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Life cycle assessment of cricket farming in north-eastern Thailand

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A B S T R A C T

Over the last few years, edible insect species have been heralded as an environmentally sustainable solution to current and future food crises. However, the few existing studies that aim to evaluate the environmental performance of insect farming systems are extremely limited in scope. This paper presents the first case of a life cycle assessment (LCA) performed on an existing production system of *Gryllus bimaculatus* De Geer (field cricket) and *Acheta domesticus* (house cricket) production in north-eastern Thailand and compares it with broiler production in the same region. The system boundaries of the production system considered the entire production cycle of edible crickets as well as processing. The study included two functional units (1 kg of edible mass and 1 kg of protein in edible mass). Irrespective of the functional unit, larger impacts were associated with broiler production. Major hotspots for cricket and broiler production were related to the production soybean meal and maize grain for feed. A scaled-up cricket farming system which was considered as a possible 'future' scenario demonstrated a reduction in overall environmental impacts when compared to current cricket production and industrial broiler production. While scaled-up cricket farming showed fewer overall environmental impacts, intensified systems could potentially have reduced socioeconomic impacts on rural areas in Thailand. Improvement options could be adopted by undertaking further research into the formulation of local feeds and acquiring improved knowledge about cricket nutrition.

1. Introduction

Cricket farming is emerging as a 'mini-livestock' production system. The environmental impact of farming crickets may be less than that of traditional livestock due to their poikilothermic nature, which allows more efficient feed conversion, and could therefore be a more sustainable kind of animal-source food. For this reason, the consumption of insects has been heralded as an environmentally-sustainable solution to current and future food crises. However, there is limited scientific evidence to support this (Halloran et al., 2016a). Empirical studies have analysed the environmental impacts associated with the production of insects, for example, by quantifying greenhouse gas emissions of five different insect species (Oonincx et al., 2010); conducting a life cycle assessment (LCA) on mealworm production (Oonincx and de Boer, 2012) and industrial production of black soldier flies (Smetana et al., 2016); assessing crickets fed waste from different side-streams such as municipal food waste (Lundy and Parrella, 2015); performing a water footprint analysis on mealworm production (Miglietta et al., 2015); and conducting a LCA on meat and meat alternatives (including insects) (Smetana et al., 2015). Other studies have used the LCA technique to examine the potential of using insects to convert waste products such as food waste and manure and subsequently produce larvae which can be used in animal feed (Roffeis et al., 2015; Salomone et al., 2017). (For a more detailed review of LCA studies conducted on insect production systems, please refer to Halloran et al., 2016a). According to Halloran et al. (2016a), only six LCA studies have been conducted on a total of five different insect species intended for food and animal feed as of October 2016 and all studies have been carried out with foreground data from Europe.

There are over 2000 insect species that are regularly eaten, of which most are mainly harvested from the wild (Jongema, 2015), and nine insect species are currently farmed for food and feed according to the European Food Safety Scientific Committee (2015). The farming systems have not yet been optimised for large-scale production and therefore there is very little information available

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about their environmental sustainability.

Cricket farming systems in Thailand are among the most advanced in the world at present. These farms – numbering over 20,000 (Hanboonsong et al., 2013) – support the livelihoods of many rural farmers (Halloran et al., 2016b, 2017), but have never been studied with respect to their environmental impacts. While cricket farming represents a million-dollar industry, the total quantity of insects produced and consumed is unknown (Hanboonsong et al., 2013). In Thailand, cricket farmers prefer rearing two species of crickets: house crickets (*Acheta domesticus*) and two-spotted crickets (*Gryllus bimaculatus*) (Halloran et al., 2016b; Hanboonsong et al., 2013). Production systems are small-scale in nature with limited inputs (Hanboonsong et al., 2013; Durst and Hanboonsong, 2015) and are easy to implement and maintain (Halloran et al., 2017).

This paper presents the first case of an attributional LCA performed on an existing production system of *Gryllus bimaculatus* De Geer and *Acheta domesticus* production in north-eastern Thailand and compares it with broiler production in the same region. The aim of this study was: i) to investigate the environmental impacts of cricket farming systems in north-eastern Thailand, ii) to identify the processes associated with the most significant impacts within the production chain, iii) to conduct a comparative study in relation to another animal production system, which in this case was a broiler farm, iv) to model a future, scaled-up scenario of cricket farming and assess the associated impacts, and v) to formulate recommendations as to how to achieve sustainable insect production systems.

2. Methods

This study uses LCA to compare the full range of environmental effects assignable to products (in the case of this study crickets and broilers) by quantifying all inputs and outputs of material flows and assessing how these material flows may affect the environment. LCA consists of four main phases: goal and scope; life cycle inventory; life cycle impact assessment; and interpretation (Baumann and Tillmann, 2004).

2.1. Systems studied

This study compared cricket farming and broiler farming in north-eastern Thailand. A future cricket production system, in which production has been optimised, was also modelled.

Broiler production was chosen as a benchmark for cricket production as they both are animal-source foods. In many low- and middle-income regions of the world, chicken is a significant source protein source. Crickets and broilers have a similar percentage protein in their edible mass (See Section 2.4).

2.1.1. Thai cricket farm description

The study took place in Mahasalakam Province in north-eastern Thailand. A medium-scale cricket farm was identified and surveyed to estimate all flows including feed, biofertiliser[1] and crickets to and from the farm. The farm was analysed in detail by field investigation as well as through an in-depth face-to-face survey carried out in November 2014. In order to estimate the content the most important elements of the different products in the system, samples of feed, crickets, and biofertiliser (manure) were taken and the C and N contents were determined on a CNS analyser (vario MACRO cube 88 CNS, Elementar). To estimate the content phosphorous (P) and potassium (K), the biofertiliser samples were taken from the farm and analysed using an inductively coupled plasma optical emission spectrometry (ICP–OES, Optima 5300 DV, Perkin Elmer, Ontario, Canada).

The selected cricket farm was a medium-scale production system of 2720 m^2 located in the village of Nacheung (Fig. 1). The buildings contained a total of 78 pens of various sizes (average of 9.43 m^2). The farm reared both *G. bimaculatus* (48% of total production by mass) and *A. domesticus* (52% of total production by mass). Thirty-eight of the pens were dedicated to the production of *G. bimaculatus* and the remaining 38 were used for *A. domesticus*. The average life cycles of *G. bimaculatus* and *A. domesticus* were estimated as 42 and 49 days respectively. The farm produced approximately 8.5 cycles of crickets per year.

Primary data (input materials, energy use, output products and waste) were collected at farm level. The questionnaire covered the farm structure (buildings, machinery and equipment), the management (colony composition, housing system, biofertiliser management, feed composition) and data on the input and output mass flow (feed, water, meat, biofertiliser). Total annual cricket yield (*G. bimaculatus* and *A. domesticus*) on the farm was 36,741 kg (17,636 kg and 19,105 kg respectively, wet weight). Data on cricket processing were obtained from a wholesale trader in Maka,

Fig. 1. The cricket farm represented in this study.

