



The potential of insect protein to reduce food-based carbon footprints in Europe: The case of broiler meat production

A. Vauterin^{a,1}, B. Steiner^{a,*}, J. Sillman^{b,3}, H. Kahiluoto^{b,4}

^a University of Helsinki, Department of Economics and Management, P.O. Box 27, FI-00014, Finland

^b LUT University, School of Energy Systems, Sustainability Science, P.O. Box 20, FI-53851, Lappeenranta, Finland

ARTICLE INFO

Handling editor: Zhifu Mi

Keywords:

Broiler meat

Carbon footprint

Insect-based protein

LCA

Review

ABSTRACT

As part of the current climate change debate, concerns have been raised over the rapid expansion of soybean cultivation as the major protein source to feed animals for human consumption. At the same time, insect-based protein is rapidly emerging as an alternative protein source to animal-based protein, both as a potential substitute for soybean-based protein for the use in animal feed, and for direct human consumption. The assessment of climate impacts and market potentials of novel animal feed and food products related to such insect-based protein requires an assessment of their carbon footprints. This paper explores the extent to which insect protein could help to reduce the Global Warming Potential (GWP) associated with food consumption in Europe. The results from a quantitative review and scenario analyses provide two key insights. First, they support previous research suggesting that insect protein has the greatest potential to reduce the carbon footprints of European consumers, if insects are directly consumed as food. Second, they suggest not only that the use of insects as animal feed can substantially contribute to the sustainability of broiler production systems with regard to lowering GWP, but also that low-value side streams are key for improving this potential.

1. Introduction

In the face of increasing environmental, biodiversity and welfare concerns associated with traditional animal-based food production (Grunert et al., 2018; Bonnet et al., 2020; Bohnes and Laurent, 2021; Raven and Wagner, 2021), the search for new and alternative plant, insect and lab-based protein sources has accelerated (He et al., 2020; Santo et al., 2020; Kyriakopoulou et al., 2021). These protein sources have not only the potentials to replace traditional meat products designated for human consumption, but also to direct the use of feeds in animal production towards more sustainable practices (Hawkey et al., 2021; Williams, 2021), and contribute through better exploitation of side streams towards a more sustainable circular economy (Ghini et al., 2020; Ojha et al., 2020). To assess these potentials in terms of their climate impact, it is instrumental to understand the carbon footprint implications of switching from animal-based protein for human

consumption to alternative protein sources, such as insect proteins (Sánchez-Muros et al., 2014). Carbon footprint-based analyses have thus emerged to complement taste-focused studies for the assessments of market potentials and consumer acceptance of novel food product attributes and protein sources (Burnier et al., 2021; Castro et al., 2020; Frigerio et al., 2020; Grebitus and SteinerVeeman, 2016; Llagostera et al., 2019; Steiner and PeschelGrebitus, 2017).

The production and consumption of animal-based food causes major environmental impacts (Poore and Nemecek, 2018), especially when ruminants are involved (Dyer et al., 2020; Rööß et al., 2014). When considering the environmental impacts of different animal production systems, such as with regard to Global Warming Potential, the impact of broiler production is typically proportionally smaller when compared to other meat types (e.g., Nijdam et al., 2012; Dyer et al., 2020). We also observe and continue to expect that Western consumption patterns will continue to shift from red meat to white meat (González et al., 2020), in

* Corresponding author.

E-mail addresses: alexis.vauterin@gmail.com (A. Vauterin), bodo.steiner@helsinki.fi (B. Steiner), Jani.Sillman@lut.fi (J. Sillman), Helena.Kahiluoto@lut.fi (H. Kahiluoto).

¹ (A. Vauterin, Master of Science).

² (B. Steiner, Professor).

³ (J. Sillman, Doctoral candidate).

⁴ (H. Kahiluoto, Professor).

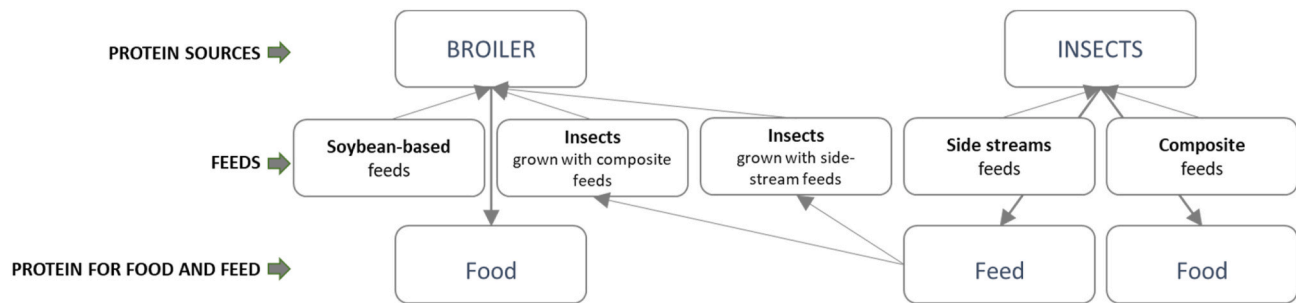


Fig. 1. The construction of items used in the analysis of the GWP of broiler and insect production (Source: own).

spite of the fact that animal-based protein intake of European consumers has gradually increased in the past, with a particular rise in the consumption of poultry (Westhoek et al., 2011). However, there is a growing interest and need to change European diets towards environmentally friendlier ones (e.g., da Silva et al., 2009; Kearney, 2010; Westhoek et al., 2014; Yang et al., 2021). In light of the above evidence, we chose broiler meat as the base scenario for the carbon footprint assessment in this paper, aiming to explore the extent to which insect protein could help to reduce the Global Warming Potential associated with food consumption in Europe.

