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ENVIRONMENTAL HEALTH | RESEARCH ARTICLE

A case study of life cycle impacts of small-scale fishing techniques in Thailand

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Abstract: Fish provides an important source of protein, especially in developing countries, and the amounts of fish consumed are increasing worldwide (mostly from aquaculture). More than half of all marine fish are caught by small-scale fishery operations. However, no life cycle assessment (LCA) of small-scale fisheries and no LCA of marine fishery operations in Asia (Thailand) exists today. We perform LCAs to compare the impacts of three different fishing techniques: crab gill-nets, squid traps, and fish traps. Primary data sourced from four different fishers were used. We distinguished the life cycle inventories for three different seasons (northeast monsoon, southwest monsoon and pre-monsoon), since the time spent on the water and catch varied significantly between the seasons. Our results showed the largest impacts from artisanal fishing operations affect climate change, human toxicity, and fossil and metal depletion. Our results are, in terms of global warming potential, comparable with other artisanal fisheries. Between different fishing operations, impacts vary between a factor of 2 (for land transformation impacts) and up to a factor of more than 20 (fossil fuel depletion and marine eutrophication). This shows that the way in which operations are performed have a very strong influence on results. Seasonality plays a relevant role for the assessment. Our results highlight that it is important to account for seasonal aspects in LCAs. We encourage a continual effort for collecting and modeling inventory processes, as well as making them available, in order to guarantee that LCA studies outside of Europe can be performed more easily.

ABOUT THE AUTHOR

Francesca Verones is an associate professor at the Industrial Ecology Programme of the Norwegian University of Science and Technology (NTNU). Her main research focus is the development of life cycle impact assessment methods for quantifying impacts on biodiversity and ecosystems. This work has been performed in collaboration with a student from NTNU (A. Bolowich) and colleagues from Japan in a project that attempts to bridge the gap between ecology, small-scale field studies, and the assessment of environmental impacts.

PUBLIC INTEREST STATEMENT

Fish is an important food source for many people around the world. However, like many human activities, also fishing may lead to environmental impacts. In order to be able to judge whether fish from specific operations and regions are sustainable in a broader sense (i.e. not only having minimal effects on the fish stocks, but also other environmental impacts like climate change and the depletion of resources), we can use life cycle assessment (LCA) to quantify multiple environmental impacts. Here, we quantified the impacts from three different, small-scale fishing techniques in Thailand. It turns out that small-scale does not need to mean more sustainable, as for example climate change impacts are in the same order of magnitude as for other studies. However, we have shown that not only is it important to use local data (if available), but that it is also relevant to distinguish between different fishing seasons.

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Subjects: Environmental Sciences; Environmental Issues; Environmental Impact Assessment

Keywords: Life cycle assessment; small-scale fishery; Thailand; squid; fish; crab

1. Introduction

On a global level, the consumption of fish to humans increased from just under 10 kg in the 1960s to more than 19 kg in 2012 (FAO, 2014a). The current capture level (2014) is 93.4 million tons (FAO, 2016). The increases took place mostly in developing countries because of rapid population growth and increases in amounts of fish consumed per person (Delgado, Wada, Rosegrant, Meijer, & Anmed, 2003).

Fish and other aquatic animals are important sources of protein, and the global market demand for them is higher than that of beef, poultry, and pork combined (numbers from 2009) (Tacon & Metian, 2013). The vast majority of fishers in the world are small-scale (50 of 52 million), and together they produce more than half of the world's total catch in marine fish (Berkes, Mahon, McConney, Pollnac, & Pomeroy, 2001). In Thailand, fish is an important contributor to food security. The annual per capita consumption of fish in Thailand is almost 31 kg—significantly higher than the global average (Lymer, Funge-Smith, Khemakorn, Naruepon, & Ubolratana, 2008). In addition, in the early 2000s, Thailand was the second largest global exporter of fishery commodities (Lymer et al., 2008). Marine capture fisheries contributed the majority of capture fisheries, but have been stagnating in recent years due to the larger establishments of aquaculture (Lymer et al., 2008). Still, in 2007, 58% of all fish caught in Thailand came from open sea fishing (not aquaculture) (FAO, 2009). The FAO (2016) report on the state of global fisheries mentions that there has been a decrease in Thai exports compared to 2013, but this decrease is attributed to diseases related to shrimp farming. However, Thailand is still one of the main, global exporters of squid and cuttlefish (FAO, 2016), which further stresses the importance of this study. Moreover, around 10 % of all marine fish and other animal species are caught from small-scale fishery operations in Thailand, the remainder from large-scale fishing (Lymer et al., 2008).

The definition of "small-scale" contains considerable ambiguity and several definitions exist (Johnson, 2006). Lymer et al. (2008) define small-scale fisheries as operations using boats with a gross tonnage of less than 10, which are either powered or non-powered, with fishing gear that is usually used inshore. Other definitions of small-scale fishery are that boats are shorter than 15 m or no boats are used at all (Chuenpagdee, Liguori, Palomares, & Pauly, 2006; Lunn & Dearden, 2006). We used the former definition for our study.

The importance of managing these small-scale fisheries well for both food and livelihoods is increasingly recognized in developing countries (e.g. Jacquet & Pauly, 2008). However, the importance of small-scale fisheries is known to be underestimated, since catch numbers of small-scale operations may not all be registered in national statistics or the small vessels may not even be registered (FAO, 2014b). FAO estimates that more than 90 % of all active fishing vessels (4.36 million) can be actually classified as small-scale (FAO, 2014b), highlighting their potential importance.

Lunn and Dearden (2006) report that the state of small-scale fisheries is poorly documented and understood in Thailand, particularly from a population management perspective; the same could be said regarding environmental impacts stemming from small-scale fisheries. Several LCA studies on fisheries exist, as highlighted in a review by Vázquez-Rowe, Hospido, Moreira, and Feijoo (2012). However, the focus of most of the investigated studies is in industrialized countries with a large significance in terms of fleet and domestic fisheries. LCA studies dealing with fisheries in developing countries focus so far on systems that are either producing for the market in developed countries or that are controlled by European nations (Vázquez-Rowe et al., 2012), such as shrimp production in Senegal (Ziegler et al., 2011) or octopus production in Mauritania (Vázquez-Rowe, Moreira, & Feijoo, 2012), thus not investigating small-scale fisheries taking place in developing countries themselves.