[1] In this study, biofertiliser consisted of cricket frass (excrement) in addition to any matter that falls to the floor of the cage, including wings, body parts, pumpkin seeds/stems, rice husks, pests, particles of uneaten feed, dust, shredded egg carton *etc.*

Mahasalakam.

2.1.2. Future scaled-up cricket production system

In order to estimate the impacts generated by a possible future scaled-up production system, a future scenario was modelled. The future farm scenario was assumed to be more efficient with a feed conversation ratio (FCR) of 1.47 (based on Lundy and Parrella, 2015). This FCR assumes the total amount of feed, including unconsumed feed. The following assumptions were also made: crickets consume the same kind of feed, production cycles are 33 days to harvest, under optimised circumstances the farm has 11 cycles per year, and there are three vertical production levels in this system. As specialisation was assumed, only *A. domesticus* were farmed under the future scenario. This was also due to a preference towards this species for their taste (Hanboonsong et al., 2013). To achieve this increased efficiency in the future scenario, walls and climate control were required to create a contained, temperature-regulated system. This requires more building materials and higher electricity consumption.

2.1.3. Thai broiler farm description

Thailand is one of the largest poultry meat producers in Asia. The majority of broilers are reared in strictly controlled facilities that are standardised according to the integrators (Chantong and Kaneene, 2011). Chicken companies are largely vertically integrated with all the actors within the value chain, including feed producers, hatcheries and broiler farms that are either owned or have contacts to the parent company (Mungkung et al., 2012). In most cases, broiler farmers are contracted out by the integrators (Chantong and Kaneene, 2011).

Data were collected from a contract broiler farm in Banfang, Khon Kaen Province (Fig. 2). This farm is representative of broiler farms contracted by a large Thai agribusiness corporation to produce broilers which are used for a specific type of Thai-style grilled chicken. This type of chicken is sold when it reaches a live weight of approximately 1 kg. This breed of chicken is characterised by slower growth and a higher FCR when compared to other industrial broiler breeds. The regular industrial broiler breeds in Thailand have higher bodyweight at slaughter (2.8–3.2 kg), grow faster and exhibit a lower FCR.

The selected broiler farm was a medium-scale production system of 3120 m^2. The total yearly broiler yield (live weight) was calculated as 150,000 kg. The average life expectancy of a broiler was 59 days and the farm produced five cycles of broilers per year. Data on broiler processing were obtained from the World Bank Poultry Processing Guidelines (World Bank, 2007). Data on the hatchery and breeding farm were obtained from expert opinion (Sukontarattanasook, pers. comm., 2017). The breeder farm, hatchery and broiler farm are grouped together under one processes called broiler production.

2.2. Functional units

Two functional units – one mass-based and one nutritionally-based – were chosen: 1 kg of edible mass and 1 kg of protein in edible mass. It can be debated whether it is realistic that the consumption of chicken is actually decreased as a consequence of the production of crickets, and that the crickets are therefore truly substituting chicken production. In north-eastern Thailand, meals are presented as a range of shared dishes which are served at the same time. These dishes can include crickets and chicken among other foods. It is therefore difficult to say exactly how the introduction of crickets will affect the consumption of other dishes. However, as production amounts increase in the region it is likely that the crickets could replace chicken to some extent. Therefore, it is argued that they can be compared on the basis of edible mass and protein in edible mass, depending on whether the food is considered to be a dietary component (edible mass) or a nutritional component (protein in edible mass). Due to limited studies, digestibility was not factored into the functional unit of 1 kg of protein in edible mass. This issue will be discussed in further details in section 4.3.

Fig. 2. The broiler farm represented in this study.

2.3. Systems boundaries

The study covered the production of construction materials, energy, transportation and the feed production process at mills. Processing and transportation processes were also included. Thus, the systems boundaries did not cover farm gate to retail (Fig. 3).

2.4. Life cycle inventory

For all three scenarios, secondary data from background input flows and processes were extracted from EcoInvent Integrated SP 22 (v. 6.110) and Gabi databases (see supplementary materials for further information).

2.4.1. Cricket production (current scenario)

Detailed data related to cricket production (current scenario) are given in Table 1 and in the description following the table. Further information can be found in the supplementary data.

2.4.1.1. Feed input. As cricket feed is very similar to broiler feed, the feed composition was estimated from typical industrial broiler diets and according to listed ingredients found on feed bags (Sukontarattanasook, pers. comm., 2015). Feed ingredients included fish meal, soybean meal, grain maize, palm oil, calcium carbonate and salt (Table 2). From the feed input and cricket output, the FCR was calculated as 2.50 for the crickets (both species combined). Pumpkins supplemented the feed at the end of the cricket