A range of previous studies have assessed the potential for climate change mitigation of switching to alternative protein production and consumption options. Alternative options include the replacement of soybean-based feeds with other feed options (Ikiamba et al., 2021) and the replacement of animal-based proteins with alternative protein sources, including lab-grown and insect-based sources of protein (Alexander et al., 2017; Tuomisto, 2019; Bohnes and Laurent, 2021; Painter et al., 2020; Williams, 2021). Noting the land-use efficiency of insects and the fact that insects are typically nutritious with healthy high protein content, the use of insect-based protein promises to provide significant potentials for increasing food security and environmental sustainability of food (Bodenheimer, 1951; van Huis, 2013; Alexander et al., 2017). Insects do not use energy to maintain a high body temperature and are therefore very efficient in converting feed into edible meal protein (Nijdam et al., 2012; van Huis, 2013). When insects are mass produced, they can also contribute to the bioconversion of large quantities of food waste (Salomone et al., 2017; Fowles and Nansen, 2020; Guo et al., 2020; Ites et al., 2020). Further, insect protein production systems promise to have lower levels of environmental impacts due to a relatively lower carbon footprint (Blonk et al., 2008; Sánchez-Muros et al., 2014), and due to lower land and water requirements as compared to crop or animal protein production systems (Sánchez-Muros et al., 2014; Alexander et al., 2017; Salomone et al., 2017). Furthermore, the use of insect protein as a sustainable feeding-alternative in aquaculture is gaining significant attention in research and practice (Riddick, 2014; Llagostera et al., 2019; Lu et al., 2020; Toviho and Bárony, 2020; Poveda, 2021).

Despite a growing interest and research base on the potential of insect protein, evidence on the environmental sustainability of insects as an alternative protein source for the poultry industry in the European context is sparse (Netherlands: Blonk et al., 2008; Smetana et al., 2016, 2019; Germany: Ites et al., 2020), and previous studies focusing on insect-based food and feed production, in general, show large uncertainties (Salomone et al., 2017). Smetana et al. (2016, 2019) provided a life cycle assessment (LCA) of insect-based food and feed production at the industrial level. Tallentire et al. (2018) studied the environmental impacts of incorporating novel ingredients such as insect protein into broiler diet formulations to replace soybean protein imported from outside Europe. Allegretti et al. (2017) evaluated the production and processing of *Hermetia illucens* (black soldier fly) larvae for insect meal as compared to the use of soybean meal in Brazilian poultry production systems. Abro et al. (2020) assessed the potential

socio-economic benefits of using larvae meal for the Kenyan poultry sector. (Roffeis et al. 2018, 2020) provide an ex-ante life cycle impact assessment of insect-based feed production and use a life cycle inventory analysis as a basis to analyze the economic performances of insect-based feed production systems for the West Africa context. Ites et al. (2020) assess the modularity of insect production and processing as a path to efficient and sustainable food waste treatment. They conduct an LCA assessment for *Tenebrio molitor* (mealworm) and *H. illucens* production, with specific consideration on the conditions of production in Germany.

The objective of this study is to contribute to the above debate by exploring the potential of insect protein to reduce the carbon footprint associated with European food consumption. We introduce three scenarios to compare alternative insect-based feed and food production systems with soybean-based feed and broiler meat production systems. In our scenarios, soybean meal-based feeds are replaced with insect-based feeds for broiler production, and broiler meat is replaced with food products made from insects for human consumption. Further, we compare industrially produced composite feeds based on insect protein production with alternative feeds produced from industrial side streams. Through these scenarios we address the following research question: how are European consumers' carbon footprints changing when they alter their food consumption patterns, by partially or completely replacing broiler meat with more insect-based protein food products? To answer this research question, we perform a quantitative review to assess the potential reduction in the carbon footprint associated with an average European consumer's diet.

The remainder of this paper is structured as follows. Section 2 introduces the study approach and methods, provides a selected review of relevant LCA studies applied to insect proteins, and describes the development of our data sets. This serves then as the basis for the selection of variables, calculation of functional unit and the scenario assessments. Section 3 discusses the scenario results, and the results of the sensitivity analysis. Section 4 outlines the study's conclusions, data validity, limitations, and indications for future work.

2. Materials and methods

First, we conduct a short and thematically focused literature review on the Global Warming Potential (GWP) values of broiler, insect, and soybean meal production from a variety of LCA studies (sections 2.1. and 2.2.), to generate a data set for further analysis. Based on the literature review, we assess the compatibility of insects as a protein source to replace soybean meal in broiler diets. The criteria for the studies included in our data set are presented in section 2.3. We used this data set to first assess the global warming impact associated with the consumption of conventionally farmed broiler meat, broiler meat farmed with insects or food products based on insects, and then outline three scenarios (Section 3).

Fig. 1 illustrates the construction of items that we used in the analysis of the GWP of broiler and insect production.

We could in the following meta-analysis validate the robustness of the data, yet in the case of LCA, the quantitative analysis is challenging

Table 1

Characteristics of the insect related LCA studies. A-LCA means attributional LCA. C-LCA means consequential LCA. Values accounting C-LCAs are given in brackets.