So far, only Avadí, Vázquez-Rowe, and Fréon (2014) present a study that includes next to export also domestic use and considers both small-scale and industrially sized vessels for the Peruvian anchoveta fisheries.

In order to quantify environmental impacts, life cycle assessment (LCA) can be a helpful and nowadays widely used tool (ISO, 2006a, 2006b). In LCA, the impacts of a product, such as one kilogram of fish, are quantified over its entire life cycle. This identifies the most relevant impacts and trade-offs of this product and its life cycle stages and thus contributes to improved decision-making, highlighting the most important starting points for ameliorating the environmental performance.

However, to our knowledge, there is so far no LCA of small-scale fisheries in Asia published and thus also no study for fisheries in Thailand specifically. Studies related to aquaculture have been published, but to compare small-scale, open ocean fishing to farmed fishing is likely to yield different environmental impacts for different reasons. For example, Pongpat and Tongpool (2013) found that the main contributor to global warming potential (GWP) from farmed, freshwater fish in Thailand was the feed which comprised soybean meal. A review of aquaculture LCAs by Henriksson, Guinée, Kleijn, and de Snoo (2012) found similar trends regarding fish feed. We will not include aquaculture in our study.

Shifting to small-scale fisheries is suggested by some authors as a measure for increasing the sustainability of fishery operations (Berkes et al., 2001), while other authors are critical towards this suggestion (Johnson, 2006). Parker and Tyedmers (2015) show that data for Asia are very limited and distinction between the fuel efficiency of the small- and large-scale fleet therefore very difficult.

Our aim is to contribute to closing the gap of non-existent LCA studies of small-scale fisheries in Asia. Thus, we conducted a case study of four different fishers in Thailand who operate using three different fishing techniques (crab gill-nets, fish traps, and floating squid traps) and distinguishing between different fishing seasons. We are aware of the fact that LCA studies for fisheries still face difficulties due to a lack of complete coverage of impact pathways (such as all impacts related to marine ecosystems). Further development is needed, as mentioned in Pelletier et al. (2006). We are also aware that four fishers is a low number, however they serve the purpose of a case study and allow for the identification of further research needs.

2. Methods

We used the SimaPro software (Pré Consultants, 2016) for analyzing the inventories (foreground and background systems) and midpoint impacts of the different fishing techniques (using ReCiPe 2008 with a Hierarchist perspective normalized to world values Goedkoop et al., 2009). We limited ourselves to midpoint indicators available in ReCiPe 2008, neglecting other, potentially interesting indicators, such as biotic resource use. We used the ecoinvent database 3.2 (Ecoinvent, 2015) for background processes.

2.1. Functional unit and objectives

The functional unit (FU) is 1 kg of caught target species landed and sold to the market in Rayong (live-weight). Non-target species are excluded from the study, as is by-catch, as the main focus is on the intended target species. Different functional units for assessing the nutrient value derived from food are addressed for example in Masset, Vieux, and Darmon (2015) and Stylianou et al. (2016). However, since the main focus of this article is on the comparison of environmental impacts per fishing technique rather than the impact of the type of fish consumed, we choose to use the mass of target species landed.

Target species vary between the fishing techniques from different fish to squid or crab. That means that differences in catch rates and weight of target species will be considered in the assessments. Data for fishing operations are available on a daily basis for at least one year (see more explanations below), allowing us to use averages per fishing season (3 per year).

The objectives of the study are to compare different traditional fishing methods regarding their impacts for Thailand at the midpoint level. We are aware, however, that the choice of our functional unit may be disadvantageous for fish and squid, since the edible weight to live weight ratio for crabs is lower than for fish and squid. We aim to present LCAs that are as complete as possible in that we account for all existing impact categories on a midpoint level. However, we acknowledge that some potentially relevant impacts on marine ecosystems will be neglected due to a lack of impact categories for this ecosystem type (Woods, Veltman, Huijbregts, Verones, & Hertwich, 2016). Some of these unaddressed impacts, such as by-catch, may also be negligible for small-scale fisheries, contrary to large-scale fishing operations (Jacquet & Pauly, 2008). We choose to report global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), agricultural land occupation, fossil and metal depletion potentials, as well as human toxicity, in the main manuscript. The other impact categories are reported in the Supporting Information. In addition, we compare our results with those from other studies regarding their carbon footprint and fuel efficiency.

2.2. System boundaries

The fishing operations are our main focus here (see Figure 1), and this includes the material and fuel used per technique. We do not include the vehicular transport of the target species to the market (Rayong) as there were no data to properly allocate the burden of caught species in this study from additional fish carried by the van. Essentially, we assume it is unlikely that a small van will only carry the catch from one fisher, and thus van transport was excluded from the study.