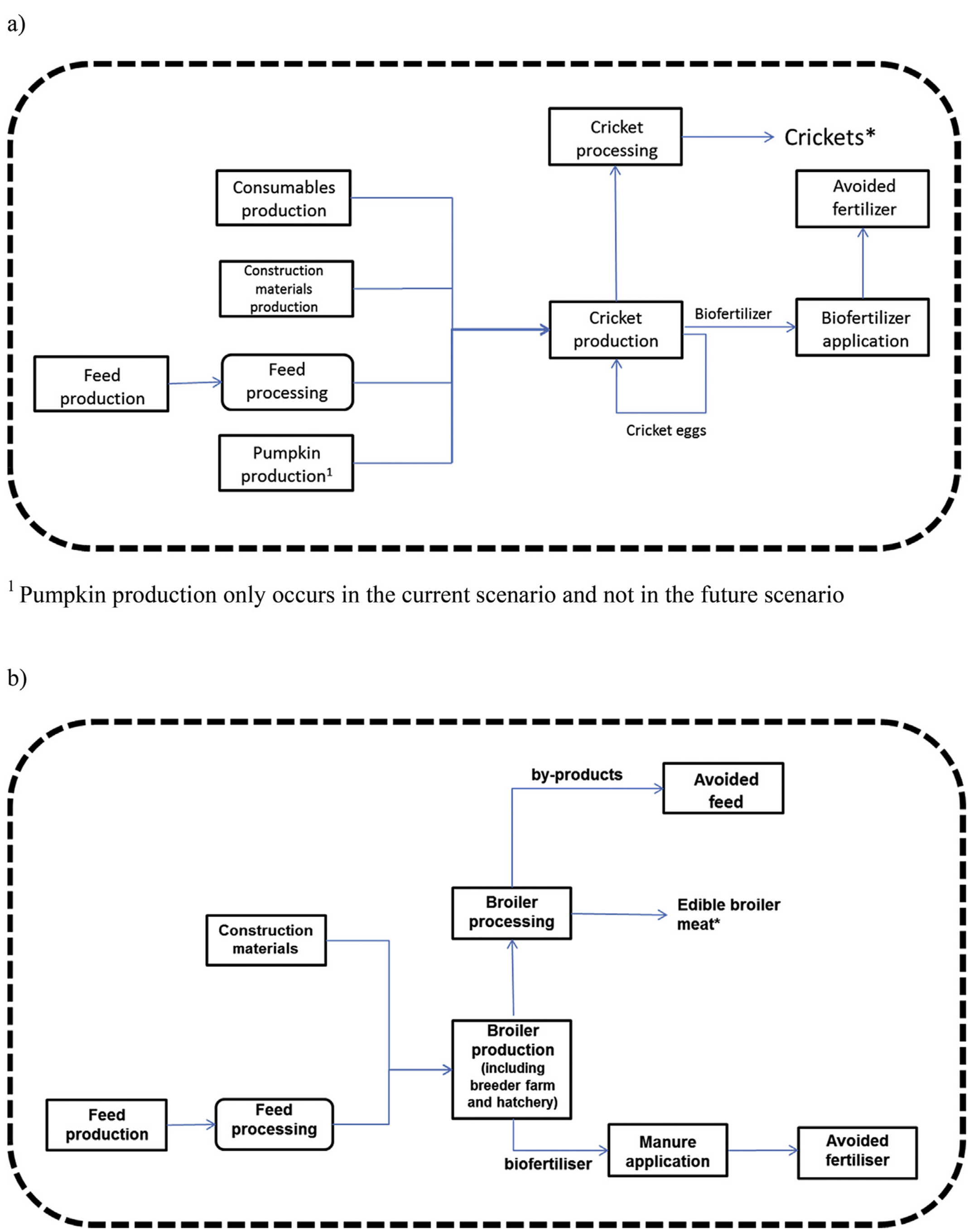

Fig. 3. a) Systems boundary of the cricket farm and b) systems boundary of the broiler farm (* denotes functional unit).

Table 1
Annual data for the cricket farm.

	Amount	Data source
Total number of concrete pens	78	Data from study farm
Number of concrete pens, *Gryllus bimaculatus*	38	Data from study farm
Number of concrete pens, *Acheta domesticus*	38	Data from study farm
Number of cycles in a year	8.5	Data from study farm
Inputs		
Feed (kg)	74,237	Data from study farm
DM of feed (%)	87	Data from study farm
Total amount of pumpkins (kg)	20,400	Data from study farm
DM of pumpkin (%)	12	(Fedha et al., 2010)
N content of feed (%)	3.04	Measured from farm samples
C content of feed (%)	44	Measured from farm samples
N content of pumpkin (%)	79	(DTU Fødevareinstituttet, 2009)
C content of pumpkin (%)	50	(DTU Fødevareinstituttet, 2009)
Water (L)	19,843	Data from study farm
Biofertiliser production		
Acheta domesticus biofertiliser (kg)	26,648	Calculated (See 2.4.1d)
Gryllus bimaculatus biofertiliser (kg)	16,150	Calculated (See 2.4.1d)
DM of biofertiliser (%)	89	Measured from farm sample
N content of *Gryllus bimaculatus* biofertiliser (%)	2.58	Measured from farm sample
N content of *Acheta domesticus* biofertiliser (%)	2.27	Measured from farm sample
C content of *Gryllus bimaculatus* biofertiliser (%)	38.08	Measured from farm sample
C content of *Acheta domesticus* biofertiliser (%)	38.38	Measured from farm sample
Cricket production		
Acheta domesticus (kg)	18,976	Data from study farm
Gryllus bimaculatus (kg)	17,765	Data from study farm
DM of crickets (%)	26	Measured from farm sample
Edible portion (%)	100	Observational data
N content of *Gryllus bimaculatus* (%)	9.02	Measured from farm sample
N content of *Acheta domesticus* (%)	10.05	Measured from farm sample
C content of *Gryllus bimaculatus* (%)	54.28	Measured from farm sample
C content of *Acheta domesticus* (%)	53.29	Measured from farm sample

Table 2
Feed composition.

Feed ingredients	Percentage of total content
Fish meal	5%
Soybean meal	28%
Grain maize	51%
Rice bran	9%
Palm oil	3%
Calcium carb powder	1%
Calcium carb 2–4 mm	2%
Salt	1%

lifecycle in order to give the inside of the cricket a desired orange-like colour.

2.4.1.2. Input of construction materials, energy and transportation. The life expectancies of each of the construction materials and consumables were factored into the specific input amounts included in the lifetime of the buildings. Life expectancies were calculated based on literature values (Hanboonsong et al., 2013; Ruskulis, 2009). Information regarding the energy, heat and water required for feed production was derived from the LCA Food Database (2007). Electricity, heat and chemical inputs required for the production of fishmeal also came from the same database (LCA Food Database, 2007). Compared with the chicken farm, fewer construction materials are needed on the cricket farm as temperature control is not needed (see supplementary materials for more information). Electricity was estimated from farm records. The transport of feed materials and the transport of the crickets to processing were included in each different production stage assuming regional and global supply. Non-regional feed materials were transported by cargo ship. Regional feed materials were transported by diesel truck. The same method was applied to the future cricket scenario.

2.4.1.3. Cricket output. To use the functional unit of 1 kg of protein in edible mass the protein content of the edible mass had to be estimated. The amount of protein was calculated as the amount of N (determined by the Kjeldahl method) divided by 6.25. The protein content in the edible mass of the *Acheta domesticus* in this study was found to be 63% and 56% for *Gryllus bimaculatus* (on a dry weight basis). Both cricket species are considered 100% edible.[2]

2.4.1.4. Biofertiliser. The total annual quantity of biofertiliser generated on the cricket farm was 26,414.5 kg. *G. bimaculatus* and *A. domesticus* converted feed into biofertiliser with a respective 38% and 62% percent of the total mass ending up as biofertiliser. Based on the samples taken, total nitrogen (N) was found to be 2.58% (*G. bimaculatus*) and 2.27% (*A. domesticus*). Total phosphorus (P) was found to be 1.55% (*G. bimaculatus*) and 2.02% (*A. domesticus*). Total potassium (K) was found to be 1.78% (*G. bimaculatus*) and 2.26% (*A. domesticus*) (Table 3). Due to large discrepancy in the annual amount of biofertiliser that the cricket farm produced, the total annual amount of C was calculated from the calculated amount of N in the biofertiliser and the measured C:N ratio of the biofertiliser.

Subsequently, the application of fertiliser was calculated based on the measured N, P and K of *A. domesticus* manure only as opposed to both species in the cricket farm scenario.

The use of cricket biofertiliser was assumed to substitute the application of mineral fertiliser on key crops in the region (*e.g.* rice paddies). Avoided ammonium nitrate, triple superphosphate and

[2] According to Nakagaki and Defoliart (1991) 80% of *A. domesticus* is considered edible. However, during this study the removal of wings and legs before consumption was not observed in north-eastern Thailand.