Literature source	Year	Country	Insect species	Type of LCA	The base approach of the study	Number of observations	Sensitivity analysis			
							One or two key parameters studied	Several key parameters studied	Methodological choices studied	Uncertainty analysis performed
Joensuu & Silvenius	2017	Finland	<i>Tenebrio molitor</i> ; <i>Zophobas morio</i>	A-LCA	Theoretical case	9		x		
Thévenot et al.	2018	France	<i>Tenebrio molitor</i>	A-LCA	Several insect farms	1		x		x
Bava et al.	2019	Italy	<i>Hermetia illucens</i>	A-LCA	Lab scale	4	x			
Oonincx & de Boer	2012	Netherlands	<i>Tenebrio molitor</i> ; <i>Zophobas morio</i>	A-LCA	Several insect farms	1				
Halloran et al.	2017	Thailand	<i>Acheta domestica</i> ; <i>Gryllus bimaculatus</i>	A-LCA	Insect farm	2		x		
Suckling et al.	2020	UK	<i>Gryllus bimaculatus</i>	A-LCA	Insect farm	2		x		
Smetana et al.	2019	Netherlands	<i>Hermetia illucens</i>	A-LCA/ C-LCA	Pilot-farm/ theory	8 (4)		x	x	x
Salomone et al.	2017	Italy	<i>Hermetia illucens</i>	A-LCA/ C-LCA	Pilot-farm	5		x		
van Zanten et al.	2015	Netherlands	<i>Musca domestica</i> L	A-LCA/ C-LCA	Lab-scale	1		x		
Tedesco et al.	2019	Italy	<i>Eisenia fetida</i>	A-LCA	Insect farm	2		x	x	x

due to the heterogeneous nature of the studies. The production practices and processes of insect protein vary widely and contribute to this heterogeneity. For instance, the production of *H. illucens* as a part of the waste management processes for providing feed for the flies (Smetana et al., 2019), and *Acheta domestica* (house cricket) production using industrial feed sources (Halloran et al., 2017) are fundamentally different protein production systems. In addition, there is a lack of peer-reviewed LCA studies on the production of specific insect species. Therefore, we attempted to improve the usefulness and validity of the results and data sets by conducting a sensitivity analysis, and by identifying the major factors affecting the results. In addition, it could be argued that because of the novelty of the insect industry, there are yet no best-practice examples and corresponding data available to inform insect production, to move towards lower GWP options. This is reflected in the fact that several of our source LCA studies use only one insect farm or a pilot scale farm as a case example, which we also indicated in the summary of characteristics of the insect-related LCA studies (Table 1). For these reasons, we examined scenarios by using only the best knowledge on production practices for each insect species.

2.1. Soybean meal as feed ingredient and its substitution with insects

Soybean meal is a widely used and major source of protein for broiler feed (van Gelder et al., 2008; Dei, 2011), yet it is also an ingredient that can contribute to negative environmental impacts in broiler feed production, for example due to its land use (e.g., Fearnside, 2001; Barona et al., 2010; Salomone et al., 2017), as well as through contributing negatively to social sustainability measures (Jia et al., 2020).

Soybean meal is a concentrated protein source from which most of the oil has been separated from soybeans. It is high on protein and contains a well-balanced composition of essential amino acids (Bansz-kiewicz, 2011). The average protein content of soybean meal is 46.0% (Florou-Paneri et al., 2014). Based on a literature review of the LCA

studies on broiler production, the share of soybean meal in broiler feed ranges from 20.1% to 39.0%, and the value of the feed conversion rate (FCR) ranges from 1.6 to 2.8. However, typically the FCR in broiler farming is approximately 2.0, and average soybean meal content in broiler feed is 36.8% in EU (van Gelder et al., 2008; Boggia et al., 2010; Thévenot et al., 2013; González-García et al., 2014; Cesari et al., 2017).

Insects are nutritionally rich in essential amino acids, and some insect species provide high good-quality fatty-acids (van Huis et al., 2013; Kourimská and Adámková, 2016). It has been shown that insects can replace partly or all the soybean meal used in the feed without compromising the FCR value (Khusro et al., 2012; Makkar et al., 2014; Bovera et al., 2015; Józefiak et al., 2016; Lu et al., 2020). In our following analysis, we assume that replacing 1.0 kg soybean protein with the same amount of insect protein has no effect on the FCR value in broiler farming.

2.2. Insects as feed and food

The general EU legislation on insects for feed or food has distinguished insects as animals that are farmed to produce food or feed (Spiegel et al., 2013; Finke et al., 2015; Lähteenmäki-Uutela and Grmelová, 2016). The EU Commission defines Novel Food as food that had not been consumed to a significant degree by humans in the EU before May 15, 1997, when the first Regulation on novel food came into force. The Novel Food Regulation requires an authorisation before a novel food product can be placed on the EU market, which is then followed by a stringent scientific assessment from the European Food Safety Authority (EFSA). EFSA verifies, based on available scientific evidence, that the food does not pose a safety risk to human health. The regulation on novel foods has recently been revised, and has from June