Within the fishing operations we include the building and maintenance of the boat (paint, antifouling agent) and motor, the wear-out and replacement necessary for (parts of) the fishing gear, as well as fuel consumption. We do not include discard of by-catch due to a lack of data, but rather all fish species that are not the intended target species were deemed to be "other" and not considered. By-catch can contain species with a market value (landed and attributed as "other" species here) or species with little market value that are discarded on sea. Also, "other" species also were caught with different gear (primarily hook and line), which was not assessed in this study; thus, the values used in the life cycle inventory reflect only the attributable burden to the target species. Different authors (e.g. Berkes et al., 2001; Jacquet & Pauly, 2008) mention low discard values for small-scale

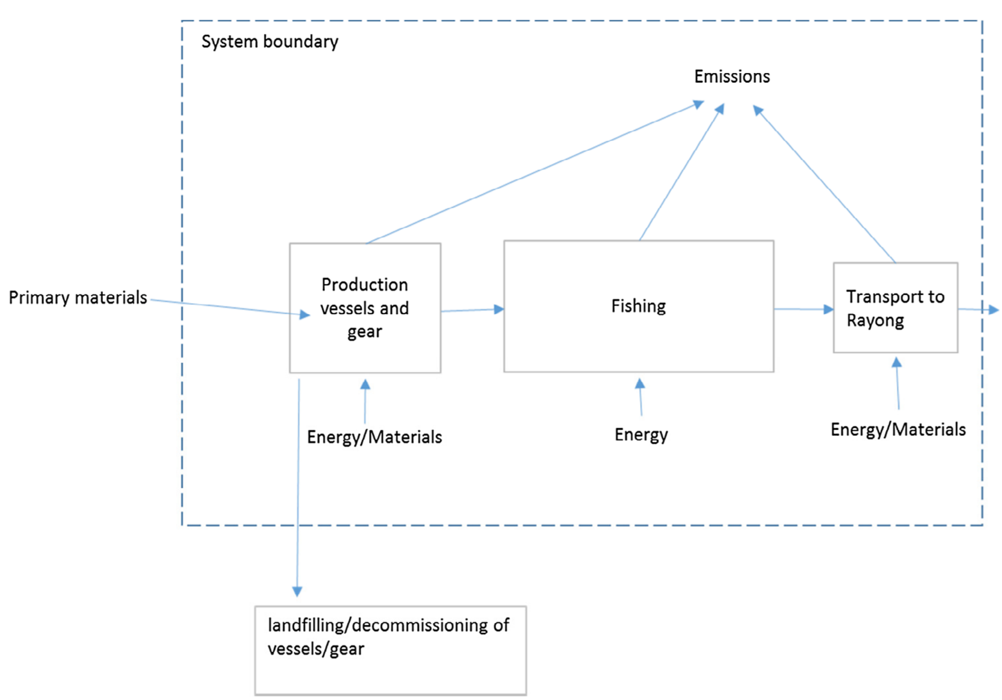


Figure 1. System boundary of the considered Thai fisheries.

Notes: We include the production of vessels and gear and follow the catch to Rayong (including van that drives to Rayong), but neglect other processes after the fish has reached the market, such as further transport and export or processing.

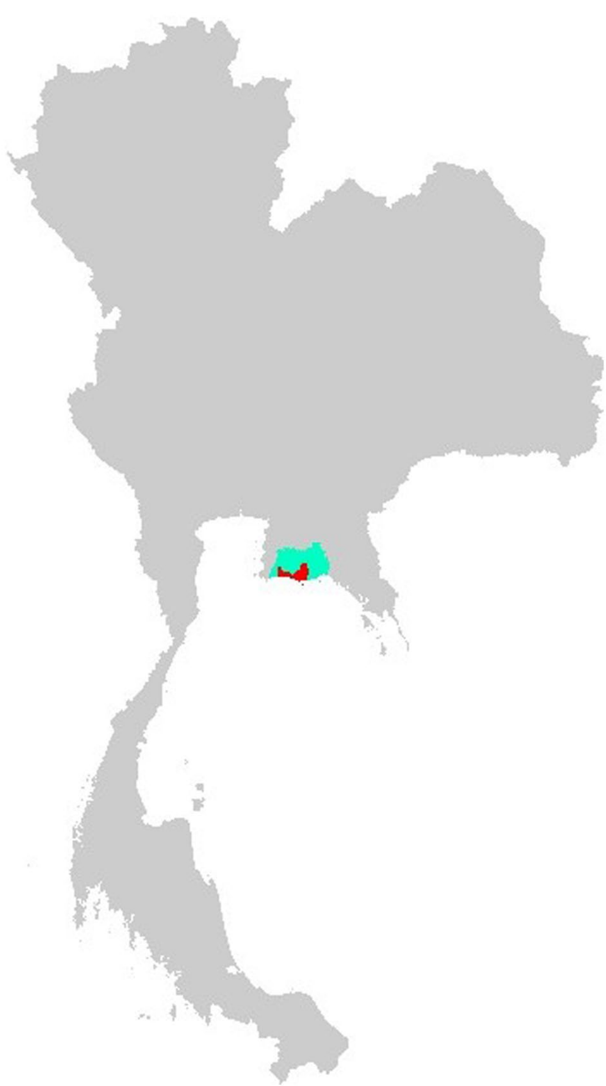
fisheries. Moreover, observations of the individual fishers have shown that discard among all fishing techniques is very small and therefore negligible.

2.3. Description of area and inventory analysis

The data for the different fishing operations were collected around the coastal area of the Rayong Province, in the Muang Rayong District (Figure 2). We have data from four individual fishers for three different types of gear. These are all representative cases for Thai small-scale fishing. The data range from one year (January – December 2013) to maximum 1.5 years (January 2013 – September 2014). The fishers report on several criteria for every day they went out to catch fish: (1) which fishing gear they used, (2) how many sets of fishing gear they used, (3) how many kilograms of catch they made, (4) what they could sell it for, (5) how many hours they were on sea, and (6) how many liters of fuel they used. Depending on the seasons, the number of hours and catch rates of fishers change considerably, therefore we distinguish between three seasons: pre-monsoon (March – May), southwest monsoon (June-October), and northeast monsoon (November-February) (Boutson, Ebata, Ishikawa, Watanabe, & Arimoto, 2016). Using the daily data, we then averaged into seasonal data. In some cases where we had additional data (e.g. January 2013 and 2014), these were averaged together. Only for Fish trap (II) was there one month (September 2013) with no data provided (for any fish caught), and thus we used data from the following year instead. The averaging and allocation of all

Figure 2. Location of Muang Rayong District (red) within Rayong province (green) in Thailand (grey).

Source: Based on data from GADM (2011).



primary data can be seen in the SI. We averaged the daily fishing data into monthly data, which, in turn, was used to calculate the average seasonal data for the values of catch, duration of operation (time on water), and fuel consumption. For allocation we used mass allocation.

The boat that all fishers, from whom we received the data, used is an open wooden boat with a length between 6.5 and 8 m and a width of 1.6–2.6 m (Boutson et al., 2016). It weighs between 1000 kg and 1700 kg and has a lifetime of 25 years. The engine is an outboard engine of 75 kg to 300 kg using diesel, with 14–19 horsepower (Boutson et al., 2016), depending on the fisher, with the assumed same lifetime as the boat. Every boat requires between 1 and 5 l of paint (assumed to be acrylic binder) and 0 and 2 l of antifouling agents (assumed to be alkyd enamel) every year. Details for each fisher can be found in Table 1. Because the wood for the boat was provided in kilograms instead of m^3, we used a density conversion factor of 825 kg/m^3 based on the ecoinvent documentation for eucalyptus wood (Althaus, Dinkel, Stettler, & Werner, 2007).

We take into account three different fishing techniques for different types of catch: crab gill-nets, fish traps, as well as floating squid traps (Table 1). Pictures of the different fishing techniques investigated can be found in Boutson et al. (2016).

Each crab gill-net is made from nylon monofilaments (1 kg) and use lead weights for weighing the net down (10 kg each). Each net has a length of 450 m and a mesh size of 100 mm. The fishers usually use four nets at the same time. The lifetime of the nets is three to five months, while the lead weights have a lifetime of 12.5 years. Polyethylene ropes (5 kg) are used to sturdy the nylon netting both at the top and bottom. Crab gill-nets are mainly used for catching the blue swimmer crab (*Portunus pelagicus*).

Fish traps (total weight 30–40 kg) are mostly made from wood (20–25 kg), chicken wire (2–3 kg), plastic polyethylene (PE) nets (0.2–0.3 kg), as well as nails and wires (included in steel calculations), weights (two cement blocks of 10 kg each with a lifetime of 12.5 years), and a plastic mid-water buoy (0.3 kg). The fish trap has an entrance of 1 m × 0.5 m and a length of 2 m. The lifetime of a fish trap is four to six months, so the assumed lifetime for one piece of gear is one season. Seven to ten traps are used for every fishing trip, depending on the fisher and the season. Target species are various fish species, such as groupers (*Epinephelus* spp.) or spinefoots (*Siganus* spp.).

Floating squid traps weigh around 16 kg in total and consist mostly of wood (ca 1.5 kg), PE nets with a mesh size of 70 mm (0.1 kg), and a plastic ball to show the location of the trap (1.5 kg), as well as nails and wire. In addition, styrofoam, or white plastic, and fresh squid eggs (ca. 0.2 kg) are used to attract the squids to the trap, but for simplicity the squid eggs have been left out of the calculation. Two to four cement blocks (10 kg each with a12.5-year lifetime) are used as weights. On average, between 16 and 20 traps are used per fishing trip. The lifetime of the floating squid trap (except for the cement blocks) is one season. Target species are mainly Bigfin reef squid (*Sepioteuthis lessoniana*) and cuttlefish (*Sepia* spp.).

2.4. Limitations, assumptions and data quality
We used the same ecoinvent 3.2 processes (Ecoinvent, 2015) across all fishing types to ensure an even comparison of data (e.g. any gear that required polyethylene used the same ecoinvent 3.2 process).

Engine components were scaled according to the diesel engine requirements used in an LCA by Jiang, Liu, Li, Zhang, and Iqbal (2014). Paint and antifouling agent data relied on densities from the Environmental Protection Agency (1995) (acrylic enamel and alkyd enamel, respectively) for conversion of kilograms to liters. The boat material was assumed to be eucalyptus grown in Thailand, a process that is included in the ecoinvent 3.2 database (Ecoinvent, 2015). The data were converted from kilograms to cubic meters using the density data provided by ecoinvent. Eucalyptus wood was also used in the gear data. Loss rates were not considered for any inventory process.

A large limitation in this study is the lack of Asian processes in the ecoinvent 3.2 database, which reduces the accuracy of our results. With the exception of Thai specific processing for eucalyptus, all background data is based on European (RER) or Swiss (CH) averages. Background processes were not adjusted (e.g. the steel process was not adjusted to account for Thai or other Asian electricity mixes used in the manufacturing).

Fuel use at sea was calculated separately, since a comparable outboard motor was not available for modeling in ecoinvent. Note that the physical parts of the engine are included in the background data (see Table 1) and only the fuel use and associated CO_2 emissions are calculated separately. For this, we used fuel use at sea values from Parker, Hartmann, Green, Gardner, and Watson (2015) to calculate the use and upstream CO_2 emissions from burning fuel. They state that one liter of diesel fuel would release approximately 3.1 $kgCO_2$. This additional calculation can be found in the SI and it is incorporated into the overall GWP. We acknowledge this fuel calculation only includes CO_2 and does not include additional contributors to GWP.

Table 1. Life cycle inventories based on ecoinvent 3.2 for three fishing techniques from four different fishers from Thailand per FU (1 kg of landed catch)

Foreground	Background inventory	Crab gill-net	Fish trap (I)	Fish trap (II)	Squid trap
Boat	Roundwood, eucalyptus ssp. (SFM), under bark, u=50%, at forest road/TH U	1.03E-05	6.09E-06	1.06E-05	2.92E-05
	Acrylic varnish, 87.5% in H2O, at plant/RER U	2.26E-04	5.60E-04	4.67E-04	1.52E-03
	Alkyd paint, white, 60% in solvent, at plant/RER U	1.02E-04	1.01E-04	4.19E-04	0.00E+00
Engine	Steel, low-alloyed, at plant/ RER U	1.40E-04	2.78E-04	1.55E-04	6.28E-04
	Cast iron, at plant/RER U	4.32E-04	8.56E-04	4.76E-04	1.93E-03
	Aluminum, primary, at plant/ RER U	2.99E-05	5.91E-05	3.29E-05	1.34E-04
	Aluminium alloy, AlMg3, at plant/RER U	2.46E-05	4.88E-05	2.71E-05	1.10E-04
	Synthetic rubber, at plant/RER U	6.27E-06	1.24E-05	6.91E-06	2.80E-05
Gear	Nylon 6, at plant/ RER/ kg	8.77E-03	–	–	–
	Lead, primary, at plant/ GLO/ kg	7.02E-03	–	–	–
	Polyethylene, LDPE, granulate, at plant/ RER/ kg	4.39E-02	3.67E-04	8.65E-03	2.75E-03
	Polypropylene, granulate, at plant/ RER/ kg	4.39E-03	5.51E-04	2.10E-03	6.88E-03
	Roundwood, eucalyptus ssp. (SFM), under bark, u=50%, at forest road/TH U	–	4.45E-05	1.40E-04	2.50E-05
	Steel, low-alloyed, at plant/ RER/ kg	–	4.77E-03	7.86E-03	2.75E-03
	Concrete block, at plant/DE U	–	2.94E-03	8.39E-03	2.20E-02
	Polystyrene, general purpose, GPPS, at plant/RER U	–	–	–	1.38E-03
Fuel	Fuel	1.02E-01	1.76E-01	1.84E-01	7.92E-01

Notes: Data is based on the SW season (June-October). The allocation of the material required for the entire lifetime of the boat is accounted for per season (1/lifetime*tot. catch). LCIs for the other seasons can be found in the Supporting Information (Excel file).

In addition, we are, as mentioned before, aware of the fact that there are missing impact categories for marine ecosystems and that we are therefore not fully available to assess all impacts. Hospido and Tyedmers (2005) suggest that 2/3 of the applied antifouling solids are lost to the sea. Due to a lack of data, we can, however, not include this in our impact assessment.

3. Results and discussion

3.1. Life cycle inventory

The life cycle inventory of the three fishing techniques are shown in Table 1 for one season and the supporting information (SI) for the remaining two seasons. The engine used by the fisher operating fish trap (I) is clearly the heaviest. Material used for the gears are different. We used mass allocation to allocate the inventory to the target species (crab, fish or squid).The total catch for the different seasons and techniques are shown in Table 2.

The crab gill-net is a case that is commonly used in Thai waters and our data and results can thus be used for other Thai (and potentially even Southeast Asian) cases. The homemade fish trap is also representative of Thai small-scale fishing, but varies in exact size and structure between individual fishers (as also shown in our results) and is thus harder to extrapolate to other regions. Finally, the squid trap is rather unique to Thailand in that it is a floating trap (not set on the seabed) and we therefore prefer to regard this as a specific Thai case.

3.2. Life cycle impact assessment

3.2.1. Total impacts

Since we assess the impacts on midpoint categories, we cannot compare across impact categories due to different units. In Vázquez-Rowe et al. (2012), the most frequently reported impact categories in seafood LCAs on a midpoint level (only two studies provide endpoint results, out of over 30 studies) are global warming potential (GWP), abiotic depletion potential (ADP), acidification and eutrophication potentials (AP and EP), as well as ozone layer depletion potential (ODP). Results for all impact categories can be found in the Supporting Information (SI).

In total, there are 18 midpoint categories (see SI). When comparing across the four fishing techniques, the crab gill net has the highest impact in 15 of these categories in the Pre-monsoon season. The most impacting season for crab fishing is the Pre-monsoon season because this season has the least amount of landed catch for the fisher.

We have two fish traps in our inventory. Impacts from fish trap (II) are almost always smaller than from fish trap (I). The fisher behind "fish trap (II)" was on the boat for an average 6.9 h, used 13.8 l of fuel during that time, and used on average 10 traps per trip. The fisher for "fish trap (I)" used on

Table 2. Total catch and catch of target species per season for the different techniques

Season	Crab gill-net	Squid trap	Fish trap (I)	Fish trap (II)
	Total catch [kg]			
NE	557	1,453	1,731	1,203
Pre	437	1,377	1,417	1,567
SW	1,969	1,174	3,979	1,908
	Catch of target species [kg]			
NE	401	1,414	1,385	1,203
Pre	96	1,355	1,141	1,567
SW	496	1,164	3,813	1,908

Notes: NE: northeast monsoon season (November-February), Pre: pre-monsoon season (March-May), SW: southwest monsoon season (June-October).The large total catch umbers for the crab gill-net are attributable to the catch of krill.

average 4 traps, spent 8.3 h on water, and used 18 l of fuel (see also Table 5). These averages are based on the daily reports from the fishers. The difference in engine and maintenance of the boat will also influence these results, but to a lesser degree.

It is important to note that the fisher from “fish trap (I),” however, did have higher catch weights than those shown in Table 2 because some of the catch came from barracuda (*Sphyraena* sp.). Barracuda were caught by hook and line instead of a trap, so the barracuda catch weights were considered “other” in the allocation of fish landed. We did not include hook and line in our assessment, since the technique is overly simple. The main importance is that the other fisher (Fish trap (II)) manages to fish using less fuel per kg of fish (both comparing target species and total catch, see SI). The impact of the trap itself is not large, and although fish trap (II) has slightly higher impacts on GWP from materials than fish trap (I), the fuel use is the most important factor contributing to the overall higher impact from fish trap (I). Fuel use may be influenced by fishing location, since every fisher has his own routes, depending also on the season, thus highlighting again the importance of the seasonality.

Fossil depletion is higher for the crab gill-net in relation to the other fishing types due to the amount of polyethylene used for the gear (in ropes). While the crab gill-net uses 5 kg of polyethylene per gear, the other three fishing types use less than 1 kg per gear (e.g. fish traps are covered with polyethylene). The fossil depletion will not account for the burned fuel while at sea, as the burned fuel was considered only for climate change impacts. The higher impact to human toxicity comes from the steel for fish trap (I) mostly attributed to the engine. 76% of the human toxicity impact is attributed to steel for fish trap (I) in the NE season (the highest impacting season over all seasons and all fishers). Marine eutrophication is attributed to the production of nylon for the crab gill net, with the pre-monsoon season having the highest impact (one order or magnitude higher than the other two seasons); moreover, the NE and SW seasons of the crab gill net are one order of magnitude higher than the other three fisher over all seasons.

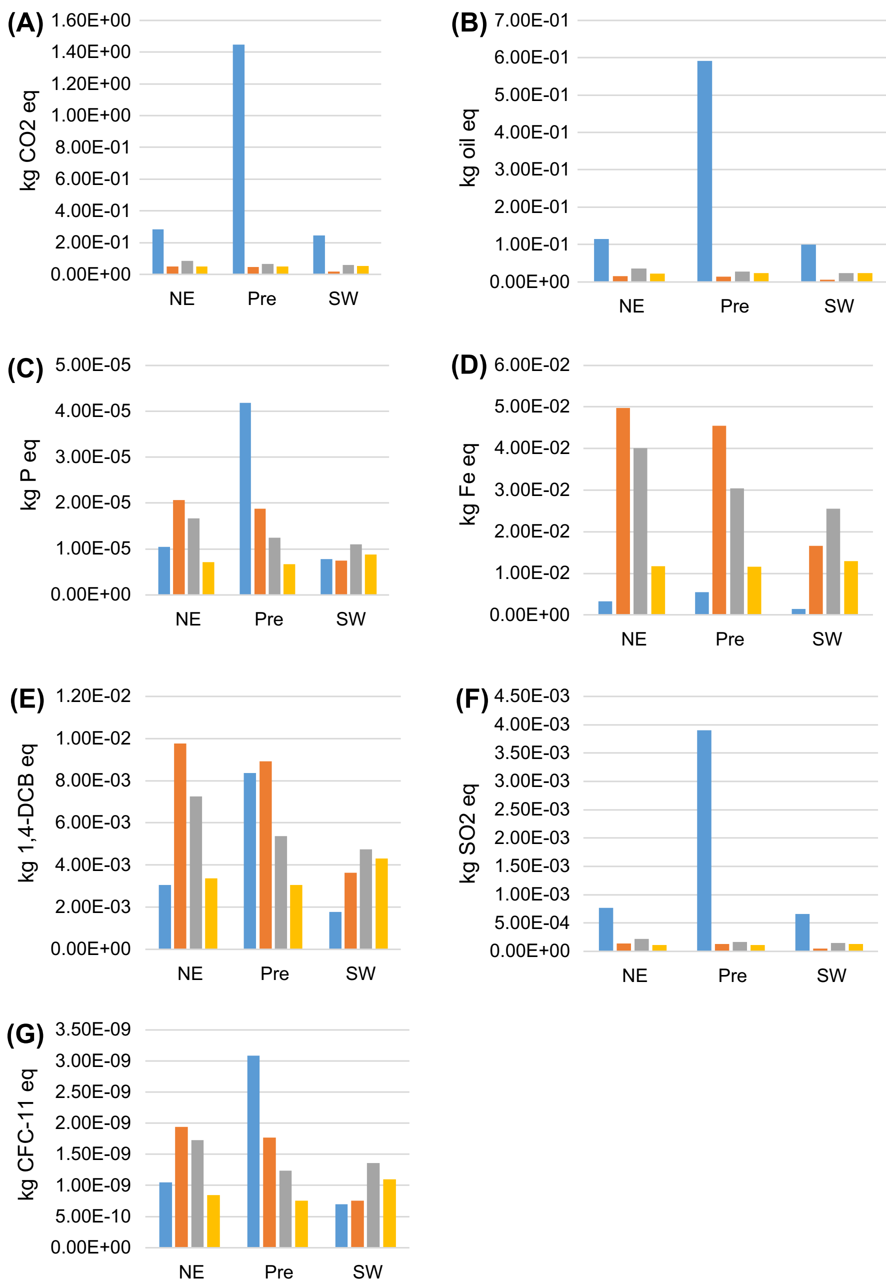
The crab gill net tended to have the largest impacts among the midpoint categories, due to the lower catch weights in comparison to the other fishers; an exception to this is for land occupation and transformation impacts, where the fish traps had higher impacts. However, it should be mentioned that for all three land impacts (agricultural, natural, and natural land transformation), all four fishers had the same order of magnitude in terms of impact with only two exceptions. The fish trap (II) in the NE season was one order of magnitude higher in relation to agricultural land occupation impacts, and the crab trap was one order of magnitude lower during the SW season for urban land occupation. This is due to the larger amount of wood needed for the fish traps (20 and 22 kg for fish trap I & II, respectively) compared to the 1.5 kg needed for the squid trap and none for the crab trap. The crab gill net still has the highest impact in the pre-season overall because of the low catch weights.

3.2.2. Seasonal differences

Seasonal differences become apparent in Figure 3. Impacts per FU are largest in the pre-monsoon season for the majority of impact categories for crab gill-nets, in the north-east monsoon season for both fish traps and the south-west monsoon for the floating squid trap. In which season impacts are largest thus depends on the target species and is directly related to the amount of target species landed. It may also be that some species, such as the crab, have seasonal patterns based on ecological changes. The blue swimmer crab (examined in this study), for example, has higher catch rates in December and January as well as June and July in Thailand (Kunsook, Gajaseni, & Paphavasit, 2014). During these drier months, the average water salinity is higher which Kunsook et al. speculate as a driving factor for increased crab abundance in certain areas. Lunn and Dearden (2006) highlight that, of the small-scale fishers they studied in the Gulf of Thailand, lunar phases (corresponding to ocean currents) also affected the catch rates on certain days. All of this shows that it can indeed be important to consider seasonal aspects in LCA. In order to work toward minimizing impacts of fishing, these

Figure 3. Results for four different techniques (blue: crab gill-net, orange: fish trap (I), grey: fish trap (II), yellow: floating squid trap) and different impact categories: (A) global warming potential, (B) fossil depletion potential, (C) freshwater eutrophication potential, (D) metal depletion potential, (E) human toxicity potential, (F) terrestrial acidification potential, G) ozone layer depletion potential.

Notes: NE: northeast monsoon season (November- February), Pre: pre-monsoon season (March-May), SW: south-west monsoon season (June-October).



seasonal aspects of natural phenomena are important to be considered and may lead to the use of different gear, fishing in different locations or targeting other species during specific seasons.

3.2.3. Comparison of GWP and fuel efficiency to other studies

As mentioned in the introduction, there are, to our knowledge, no published studies on Asian fishing operations, nor full LCA studies for small-scale fisheries. Comparisons are therefore only possible for some individual impact categories and also considered with the utmost caution and reserve.

Iribarren, Vázquez-Rowe, Hospido, Moreira, and Feijoo (2011) report a carbon footprint of 1.49 tCO_2/t of landed fish from artisanal fishing operations in Northwestern Spain, which is probably the most comparable option. Still we also looked for values from large-scale fisheries as a second comparison option. For large fishing fleets, Winther et al. (2009), for example, report a carbon

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footprint for the fishing stage (excluding transport and processing, but including cooling agents on board the vessel) for captured cod (2.01 kg CO_2-eq/kg), saithe (2.13 kg CO_2-eq/kg) haddock (3.33 kg CO_2-eq/kg) and mackerel (0.54 kg CO_2-eq/kg).

The GWPs in our study of fishing techniques vary for a year between 653 g CO_2-eq/kg of target species (fish trap (II)) and 2.2 kg CO_2-eq/kg (squid trap), with the fish trap (I) (834 g CO_2-eq/kg) and the crab gill-net (1.7 kg CO_2-eq/kg) in between. The GWP ranges from 38 g CO_2-eq/kg of target species (fish trap (I)) and 658 kg CO_2-eq/kg (crab gill-net) (Table 3), without the fuel. Carbon footprints for floating squid traps (50 g CO_2/kg) and fish trap (II) (70 g CO_2-eq/kg) are in between. Our results (including fuel) are both smaller and larger than the one reported by Iribarren et al. (2011) depending on the season. When comparing to Winther et al. (2009), our results are smaller than or the same as all large-scale fished fish except for mackerel. Additionally, our results follow the suggestion put forth by Tyedmers (2004) who state that direct fuel consumption for industrial fisheries will account for 75–90% of the greenhouse gas emissions for landed fish. The squid and fish trap (I) are above the 90% mark for all seasons, and fish trap (II) is within that range for the northeast- and pre-monsoon seasons (above for the southwest-monsoon season) (Table 4 and Figure 4). The crab trap is below the range stated by Tyedmers (2004) likely because of the low catch numbers giving more weight to the climate change impacts imposed by the materials.

On average, our four fishers have a GWP of 1.34 kg CO_2/kg, which is very similar to the result from Iribarren et al. (2011) for artisanal fisheries (1.49 t CO2e/ t landed species). The considered system boundaries are similar, since most fishing operations are included. However, processing steps onboard the ships are included in the other study as well (Iribarren, Vázquez-Rowe, Hospido, Moreira, & Feijoo, 2010), in contrast to our study, although a detailed description on how small-scale Spanish artisanal fisheries are operating (e.g. type of boat used, gear used, fuel consumption, etc.) is missing. Catch rates per year are much higher than in our study, but this can of course also be caused by summing data of several artisanal fishers. Reasons for the differences in carbon footprint can therefore be assumed to be influenced by the scale of the operations, but, most importantly, also by the efficiency displayed (e.g. more fuel-efficient boats, but also more technology on board). Even though the carbon footprint in Spain is for artisanal fisheries, the boats are likely much larger and can hold more catch than the small boats in Thailand. Also, the fishing techniques of Iribarren et al. (2010) (trawlers, purse seiners and long-liners) are different than in Thailand and difficult to compare to our fish and squid traps since it is not entirely clear which technique was used by their artisanal fishers. That efficiency in general has a considerable influence can be deducted when comparing the two fish traps in our case study: both traps are the same, but the one using it more efficiently and consuming less fuel, has considerably smaller impacts. An additional influence can come from the so called "skipper effect" (Vázquez-Rowe & Tyedmers, 2013), meaning the skill of the fishers. Moreover, fish trap (II) has a much smaller engine (80kgs) compared to fish trap (I) (300 kg).

Table 3. Total impacts at midpoint level for selected impact categories (see main text) per functional unit, averaged over the year

Impact category	Crab gill-net	Fish trap (I)	Fish trap (II)	Squid trap
Climate change [kg CO_2 eq]	6.58E-01	3.84E-02	6.98E-02	5.01E-02
Ozone depletion [kg CFC-11 eq]	1.61E-09	1.49E-09	1.44E-09	8.99E-10
Terrestrial acidification [kg SO_2 eq]	1.78E-03	1.09E-04	1.79E-04	1.20E-04
Freshwater eutrophication [kg P eq]	2.00E-05	1.56E-05	1.34E-05	7.52E-06
Human toxicity [kg 1,4-DCB eq]	4.40E-03	7.44E-03	5.79E-03	3.57E-03
Metal depletion [kg Fe eq]	3.38E-03	3.72E-02	3.20E-02	1.21E-02
Fossil depletion [kg oil eq]	2.69E-01	1.18E-02	2.88E-02	2.25E-02

Notes: Results for the different seasons are shown in the SI and Figure 3, fuel efficiency is shown in Table 5 (fuel is not included here).

Table 4. Relative contribution per season of the direct fuel emissions in relation to the total climate change impacts from the four artisinal fisher

	NE (%)	Pre (%)	SW (%)
Crab gill-net	87	38	56
Fish trap (I)	94	96	97
Fish trap (II)	89	88	91
Floating squid trap	98	97	98

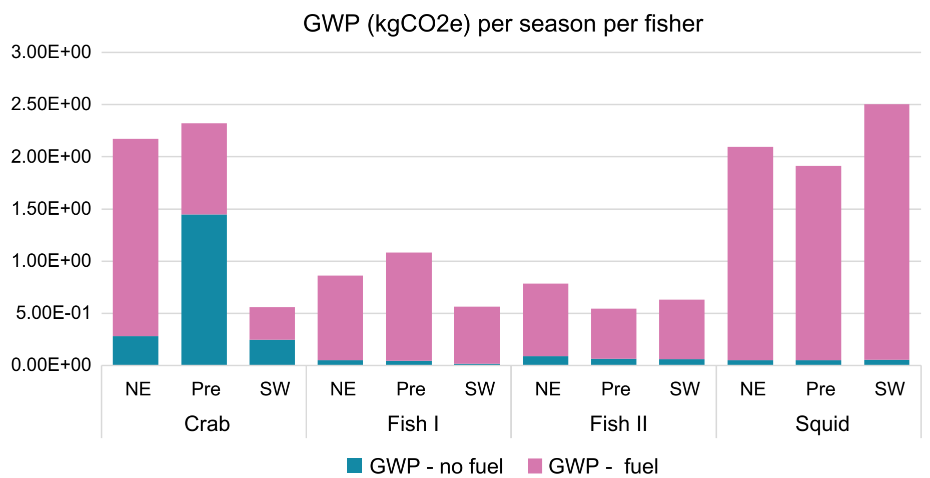

Figure 4. Visual representation of the predominance of direct fuel use emissions in regards to global warming potential (GWP) per season per fisher.

Pomeroy and Andrew (2011) had estimated that small-scale fisheries use four times less fuel than large-scale fisheries for the same amount of fish. Winther et al. (2009) report fuel factors for cod 0.24 l fuel/kg landed fish), haddock (0.29 l/kg), saithe (0.29 l/kg), herring (0.091 l/kg), and mackerel (0.094 l/kg). The results in Table 5 for our case study show that the best fuel efficiency is 0.1 l/kg total catch or 0.15 l/kg targeted catch. Fish trap (II) is in fairly the same range as the values from Winther et al. (2009) for different fish. However, the other small-scale fishing techniques are above that for most of the seasons. With the given information, we can therefore not confirm the statement of Pomeroy that small-scale fisheries use up to four times less fuel for similar amounts of fish.

Table 5. Fuel efficiency [l/kg total and target catch landed] of the different fishing techniques on a yearly average, as well as for the different seasons

Season	Crab gill-net	Fish trap (I)	Floating squid trap	Fish trap(II)
	For total catch			
NE	0.61	0.26	0.66	0.23
Pre	0.28	0.33	0.6	0.15
SW	0.1	0.18	0.79	0.18
Average	0.33	0.26	0.68	0.19
	For target catch only			
NE	0.85	0.33	0.68	0.23
Pre	1.28	0.41	0.61	0.15
SW	0.44	0.18	0.8	0.18
Average	0.86	0.31	0.7	0.19

Notes: NE: northeast monsoon, Pre: pre-monsoon, SW: southwest monsoon.

3.2.4. Limitations and uncertainties

Not explicitly stated or measured in the LCA results are the potential ecotoxicological damages due to the use of specific antifouling paints due to missing information. The crab gill-net and fishing trap (II) use TOA Vinyl Copper antifouling paint and do not contain any organotin components (AkzoNobel, 2015), which could be harmful to rock shell (*Thais clavigera*) (Horiguchi, Shiraishi, Shimizu, & Morita, 1997), native to Asian waters (Ge et al., 2015), as well as other shellfish. It is unknown whether the antifouling paint used by fishing trap (I) contains any organotin components.

The assumptions mentioned previously present us with varying degrees of uncertainty. For one, there is a large uncertainty based on emissions and impacts, since the background processes were largely evaluated in a European or Swiss context instead of Asian.

Additionally, there is some uncertainty in the data. The data do not include information on by-catch, nor is it entirely complete and assumptions on the precise materials used were necessary. Additionally, this LCA does not account for emissions post landing. For example, the majority of the floating squid trap catch is exported to Taiwan. This export was not included in the study, but would undoubtedly increase the overall life cycle impacts.

4. Conclusion and recommendation

Our results show that impacts from small-scale fisheries can be relevant indeed, like the comparison with GWP of other studies showed. We also see that there are differences in the type of gear used, but most notably, differences in the operations drive the magnitude of impacts. The fish trap (II) had the largest fish catch and also did not use a copious amount of materials to do this and thus had a smaller overall impact and a larger fuel efficiency than fish trap (I). Also, the seasonality plays a role for some of the fishing techniques with highest impacts related to seasons with lowest catch and longer fishing operations. This highlights the fact that seasonal considerations may be very important to be included in future LCA studies, both regarding inventories and impact assessment development. This has been discussed by Pfister and Bayer (2014) regarding water stress and irrigation, but our results show that this aspect is relevant beyond the issue of water consumption.

On the other hand, the study was plagued with assumptions and a lack of appropriate, Thai-specific background processes. This highlights the need for a perpetual effort for collecting inventory data and make them available in databases. Uncertainties of the background processes could thus be reduced significantly.

We recommend optimizing the fishing strategies based on gear required, seasonality, and potentially the fishing location. Fishers should ideally be taught how to minimize the environmental impacts (and reduce e.g. fuel consumption) by optimizing their fishing routes and type of fish caught, depending on seasonal and location-specific aspects. These are some ways to reduce the potential impacts of small-scale fishing operations in Thailand. Simultaneously, we call on the research community to invest in the modeling and collecting of region- and country-specific inventory data, with a special focus on countries outside Europe, which will become increasingly important due to more and more globalized supply chains.

Supplementary material
Supplementary material for this article can be accessed here https://doi.org/10.1080/23311843.2017.1387959.

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Competing Interests
The authors declare no competing interest.

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