Table 3
N, P, K of *G. bimaculatus* and *A. domesticus* biofertiliser (measured) and broiler manure (from literature).

Elements	Farmed species	% in biofertiliser
Nitrogen	*G. bimaculatus*	2.58%
	A. domesticus	2.27%
	Broilers (CP Brown)	1.7%
Phosphorous	*G. bimaculatus*	1.55%
	A. domesticus	2.02%
	Broilers (CP Brown)	1.33%
Potassium	*G. bimaculatus*	1.78%
	A. domesticus	2.26%
	Broilers (CP Brown)	1.58%

potassium chloride were modelled by system expansion assuming 100% substitution of N, P and K in the biofertiliser. Emissions such as nitrate leaching and P losses associated with the use of the biofertiliser were assumed to be the same for the saved fertiliser, so they cancelled each other out.

2.4.1.5. Emissions. CO_2 emissions were calculated from a carbon mass balance. The direct nitrous oxide (N_2O) and methane (CH_4) emissions at cricket farm level were estimated from a pilot experiment. 140 g of live crickets were added to a 1300 mL vacuum container (Exetainer ©LABCO) and provided with 8 g of feed and 8 g of water. Air samples were taken by a 5 ml syringe (Braun Omnifix) in 10-min intervals for 80 min. All gas samples were analysed using gas chromatography (Greenhouse Gas Analyser, 450-GC, Bruker, Germany). From the GHG calculations, N_2O and CH_4 were found to be 0.066 kg and 0.034 kg per year respectively, which was insignificantly higher than the control and therefore ignored.

The estimation of ammonia (NH_3) emissions from the cricket biofertiliser after application was assumed to be minimal since the biofertiliser was already very dry and the majority of the ammonia and water had already evaporated. Ammonia emissions were therefore assumed to be zero. Ammonia emissions were therefore assumed to be zero. During cricket production, however, NH_3 emissions are likely to be high and therefore were assumed to be as high as for chicken, with 23% of annual input feed N (EPA, 2004). This assumption was made based on the United States Environmental Protection Agency National Emissions Inventory – Ammonia Emissions from Animal Husbandry, which estimates that 23% of input N leaves poultry production houses as NH_3-N. All of the carbon held in the biofertiliser was considered to be released as CO_2 after land application and thus sequestration of CO_2 in the soil was not considered.

2.4.2. Cricket production (future scenario)

Detailed data related to cricket production (future scenario) are given in Table 4 and elaborated below. Further information can be found in the supplementary data.

2.4.2.1. Feed input. The feed composition and subsequent analysis was the same for cricket production (current scenario) (Table 1 and 2.4.1a). FCR was assumed to be 1.47 based on Lundy and Parrella (2015). After this, the amount of feed was calculated as: $Feed = crickets\ produced \times FCR$. The total annual amount of feed was thus estimated to be 223,522 kg. Pumpkins were not used to supplement the feed in the future scenario as they were in the current cricket farm scenario.

2.4.2.2. Input of construction materials and energy. The future cricket farm scenario differed from the current scenario because the production facility was contained. The facility was constructed in a similar way to the broiler facility. The pens were made from plywood instead of concrete (see supplementary material for further information). The inputs used during the processes of the crickets were assumed to be the same in both the current and future cricket scenarios.

2.4.2.3. Cricket output. The number of crickets in the future scenario were calculated based on a life cycle of 33 days (Lundy and Parrella, 2015) growing in 234 pens (three times that of the current scenario). The amount of crickets per cycle per pen was assumed to be the same as in the current scenario. Continuous (back-to-back) production was assumed.

2.4.2.4. Biofertiliser. The amount of biofertiliser was calculated as $Biofertiliser = feed \times (1 - digestibility)$ where digestibility was calculated from the assumed feed conversion ratio. The use of cricket biofertiliser in the future scenario was also assumed to substitute the application of mineral fertiliser (see 2.4.1d for further details).

2.4.2.5. Emissions. The emissions were calculated in the same way as for the current scenario.

2.4.3. Broiler production

Data about input and outputs from broiler production were mainly estimated based on information collected from the study farm or based on mass balances. Additional information about the composition of the flows was derived from the literature. Further information about the foreground data is given in Table 5.

2.4.3.1. Feed input. The feed composition and subsequent analysis was the same as for the cricket production (current scenario) (Table 1). The total amount of feed consumed was 310,475 kg. The FCR was assumed to be 1.83 for the broilers based on an industry standard (Sukontarattanasook, pers. comm., 2015).

Table 4
Additional information for the future cricket farm scenario.

Future scenario (*Acheta domesticus* only)	Amount	Source
Future scenario FCR	1.47	Based on Lundy and Parrella, 2015
Length of lifecycle of *Acheta domesticus* (days)	33	Based on Lundy and Parrella, 2015
Cycles per year	11	Based on Lundy and Parrella, 2015
Amount of total pens	234	Based on 3 times the amount of current scenario
Inputs		
Feed (kg)	223,522	Calculated (see 2.4.2a)
Water (L)	56,991	Data from study farm
Biofertiliser		
Biofertiliser	128,860	Calculated (see 2.4.1d)
Cricket production		
Crickets	152,056	Calculated (see 2.4.2c)

Table 5
Annual data for the broiler farm.

	Amount	Source
Total number of pens	333	Data from study farm
Number of cycles in a year	5	Data from study farm
FCR	1.83	Sukontarattanasook, pers. comm., 2015
Lifespan (days)	59	Data from study farm
Total number of birds per cycle	30,000	Data from study farm
Average weight of broiler (kg)	1	Data from study farm
Inputs		
Feed (kg)	310,475	Data from study farm
DM of feed (%)	87	Data from study farm
N of feed (%)	3.04	Measured from farm sample
C of feed (%)	43.91	Measured from farm sample
Water (L)	1,104,398	Data from study farm
Manure		
Manure production (kg)	137,726	Data from study farm
DM of manure (%)	72	(Griffiths, 2011)
g N/kg	30.46	(Guiziou and Béline, 2005)
C content of broiler manure (%)	42	(Griffiths, 2011)
Ammonia emission (% of total feed N)	23	(USEPA, 2004)
Broilers		
Broilers (kg)	150,000	Assumed from industry standard
DM of broilers (%)	34	(USDA, 2011)
N content of broilers (%)	7.80	(DTU Fødevareinstituttet, 2016)
Ash content broilers (%)	2.7	(Latshaw and Bishop, 2001)
C in volatile solids (%)	50	Assumed

2.4.3.2. Input of construction materials, energy, other materials and transportation. Construction materials consisted of metal cages, wall/roofing materials and reinforcements. Electricity was estimated based on farm records. Minor staple supplies such as antibiotics and vitamin supplements (broiler farms only) were omitted from the LCA. The transport of feed materials and the transport of the chickens to processing were included in each different production stage assuming regional and global supply. Non-regional feed materials were transported by cargo ship. Regional feed materials were transported by diesel truck.