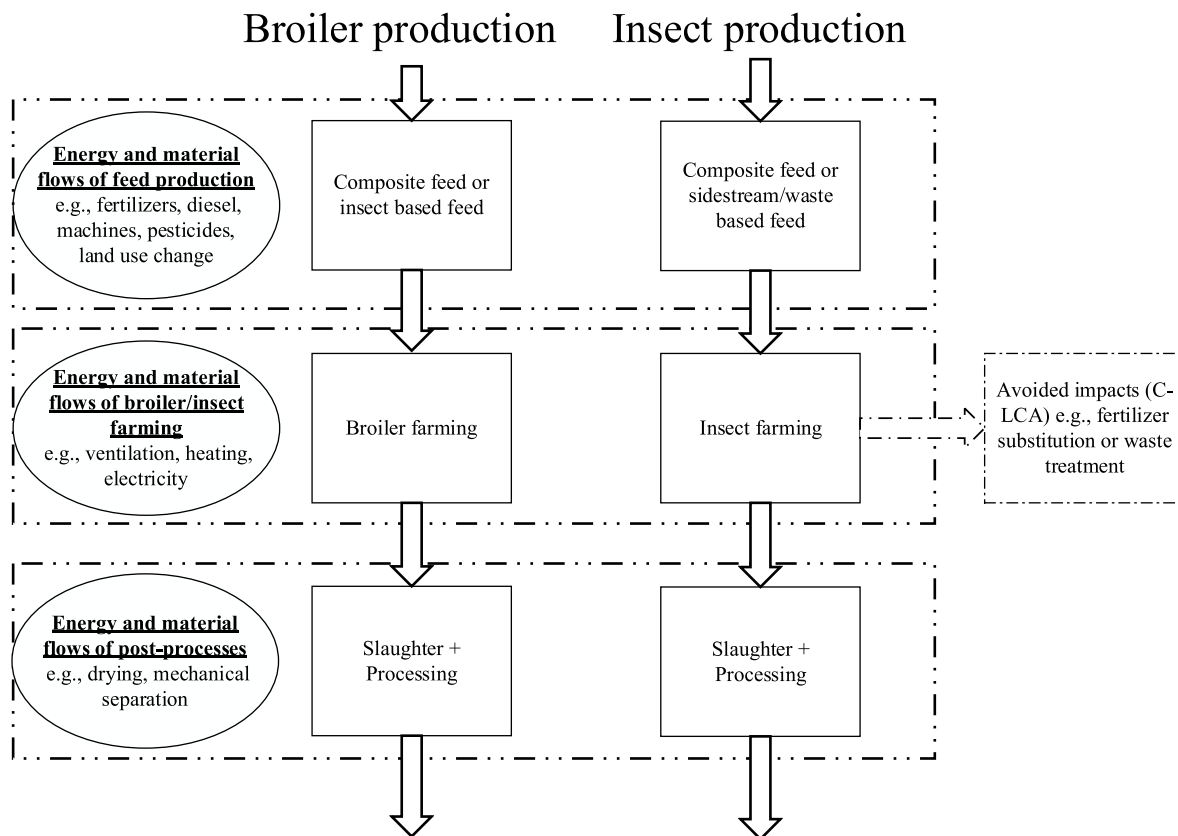


Fig. 2. Simplistic system boundaries of the LCAs included (Source: own).

1, 2021, authorized the placing on the market of dried yellow mealworm as a novel food.⁵

Several LCAs focus on insect production for human food (e.g., Oonincx and de Boer, 2012; Halloran et al., 2017), although the same insect species can also be produced for animal feed (e.g., Thévenot et al., 2018). We could argue that if the nutritional quality of insects produced beyond the farm gate is good enough for direct human consumption, the use of unprocessed insects should be acceptable also for feeding animals. For instance, SucklingDruckman et al. (2020) studied the production of *A. domesticus* for use in food and feed when the same production processes are applied while assuming that if insects are produced for food, they could also be used for feed production. However, we should also note that while most insect species are suitable for use in feed, the same species are not necessarily suitable for human consumption, keeping also EU hygiene regulations in mind (e.g., Regulation No 852/2004 and Regulation No 183/200).

2.3. LCA studies used to generate the data set

LCA is a standardized method which is internationally used to quantify the environmental impacts of a product throughout its entire life cycle (ISO 14040). The use of LCA has rapidly increased as a tool when studying environmental impacts of agricultural and food products (e.g. Ponstein et al., 2019; Roy et al., 2009; Thomas et al., 2020). The

LCA studies that we selected for this study can be divided into attributional LCAs (A-LCA) and consequential LCAs (C-LCA). Broadly speaking, the A-LCAs focus on describing the impacts of existing production systems, and the C-LCAs focus on describing how the impacts could change based on decisions (Curran et al., 2005; Yang, 2016).

For those studies included in our analysis that encompass more than one insect species produced by the same production processes (e.g., Oonincx and de Boer, 2012; Halloran et al., 2017), we consider different insect species as a separate observation in the same studies. To ensure study validity and a robust, data-driven approach to the construction of the scenarios, we used only peer-reviewed studies (Table 1) that are comparable by the use of variables and parameters.

For LCAs to be comparable, they should apply equivalent definitions of the system boundaries for the alternative production systems, and they should make similar delimitations within the systems (Tillman et al., 1994). To suit the context of our study, the LCAs should include similar system boundaries, a functional unit (FU) using mass unit or protein content, the GWP as an environmental indicator, and the results should be expressed in CO₂-equivalents (CO₂-eq.). We describe the requirements for similarities in greater detail in the following sub-sections.

2.3.1. System boundaries

Ideally, the LCA studies we used for our analysis should evaluate the various environmental impacts of broiler meat and insect products over their entire life cycle. However, in the literature (Tables 3–5), the impacts of broiler and insect farming are typically evaluated until the slaughter and/or package stage, and do not consider later stages, such as retail, use and disposal. For our study, we included (Fig. 2, below) LCAs which encompass also processing stages beyond the farm gate, such as drying, slaughter, mechanical separation and/or package (e.g., González-García et al., 2014; van Zanten et al., 2015; Cesari et al., 2017; Halloran et al., 2017; Thévenot et al., 2018), while keeping in mind that the LCAs on broiler and insect production consider different processing

⁵ On 1st June 2021, the Commission has adopted the regulation (EU) 2021/882 authorising the placing on the market of dried *T. molitor* larva as a novel food under Regulation (EU) 2015/2283 of the European Parliament and of the Council, and amending Commission Implementing Regulation (EU) 2017/2470. https://ec.europa.eu/food/food/novel-food/authorisations/approval-first-insect-novel-food_en; <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A3A2021R0882&qid=1622617276506>.

stages beyond the farm gate, yet as a commonality they consider that the actual product is ready for use.

The use of C-LCAs differ most strikingly in terms of system boundaries. For instance, farming of *H. illucens* for food or feed produces compost, which stems from the production and use of feed sources, and comes in the form of, for example, biowaste or manure. For this case, it is possible to include consideration of the avoided impacts, such resulting for example from differences in fertilizer use or waste treatment (e.g., Smetana et al., 2019), thus allowing for a subsequent data set to assess and highlight the systemic benefits of protein production from *H. illucens* as compared for example to protein production from broiler. However, the LCAs reporting the impact estimates of production of insect meal from *H. illucens* for substitution of other protein sources (e.g., van Zanten et al., 2015; Salomone et al., 2017) do not include consideration of the avoided impacts as this would create double counting. Which factors to include in C-LCA models is vital for the reliable evaluation of the impacts (e.g., Sillman et al., 2020). Therefore, we separately indicate which data was provided by the C-LCAs.

2.3.2. Functional unit (FU)

A well-defined functional unit (FU) allows to make adequate and informative evaluations across LCAs. The FU should be linked to one or more of the characteristics that are in common between the products. In the data sources employed, the LCA results are represented in terms of kg of CO₂-eq. per kg of protein. Most of the studies report their results per kg or tonne of product at the processing or slaughterhouse gate. For our study, the nutrient-based FU was of primary importance, because we aim to present the results to inform recommendations for the consumption of protein-based food. Thus the FUs used in the literature are converted from kg of product to kg of protein based on the protein contents of the products, as applicable.

2.3.3. Global Warming Potential (GWP)

Protein production systems are sources of Greenhouse Gas (GHG) emissions, such as carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O). The impact of these emissions can be evaluated in different impact categories or by types of indicators (Hellweg and i Canals, 2014). The characterization factors used to convert GHG emissions other than CO₂ into the common unit of the GWP impact category (CO₂-eq) were derived from Myhre et al. (2013). In the data sources selection we used GWP₁₀₀ as the environmental indicator.

2.3.4. LCAs with different allocation methods

Some food and feed production systems may produce more than one single product. For example, *H. illucens* production systems may also include co-production in waste treatment and processing facilities. For such systems, the global warming impacts must be allocated to the various inputs and outputs of the production processes and divided over the products resulting from the system by using, for example, the economic, mass and energy allocation methods. Several problems are involved with the use of such allocation methods, because the use of the method, and the choices and assumptions made prior to the LCA analysis may all influence the robustness of the results (e.g., Ekvall and Finnveden, 2001; Cederberg and Stadig, 2003; Svanen et al., 2011). In other

words, not considering these allocations could overestimate the actual impact of production in multiple-product systems. Therefore, for our data set, we used LCAs with diverse allocation approaches.

2.3.5. Selection of LCA studies on soybean meal, broiler and insect production

Most of the soybean meal used in the broiler industry is imported into the EU from Brazil and Argentina (van Gelder et al., 2008; Voora et al., 2020). To get the relevant data linked with appropriate analysis approaches, we selected LCAs focusing on the use of soybean meal from South America. Because the impact of land use or land use change on the total GHG emissions of soybean meal production is significant (Hörtenhuber et al., 2014), we considered only LCAs including land use or land use change impacts.

As the focus of this study is on European consumers, the LCA studies we selected have a corresponding focus on broiler production in the EU. Further criteria for selection was that soybean meal production must be included as a feed-ingredient variable in the broiler production function. This criteria could not be applied for the insect studies, because the European markets are yet to capitalize on the potential of insects for food and feed, and the corresponding value chains in emerging markets are highly globalized. Therefore, LCAs on insect production for regional feed and food systems need to take a global perspective.

2.4. Generation of data sets and scenarios

2.4.1. Scenario I

Broiler production was selected as a baseline for scenario development and analysis. Broiler production systems can be categorised by farming programs into free-range broiler systems, where broilers have free access to pasture area, and conventional broiler systems, where broilers are grown indoors. In both systems, broilers are fed with industrially produced feed as their base diet (e.g., Lima and Nääs, 2005; Coletta et al., 2012). In this scenario, we assessed the carbon footprint of conventionally farmed broiler meat against the potential of reducing the food carbon footprint of protein consumption through an increase in insect consumption. We assumed that the protein intake from conventionally farmed broiler meat remains constant.

2.4.2. Scenario II

Emissions from feed production are typically the main source of environmental burden in broiler production. The protein sources used in feed and the feed efficiency rate have significant impacts on the GWP of broiler production systems (e.g., González-García et al., 2014; Leinonen and Kyriazakis, 2016; Cesari et al., 2017). Therefore, in this scenario, we assessed the GWP of insect meal production relative to soybean meal production, to examine the potential of insects as a more climate-friendly protein source for broiler feed. In this scenario, we examined how consumers' food carbon footprints change if they shift their protein consumption from conventionally farmed broiler meat, where soybean meal is typically used, to protein consumption from broiler meat farmed with insect-based feeds. To assess this scenario required that we first calculated the data sets for scenario I and scenario III.

2.4.3. Scenario III

Insects are generally assumed to be more environmentally sustainable compared to conventional animal-based protein sources (Alexander et al., 2017). This is largely due to relatively high FCRs and reproduction rates, because insects are cold-blooded (van Huis, 2013; van Huis et al., 2013). To further assess the degree of their environmental sustainability, we evaluated LCA data on the GHG emissions from insect production. In this scenario, we investigated how consumers' food carbon footprints will change if they were to replace protein consumption from broiler meat with protein consumption from insect-based food products.

Table 2

GWP values of soybean meal production with the impact of land use change included in South America (MIN., MAX., and MEAN in kg of CO₂-eq. per kg of protein). N means the number of observations of different production practices.

SOYBEAN MEAL FOR FEED	N	MIN.	MAX.	MEAN
Soybean meal ^{a-c}	4	3.13	6.99	5.21

References.

- ^a Tallentire et al. (2018).
- ^b Thévenot et al. (2018).
- ^c Hörtenhuber et al. (2014).

Table 3

GWP values of broiler production in EU (MIN., MAX., and MEAN in kg of CO₂-eq. per kg of protein). N means the number of observations of different production practices.

CONVENTIONAL BROILER PRODUCTION	N	MIN.	MAX.	MEAN
Broiler ^{a,g}	9	12.50	27.60	18.55

References.

- ^a (2014).
^b González-García et al., 2014.
^c da Silva et al., 2012.
^d Cesari et al. (2017).
^e Leinonen et al. (2012).
^g Katajajuuri et al. (2014).

Table 4

GWP values for insect production for broiler feed (MIN., MAX., and MEAN in kg of CO₂-eq. per kg of protein). N means the number of observations of different production practices. The values accounting for the C-LCA results are given in brackets. The protein content values (where 1 = 100%) indicate the values obtained from the original data in the source LCAs.

INSECT PRODUCTION FOR FEED	PROTEIN CONTENT	N	MIN.	MAX.	MEAN
Insects fed with industrially produced composite feeds					
<i>Hermetia illucens</i> ^a	0.53	1	10.89	10.89	10.89
<i>Tenebrio molitor</i> ^{b-d}	0.53–0.65	5	4.43	13.48	7.66
<i>Zophobas morio</i> ^{c-d}	0.45	4	5.22	15.87	9.58
<i>Acheta domesticus</i> ^e	0.63	2	2.90	5.40	4.20
<i>Gryllus bimaculatus</i> ^{e-f}	0.56	4	2.82	33.49	15.24
Total average					9.51
Insects fed with feeds from industrial side streams					
<i>Hermetia illucens</i> ^{a,g,h} (C-LCA)	0.17–0.56	16 (4)	1.10 (–12.77)	9.51 (2.53)	3.63 (–5.74)
<i>Musca domestica</i> L ⁱ	0.42–0.68	1	1.13	1.83	1.48
<i>Zophobas morio</i> ^j	0.45	6	1.36	10.54	5.84
<i>Tenebrio molitor</i> ^j	0.53	6	1.16	8.95	4.96
<i>Eisenia fetida</i> ^k	0.64–0.72	2	3.09	9.32	6.70
Total average (Total average including C-LCA)					4.52 (2.81)

References.

- ^a Bava et al. (2019).
^b Thévenot et al. (2018).
^c Ooninx and de Boer (2012).
^d Joensuu and Silvenius (2017).
^e Halloran et al. (2017).
^f SucklingDruckman et al., 2020.
^g Smetana et al. (2019).
^h Salomone et al. (2017).
ⁱ (2015).
^j Joensuu and Silvenius (2017).
^k Tedesco et al. (2019).

2.4.4. Calculations for scenario II

To be able to compare the GWP of the broiler protein production by using either soybean meal or insects as a feed ingredient, first, the impact of the feed ingredients must be known. Then, the amount of the consumed insect ingredients is to be calculated. We used the FCR value of 2 in the following calculations. For the mean value, we used the average of 36.8% as the share of soybean meal content in broiler feed. For the minimum and maximum (minmax) values, we used the shares of 20.1% and 39.0%, respectively (see section 2.1.). We used the GWP impact of total average (Tables 2–5) to calculate the mean value, and calculated the GWP of insect and soybean ingredients by using the

Table 5

The GWP values for insect production for food (MIN., MAX., and MEAN in kg of CO₂-eq. per kg of protein). N means the number of observations of different production practices. The values accounting for the C-LCA results are given in brackets. The protein content values (where 1 = 100%) indicate the values obtained from the original data in the source LCAs.

Insect production for food	Protein content	N	MIN.	MAX.	MEAN
Insects fed with industrially produced composite feeds					
<i>Tenebrio molitor</i> ^{a,b}	0.53–0.65	4	4.43	13.48	8.13
<i>Zophobas morio</i> ^{a,b}	0.45	4	5.22	15.87	9.58
<i>Acheta domesticus</i> ^c	0.63	2	2.94	5.38	4.16
<i>Gryllus bimaculatus</i> ^{c-d}	0.56	4	2.82	33.49	15.24
Total average					9.28
Insects fed with feeds from industrial side streams					
<i>Hermetia illucens</i> ^e (C-LCA)	0.17	4 (2)	1.38 (–12.77)	6.81 (–7.51)	4.46 (–10.14)
<i>Eisenia fetida</i> ^f	0.64–0.72	1	8.21	9.32	8.73
<i>Zophobas morio</i> ^b	0.45	6	1.36	10.54	5.84
<i>Tenebrio molitor</i> ^b	0.53	6	1.16	8.95	4.96
Total average					6.00
(Total average including C-LCA)					(2.77)

References.

- ^a Ooninx and de Boer (2012).
^b Joensuu and Silvenius (2017).
^c Halloran et al. (2017).
^d SucklingDruckman et al., 2020.
^e Smetana et al. (2019).
^f Tedesco et al. (2019).

following equation:

$$GWP_{\text{feedingredient}} = \frac{m_{\text{broiler}}}{n_{\text{broilerprotein}}} * FCR * m - \%_{\text{ingredient}} * n_{\text{feedingredientprotein}} * GWP_{\text{ingredient}} \quad (1)$$

where.

$GWP_{\text{feedingredient}}$ = kgCO₂-eq. per kg of broiler protein

$GWP_{\text{ingredient}}$ = kgCO₂-eq. per kg of feed ingredient protein

m_{broiler} = kg of broiler

FCR = kg of feed per kg of broiler protein

$n_{\text{broilerprotein}}$ = kg of broiler per kg of broiler protein

$m - \%_{\text{ingredient}}$ = kg of feed ingredient per kg of feed

$n_{\text{feedingredientprotein}}$ = kg of feed ingredient protein per kg of feed ingredient

Once we calculated the GWP of the insect feed ingredients, we calculated the GWP of insect-fed broiler. We calculated this by using the minmax and mean values in the following equation:

$$GWP_{\text{insectfedbroiler}} = GWP_{\text{broiler}} - GWP_{\text{soybean meal}} + GWP_{\text{insectfeed}} \quad (2)$$

where.

GWP_{broiler} = kgCO₂-eq. per kg of broiler protein

$GWP_{\text{soybean meal}}$ = kgCO₂-eq. per kg of broiler protein

$GWP_{\text{insectfeed}}$ = kgCO₂-eq. per kg of broiler protein

2.4.5. Data sets

The scenarios I, II and III are developed from the data sets summarized and represented in Tables 2–5, which list the GWP values as minimum (MIN.), maximum (MAX.) and mean (MEAN). The GWP values are represented in kg of CO₂-eq. per kg of protein. The number of observations (N) and reference sources from which the original values

Table 6

GWP values (MIN., MAX., and MEAN in kg of CO₂-eq. per kg of protein) for each scenario and the number of observations. N means the number of observations of different production practices. The values accounting for the C-LCA results are given in brackets.

SCENARIO	PRODUCTION OF PROTEIN FOOD	N	MIN.	MAX.	MEAN
Scenario I	Broilers fed with soybean meal	9	12.50	27.60	18.55
Scenario II	Broilers fed with insects produced with industrially composite feeds	16	12.21	75.14	25.82
	Broilers fed with insects produced with feeds from industrial side streams (C-LCA)	31	10.65	33.97	17.38
		(4)	(-2.19)	(19.60)	(0.01)
Scenario III	Insects fed with industrially produced composite feeds	14	2.87	33.49	9.28
	Insects fed with feeds from industrial side streams (C-LCA)	17	1.16	10.54	6.00
		(2)	(-12.77)	(-7.51)	(-10.14)

were obtained are also given in the tables.

Based on the Dutch Food Composition Database (NEVO),⁶ which contains data on the composition of foods, Nijdam et al. (2012) estimated that the average protein content of poultry is 20.0% (without bones). We used this value in our study, where we compared the GWP values of broiler production in the different scenarios (Table 3).

In our analyses, we assumed that the insects are fed to broilers (Table 4) or consumed directly as food (Table 5). The production of insects was also divided into two feed categories: insects fed with industrially produced composite feed, and insects fed with industrial side streams. The specific insect species and their respective impacts are accounted for in Tables 4 and 5. Where the source LCA reported several protein content values for a given insect product, we used the average and minmax protein content values to calculate the impact values.

3. Results

The results of scenarios I to III are represented in Table 6. Scenario I uses the calculated data from Table 3. Scenario II uses the calculated data from Tables 2 and 4, which is the data from which the GWP of broiler production with insect feed was calculated using equations (1) and (2). Scenario III uses the data from Table 5.

By comparing the minimum (MIN.) GWP values for broiler production in baseline scenario I and scenario II, we can see that switching to feeding broilers with insects that are fed with industrially composite feeds can reduce the GWP impact of broiler production to a lesser extent than if broilers were fed with conventionally produced soybean meal.

When broilers are fed with insects produced with feeds from industrial side streams, the GWP impact is lower for both the minimum and mean value cases, 22.0% and 8.0%, respectively. However, scenario II also indicates that the maximum GWP value for insect-fed broiler production can be higher than that for conventional broiler production. In scenario III, where insects are used directly as a protein source for human consumption, the GWP values are lower in all considered categories, except for the maximum value of insects fed with industrially produced composite feeds. Further, when we consider in scenarios II and III also the systemic benefits by including in our scenario assessments the GWP values from the C-LCAs, the results show net-positive GWP impacts when *H. illucens* is used in waste processing for compost.

3.1. Sensitivities of different factors considering insect production

The results show a wide range of GWP values in scenarios II and III. Greatest uncertainty and impact on the sensitivities concern the location of production, insect species and sources of feed and energy.

3.1.1. Climatic conditions

The insect species *G. bimaculatus* (field cricket) shows the greatest range of GWP when industrially produced composite feeds are used, for both scenarios II and III. It also has the highest mean GWP value, being 38.0% higher than the total mean average (Table 4). If *G. bimaculatus* is not used to feed broilers in scenario II, the mean and maximum values decrease by 9.4% and 42.0%, respectively. We note that the GWP values for the species *G. bimaculatus* are obtained from two different LCA studies, which both use broiler feed as a feed source for crickets, and present scenarios to decrease the environmental impacts from *G. bimaculatus* production processes. The difference between both studies is related to the conditions of production, which is also the reason for the widely varying range of GWP values. Halloran et al. (2017) studied the production of *G. bimaculatus* in outdoor facilities and climatic conditions that are natural for species productivity, which means less energy is needed in the farming processes. SucklingDruckman et al. (2020) studied the case of UK production of *G. bimaculatus* in warm indoor facilities, where higher energy consumption is required to secure optimal levels of humidity and temperature. Consequently, the species of *G. bimaculatus* show lowest values in terms of GWP if the production systems are operated in optimal climatic conditions. The low GWP values associated with *G. bimaculatus* decrease the mean values in scenario II by 14.9%, and in scenario III by 30.6%. The other LCAs studied the production of other than cricket species, and the production systems under investigation were located in Europe (Table 1), which cannot be considered to explain the differences in GWP values.

3.1.2. Insect species

The use of different insect species may significantly influence the GWP of broiler production. If, for the example considering scenario II, industrial side streams would be used in the production of the fly species *H. illucens* and *M. domestica* as ingredients for broiler feed, the GWP values could be considerably lower. The mean values for *H. illucens* and *M. domestica* are 20.0% and 67.0% lower than the total average (Table 4). In other words, the mean value for the case of scenario II where industrial side streams are used to produce insects could decrease the overall GWP impacts in scenario II by 20.0%. The review of the GWP of different insect species for food use produces a similar wide range of GWP values. Only for the cricket species and if produced in the UK, the GWP of production is greater than that of broiler production (SucklingDruckman et al., 2020, Table 5).

3.1.3. Feed and energy

If climatic conditions are not considered, feed and energy consumption are the major contributors to the total GWP of insect protein production. Some LCA studies investigated the extent of influence of the feed and energy sources on the GWP impacts (e.g., Joensuu and Silvenius, 2017; Smetana et al., 2019). Specifically, Joensuu and Silvenius (2017) studied the GWP of *Z. morio* (mealworm) production processes and estimated the potential for GWP reduction, when feed or energy sources are changed to contain higher levels of renewable energy and better meet GHG reduction targets. The authors estimated that the GWP impact may change even by 22.0%, depending on the composition of the industrially produced composite feeds. When by-products are used as a feed and the share of renewables are increased, a GWP reduction of 67.0% can be achieved, when compared to reference production practices in this study. Smetana et al. (2019) studied the GWP of *H. illucens* production by using different shares of feed from side streams and renewables. Considering the best-case scenario with the highest amount of feed from side streams and the highest share of renewable energy, the

⁶ <https://www.rivm.nl/en/dutch-food-composition-database>.

GWP impact is reduced by 80.0% compared to the reference production practice in this study. Bava et al. (2019) studied the impacts of *H. illucens* production by using different feed sources. The GWP reduction can be 88.0% when insects are fed with feeds from side streams instead of industrially produced feeds. If avoided emissions are considered, e.g., by using flies to treat organic waste, the lowest GWP impacts are gained (Table 6).

3.1.4. Best practices

Table 7 summarizes the best practices for our three scenarios. In all cases – except for the maximum and mean values in scenario II where broilers are fed with insects produced with industrially composite feed – the GWP is lower than for the base case of broiler production. If we exclude from our calculations the high GWP values for the *H. illucens* species produced with industrially produced composite feeds (Tables 4 and 5), then we obtain for all scenario cases that the GWP of production insects as a protein source for feed and food is lower than the GWP of conventional broiler production. Furthermore, when the GWP values from the C-LCAs are considered, the results are net-positive in all cases.

3.2. Discussion of scenario results and data validity

Most of the cases in scenarios II and III with insects fed with feed from industrial side streams suggest that the protein produced causes less GWP than protein production in scenario I. The values in scenario III suggest that insects are a good alternative protein source to reduce GHG emissions. The mean values in scenarios II and III are 6.3%, 50.0% and 67.8% lower than the mean value in scenario I, respectively. However, an even greater reduction potential exists, when using the best practices of insect production (Table 7) or when larvae are used to process organic waste (e.g., Smetana et al., 2019). By considering avoided impacts, the use of insects as animal feed can substantially contribute to the sustainability of the broiler production system with regard to lowering GWP. