schemes. Instead, for LCA to be utilized more successfully in eco-certification programs, we suggest that (i) detailed LCAs are only applied at a sector level from where hot-spots and detrimental practices can be identified, (ii) mechanisms are implemented for continuous inventory data collection and sharing, and (ii) standardized LCA methods are systematically applied.

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Paper highlights

Organic and non-organic mangrove-shrimp farms were investigated using LCA

There were no substantial differences between organic and non-organic farms

Mangrove-shrimp farms showed a net uptake of eutrophying substances

Mangrove-shrimp farming can cause substantial emissions of GHG from mangrove LULUC