2.4.3.3. Broiler output. Broiler by-products including blood, giblets and chicken feet in addition to the meat were all considered as edible mass. These were considered to contain approximately 58% edible mass (Sukontarattanasook, pers. comm., 2016). Feathers, heads, intestines, fat, leg skin and bones were considered to be broiler by-products processed into animal feed. The nutritional functional unit of protein in edible mass was calculated based on the same equation used in 2.4.1c. The protein content of broiler meat in the edible mass was calculated as 63% on a dry weight basis (DTU Fødevareinstituttet, 2016). The broiler by-products were assumed to replace the production of poultry by-product meal, which can subsequently be used as a feed ingredient, thus avoiding fishmeal[3] production.

2.4.3.4. Biofertiliser output. The nitrogen, phosphorous and potassium contents of the broiler manure were estimated to be 1.7%, 1.33% and 1.58% respectively (Griffiths, 2011; Temple et al., 2007) (Table 3). The carbon content of manure was assumed to be 42% (Griffiths, 2011). The use of chicken manure was assumed to substitute the application of mineral fertiliser on key crops (see 2.4.1d for further details).

2.4.3.5. Emissions. CH_4 and N_2O emissions are very minimal in broiler production systems (Guiziou and Béline, 2005) and were therefore omitted from the broiler inventories. CO_2 was estimated through carbon balance equations of inputs (feed) and outputs (biofertiliser/manure). NH_3 emissions during broiler production were assumed to be 23% of annual input feed N (EPA, 2004). All of the carbon held in the chicken manure was considered to be released as CO_2. No sequestration of CO_2 in the soil was considered.

2.5. Allocation

Allocation was used to avoid output of several by-products. Allocation by mass was used for rice husks and fishmeal and their by-products' production. According to Ayer et al. (2006), the relative masses of edible rice, rice bran and rice husk are 92%, 3% and 5% respectively. According to Shepherd and Jackson (2013), the processing of whole fish catches and fish processing by-products yields an average of 22.2% fishmeal and 5% oil.

2.6. Life cycle impact assessment (LCIA)

To assess the environmental impacts of the systems, the set of impact categories included in the International Reference Life Cycle Data System (ILCD) method were used: climate change (Global warming potential), ozone depletion, human toxicity (cancer effects), human toxicity (non-cancer effects), particulate matter/respiratory inorganics, ionising radiation, photochemical ozone formation, acidification, terrestrial eutrophication, aquatic eutrophication, ecotoxicity, water resource depletion and mineral and renewable resource depletion. The ILCD method (EU Commission Joint Research Centre, 2010) is the result of a consensus work in which it has been assessed with impact assessment method is the best for assessing each impact category. The method provides characterization factors which can be used to convert emissions and resource consumption into potential environmental impacts. The formula used to calculate the impact potential of the impact category j is $IP(j) = \sum_{i=1}^{n} CF_i e_i$ where CF_i is the characterization factor for substance i and e_i is the emission of substance i (EU Commission Joint Research Centre, 2012).

GaBi ts software (2015, compilation 7.0.0.19) was used to assess the environmental impact of the systems under consideration.

[3] The use of poultry by-product meal can serve as an alternative dietary protein source, such as fishmeal.

Table 6
Comparison (mid-point) of environmental impacts of 1 kg of edible mass (FU) and 1 kg of protein in edible mass (FU).

Impact category	Unit	1 kg edible component			1 kg edible protein content		
		Broiler farm	Current cricket farm	Future cricket farm	Broiler farm	Current cricket farm	Future cricket farm
Acidification	Mole of H+ eq	0.12	0.08	0.05	0.25	0.14	0.079
Climate change, excl. biogenic carbon	kg CO_2 eq	3.90	2.57	1.71	8.21	4.35	2.71
Climate change, incl. biogenic carbon	kg CO_2 eq	4.06	2.29	1.55	8.57	3.87	2.46
Freshwater ecotoxicity	CTUe	35.45	26.41	17.40	74.81	44.64	27.60
Freshwater eutrophication	kg P eq	0.00052	0.00047	0.00031	0.0011	0.00075	0.00050
Marine eutrophication	kg N-Equiv	0.031	0.020	0.013	0.065	0.033	0.021
Terrestrial eutrophication	Mole of N eq	0.49	0.40	0.20	1.02	0.55	0.32
Human toxicity, cancer effects	CTUh	0.00000013	0.00000010	0.000000087	0.00000028	0.00000017	0.00000014
Human toxicity, non-cancer effects	CTUh	0.00000075	0.00000050	0.00000034	0.0000016	0.00000085	0.00000054
Ionizing radiation, human health	kBq U235 eq	0.19	0.19	0.13	0.40	0.32	0.21
Ozone depletion	kg CFC-11 eq	0.00000010	0.00000013	0.000000062	0.00000023	0.00000027	0.000000099
Particulate matter/Respiratory inorganics	kg PM2,5-Equiv	0.0086	0.0050	0.0035	0.018	0.0085	0.0056
Photochemical ozone formation, human health	kg NMVOC	0.021	0.013	0.0088	0.043	0.022	0.014
Water depletion	m^3 eq	0.44	0.42	0.30	0.94	0.71	0.47
Resource depletion, mineral, fossils and renewables	kg Sb-Equiv	0.000020	0.000026	0.000015	0.000041	0.000043	0.000024

3. Results

Overall, the environmental impacts associated with broiler production were greater than for cricket production. Considering 1 kg of edible mass as the functional unit, broiler production had the greatest impacts in the majority of the impact categories, except for ozone depletion and resource depletion (Table 6). Notably, broiler production resulted in an acidification potential of 0.12 Mole of H+ eq compared to 0.08 Mole of H+ eq on the current cricket farm respectively, GWP of 3.90 kg CO_2 eq compared to 2.57 kg CO_2 eq, freshwater ecotoxicity of 35.45 CTUe compared to 26.41 CTUe, and terrestrial eutrophication of 0.49 Moles of N eq compared to 0.40 Moles of N eq. The impact of the ionizing radiation category was the same (0.19 kBq U235 eq) on the broiler farm and on the current cricket farm (Table 6). The current cricket farm resulted in slightly higher ozone depletion of 0.00000013 kg CFC-11 eq compared to 0.00000010 kg CFC-11 eq, and 0.000026 kg Sb-eqv of natural resource depletion compared to 0.000020 kg Sb-eqv respectively (Table 6).

When considering 1 kg of protein content as the functional unit, the broiler production was still associated with the greatest environmental impacts compared with the cricket production in the majority of the impact categories. Only ozone depletion and resource depletion were higher under the current cricket farming scenario (Table 6).

As cricket farming becomes more resource efficient (*i.e.* a higher FCR and therefore less feed consumed per kg of crickets produced) under the future cricket farming scenario, the environmental impacts become reduced and less than those of the broilers for all impact categories.

For broiler and cricket production (both current and future scenarios), the process of feed production was responsible for a major part of the environmental impacts (Fig. 4). The only categories where the animal production itself was dominating were the terrestrial eutrophication and acidification categories. Ammonia volatilisation was responsible for the majority of acidification and terrestrial eutrophication in broiler farm (80% and 87% respectively), current cricket farm (82% and 91% respectively) and future cricket farm scenarios (79% and 87% respectively). The estimates of ammonia emissions based on a simple assumption of 23% of feed N were eventually emitted as ammonia N from broiler production. Whether this is a good assumption for crickets is uncertain, but it remains valid that increasing efficiency of the production system is also likely to decrease ammonia volatilisation.

Non-biogenic CO_2 emissions were responsible for the majority of climate change impacts (78%, 81% and 81% for broiler, current cricket and future cricket farms respectively) and were mainly due to maize production and land use change caused by soybean production. Pesticide run-off, especially those used in soybean production, was responsible for between 75% and 87% freshwater ecotoxicity in the three scenarios. Nitrate leaching to fresh water (mainly from maize grain production) was the leading cause of marine eutrophication (80%, 86% and 87% on the broiler, current cricket and future cricket farms respectively). No nitrate emissions were associated with application of biofertiliser because it was assumed to replace an equal amount of mineral fertiliser, leading to the same amounts of saved nitrate leaching. Phosphorous and phosphate losses – mainly from soybean production – were responsible for 99.5% of freshwater eutrophication in all scenarios. Again, this result was heavily dependent on the assumption that application of biofertiliser replaces a similar amount of phosphorous mineral fertiliser and that the chances of losses are the same. Human toxicity (cancer) was mainly caused by heavy metal losses into freshwater (52%, 51% and 39% on the broiler, current cricket and future cricket farms respectively) primarily during maize production. Human toxicity (non-cancer) was mainly caused by heavy metal to the soil (72%, 70% and 66% on the broiler, current cricket and future cricket farms respectively), primarily during maize production.

A sensitivity analysis was carried out to check how a 20% increase in transportation distance and a 20% substitution of fishmeal for soymeal would affect the final results. No substantial variability was found across the three scenarios (broiler production, current cricket production and future cricket production) (Table 7). As such, uncertainty associated with transport distances and the composition of the feed in terms of protein rich ingredients would therefore have very little effect on the conclusion of this LCA.

4. Discussion

When comparing the results of this study to mealworm production, the GWP of the current cricket farm scenario is comparable to two LCAs of mealworm production with findings of 2.7 kg CO_2-eq. per kg of fresh weight (Oonincx and de Boer, 2012) and 2.84–3.02 CO_2-eq. per kg of fresh weight[4] (Smetana et al., 2015). One of the major hotspots in these two studies was also identified as the feed production phase. The second largest impact identified

[4] This study used data from Oonincx and de Boer, 2012.

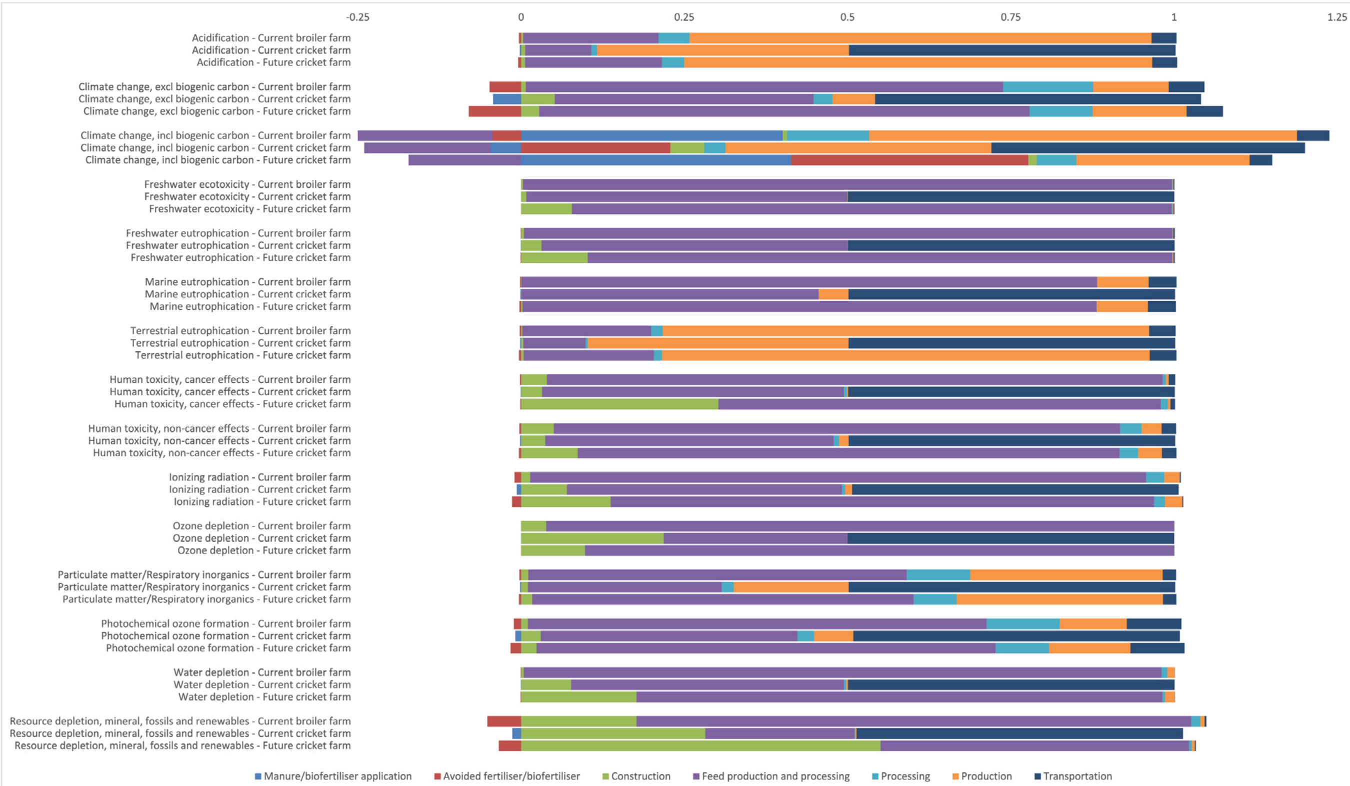

Fig. 4. Contribution of different life stages to the impact potentials at midpoint for current cricket production, future cricket production and broiler production (positive impacts are scaled to 1).

Table 7
Sensitivity analysis applied to a) 20% increase in transportation distance and b) substitution of 20% of fishmeal for soymeal for 1 kg of edible mass.

Impact category	Broiler production			Current cricket production			Future cricket production		
	BAU	Sensitivity test A	Sensitivity test B	BAU	Sensitivity Test A	Sensitivity test B	BAU	Sensitivity test A	Sensitivity test B
Acidification [Mole of H+ eq.]	1.20E-01	0.8% BAU	0.2% BAU	8.01E-02	0.8% BAU	0.2% BAU	4.98E-02	0.8% BAU	0.2% BAU
Climate change, excl biogenic carbon [kg CO2-Equiv.]	3.90E+00	1.1% BAU	1.2% BAU	2.58E+00	1.9% BAU	1.0% BAU	1.71E+00	1.0% BAU	1.1% BAU
Climate change, incl biogenic carbon [kg CO2-Equiv.]	4.06E+00	1.0% BAU	0.1% BAU	2.29E+00	1.1% BAU	0.1% BAU	1.55E+00	1.1% BAU	0.1% BAU
Ecotoxicity freshwater [CTUe]	3.55E+01	0.0% BAU	2.8% BAU	2.64E+01	2.2% BAU	2.2% BAU	1.74E+01	0.0% BAU	2.4% BAU
Eutrophication freshwater [kg P eq]	5.25E-04	0.0% BAU	1.9% BAU	4.46E-04	1.3% BAU	1.3% BAU	3.14E-04	0.0% BAU	1.3% BAU
Eutrophication marine [kg N-Equiv.]	3.08E-02	0.8% BAU	0.8% BAU	1.96E-02	1.4% BAU	0.7% BAU	1.29E-02	0.8% BAU	0.8% BAU
Eutrophication terrestrial [Mole of N eq.]	4.86E-01	0.8% BAU	0.2% BAU	3.30E-01	0.8% BAU	0.1% BAU	2.02E-01	0.8% BAU	0.2% BAU
Human toxicity, cancer effects [CTUh]	1.34E-07	0.2% BAU	0.7% BAU	1.01E-07	0.6% BAU	0.6% BAU	8.74E-08	0.1% BAU	0.5% BAU
Human toxicity, non-cancer effects [CTUh]	7.53E-07	0.4% BAU	0.5% BAU	5.03E-07	0.5% BAU	0.4% BAU	3.42E-07	0.4% BAU	0.4% BAU
Ionizing radiation, human health [kBq U235 eq]	1.89E-01	0.0% BAU	0.4% BAU	1.89E-01	0.3% BAU	0.3% BAU	1.32E-01	0.0% BAU	0.3% BAU
Ozone depletion [kg CFC-11 eq]	1.10E-07	0.0% BAU	0.9% BAU	1.34E-07	0.4% BAU	0.4% BAU	6.22E-08	0.0% BAU	0.6% BAU
Particulate matter/Respiratory inorganics [kg PM2,5-Equiv.]	8.56E-03	0.4% BAU	1.5% BAU	5.03E-03	1.8% BAU	1.4% BAU	3.52E-03	0.4% BAU	1.5% BAU
Photochemical ozone formation, human health [kg NMVOC]	2.06E-02	1.7% BAU	1.6% BAU	1.25E-02	3.0% BAU	1.5% BAU	8.83E-03	1.6% BAU	1.5% BAU
Resource depletion water [m^3 eq.]	4.44E-01	0.0% BAU	0.9% BAU	4.19E-01	0.5% BAU	0.5% BAU	2.96E-01	0.0% BAU	0.5% BAU
Resource depletion, mineral, fossils and renewables [kg Sb-Equiv.]	1.95E-05	0.1% BAU	0.8% BAU	2.55E-05	0.3% BAU	0.3% BAU	1.52E-05	0.0% BAU	0.4% BAU

BAU = business as usual; Sensitivity test A = 20% increase in transportation distance; Sensitivity test B = Substitution of 20% of fishmeal for soymeal.

by Smetana et al. was fossil depletion (2015) which is similar to the significant energy use measured by Oonincx and de Boer (2012). Miglietta et al. (2015) found that mealworms required 4.3 m^3 of water per kg of edible mass, a value which is approximately 10 times more than the current cricket farm in Thailand. The water footprint of mealworms can be attributed mostly to the feed.

For broiler production, a Danish LCA study found much lower GWP per 1 kg of edible mass[5] (2.31 kg CO_2-eq.) (Nielsen et al.,

[5] In this study, edible mass was defined as carcass weight for human consumption, i.e. meat, bones, liver, heart, kidneys, feet and neck were included while feathers, head, blood and intestines were excluded.

2012). The large difference between broiler production in Denmark and Thailand was due in part to the difference in the broiler breeds in question, leading to different production times (38 days vs. 59 days) and slaughter weights (2.13 kg vs. 1 kg). In a study in the UK, Leinonen et al. found that standard indoor broiler production produces 4.41 kg CO_2-eq. per 1 kg of edible carcass weight, a value higher than the broiler farm in this study. Pelletier (2008) also found that the majority of impacts of broiler production in the USA are associated with the feed production: 82% of greenhouse gas emissions, 98% of ozone depleting emissions, 96% of acidifying emissions and 97% of eutrophying emissions.

The chosen broiler production system is not the most efficient production system that can be found in Thailand. However, it is representative of a production system for a specific kind of chicken meat which is eaten throughout the Isan region. Had a more efficient production system been chosen, the results could have been different.

4.1. Inputs

Similar to the findings of this study, Smetana et al. (2016) found that protein diets are responsible for high environmental impacts and high insect yields. Major improvements can be made in the sourcing of local feed ingredients. In fact, one of the advantages of insects over traditional livestock is that they are able to live on feed from other sources (van Huis et al., 2013). As other studies have shown, these sources could come from surplus production and perhaps even waste side streams or ingredients that cannot be used for feeding traditional livestock species (Collavo et al., 2005; Lundy and Parrella, 2015; Oonincx et al., 2015; Smetana et al., 2016). Current trials at Khon Kaen University aim to find alternative feed ingredients to replace the commercial chicken feed commonly used on small and medium-scale cricket farms in Thailand. Farmers are recommended to increase the amount of vegetables in order to reduce the reliance on commercial chicken feed (Hanboonsong, unpublished research). Future recommendations for improving the environmental sustainability of cricket and broiler feeds should be in line with the conceptual framework of sustainable animal diets (StAnD) of Makkar and Ankers (2014). StAnD integrates the importance of using natural resources efficiently, generating socioeconomic benefits for farmers, and generating safe, nutritional and economically-viable animal feeds. As such, this presents both an opportunity and a challenge for the expanding cricket farming industry in Thailand.

4.2. Outputs

This study assumed the impacts or benefits of the cricket biofertiliser and the broiler manure to be the same as the substituted fertiliser as there has never been a study published on the impacts or benefits of cricket biofertiliser. Biofertiliser application may have negative environmental impacts that are greater than the ones from the substituted fertiliser in several impact categories, for example freshwater eutrophication and climate change, especially if the nutrients in the fertiliser are not substituted 100%, but may also have benefits over mineral fertiliser, such as in terms of carbon sequestration in the soil and improved yields. Further studies into this area would greatly help complete the picture of the overall cradle-to-cradle life cycle assessment.

According to McFarlane and Distler (1982), frass (insect faeces) production by *A. domesticus* equals 33% of the feed consumed. In this present study, the biofertiliser equalled 35% percent of the feed consumed. This indicates that there is still room for efficiency improvements and that industrial entomology, which focuses on the farming of edible insect species, is in its infancy. The efficiency improvement as stipulated in the future scenario is clearly a major advantage in terms of reducing the environmental impacts associated with cricket production.

4.3. Functional unit

In this study, we chose 1 kg protein in edible mass as one of the functional units. As stated in section 2.2, this did not include digestibility. The quality of the protein, and consequentially the nutritional value, is determined by the amino acid composition and the digestibility of the proteins. The protein digestibility of some cricket species (*Acheta domesticus* and *Anabrus simplex*) has been estimated to be superior to soy protein in trials with rats (Finke et al., 1989). However, according to Klunder et al. (2012), the measured amounts of nitrogenous substances found in insects may be higher than their actual protein content since some nitrogen is also bound in the chitin of the exoskeleton, which consists of both chitin and protein (Finke, 2013). For populations without chitinases, digestibility was found to be comparable to meat when the exoskeleton is removed (Paoletti et al., 2007). It is therefore expected that the digestibility of nitrogenous compounds may be slightly lower than in meat. Sonesson et al. (2017) note that protein as FU in food LCA was found to affect conclusions when compared to a mass-based FU.

There are many studies that highlight the importance of using more than one functional unit, especially when comparing food from different categories (see, for example, Heller et al., 2013; Notarnicola et al., 2015; Sonesson et al., 2017; van der Werf and Salou, 2015). However, there is little consensus on which types of FUs to include. Halloran et al. (2016a, b) recommend including at least two FU categories – mass-, nutritional, and/or economic-based – in order to provide a better overview of the impact of the FU on the conclusion when evaluating edible insect production systems for food. Our study has exemplified the need for multiple FUs; for example, the values under each impact category doubled under the broiler farm scenario. On the other hand, the values of the impact categories increased by 37–70% under the two cricket farm scenarios when comparing the FU of 1 kg of edible mass and 1 kg of protein in edible mass.

4.4. Limitations

A major difference between industrial broiler production and small-scale cricket farming is the use of antibiotics and other inputs such as vitamins and vaccines. Antibiotics and pharmaceuticals are ignored in this LCA, mainly due to the lack of impact assessment methodology (Opio et al., 2013). These inputs are associated with special risks such as the development of resistant strains of pathogenic microorganisms, which is not easily assessed using currently available impact assessment methods. In addition, they represent a substantial cost for contract broiler farmers. Whether future cricket production systems will also adopt antibiotics to increase efficiency or prevent disease or whether they can be optimised without the use of antibiotics is still an open question.

The data used in this study were derived from a medium-scale farm in Thailand. Insect production in tropical and sub-tropical regions of the world consists of a very diverse set of production systems, both in terms of methods and species, and therefore generalisations should be made with caution and consideration of the site-specific requirements. Materials used as feed ingredients may especially influence the overall environmental impacts associated with the feed ingredients.

Although a cooking phase was not included within this study, possible hotspots may occur in the cooking phase of the two food categories. In Thailand, broilers are traditionally prepared as *gai* *yang* (lit. grilled chicken) on a charcoal barbeque. Crickets, on the other hand, are often stir-fried together with salt, fragrant leaves and oil over a stove fuelled by liquefied petroleum gas.

4.5. Socio-economic considerations

Resource efficiency in scaled-up future scenarios may indeed improve the environmental sustainability of cricket farming in north-eastern Thailand. However, as Halloran et al. (2016b, 2017) suggest, such a scenario may marginalise small-scale farmers and have fewer positive socioeconomic impacts than exist today as scaled-up facilities may incur greater start-up costs which are off-limits to small-scale farmers. To date, small-scale cricket farming has improved the lives of farmers in northern and north-eastern Thailand (Halloran et al., 2017), and in this context the other options for a future production system described above, where surplus and waste production from the vegetable industry is used in less intensive production systems, may be even more advantageous. No matter what direction the production systems take, there is considerable potential for optimisation and future research of small and medium-scale cricket production systems.

5. Future considerations and conclusion

The results of this study depended heavily on the data and assumptions about the efficiency with which feed is converted into animal-based food. Large differences can be seen in studies that use different feed sources for experiments with crickets (Halloran et al., 2016a) and therefore the conclusions are also uncertain, especially the ones related to the future scenario. While it may be possible that farmed crickets can have similar or lower FCRs than industrially-farmed broilers, as stipulated in the future scenario, such ratios have not yet been realised *in situ*. In the future scenarios it was stipulated that this required temperature control, but in fact it is not really known what is required to optimise cricket production and it may in fact require completely different strategies, such as changes in diet. Further research into this area is needed.

The high cost of commercial feed is already one of the main disadvantages of rearing crickets (Hanboonsong et al., 2013; Caparros Megido et al., 2016). Another future scenario that may be more economically viable could therefore involve extensification of the production using surpluses and waste from vegetable production. This may also be more desirable from an environmental perspective. This is because although high-protein feeds result in the lowest feed conversion ratios and are thus most efficient (Tongpool et al., 2012), the high impact associated with the production of the feed could mean that alternative feed sources could help decrease the environmental impacts. The results of the present analysis clearly demonstrated that the environmental burden of feed ingredients is significant in both broiler and cricket farming. In agreement with this, Tongpool et al. (2012) found that the most significant impact of broiler feeds is the production of soybean meal, rapeseed meal, fishmeal, and meat and bone meal. Traditional protein sources such as soybean meal and fishmeal are also expensive. Cricket feeds, which are similar in composition to commercial chicken feed, are preferred by farmers because the crickets have shorter life cycles and therefore can be sold more quickly; farmers who use only fresh vegetables have experienced longer life cycles. When the first cricket farmers in Thailand were trained, they were taught to use a variety of vegetables combined with 10% broiler feed, however this practice has largely been abolished in order to increase productivity. Future research into the economics and environmental consequences of alternative feed sources for cricket production is highly relevant.

This paper has presented the first known LCA study of a medium-scale cricket farm in north-eastern Thailand. By including a future scenario a preliminary assessment was made of the additional impacts associated with scaling up production. Current medium-scale cricket farming systems have fewer environmental impacts when compared to industrial broiler farming systems in most impact categories. However, the environmental impacts are reduced compared to current cricket farming systems and broiler farming systems in Thailand by intensifying cricket production. The environmental impacts of cricket farming are mainly associated with the feed production. The major hotspots associated with the feed were soybean and grain maize production. Thus, future research should be focused on identifying alternative feed sources to the conventional chicken feed that is currently used by many cricket farmers in Thailand. Social, cultural and economic sustainability must also be considered when promoting insect farming in rural communities. The results of this research have both practical and academic implications on the improvement of insect farming systems in the future.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2017.04.017.

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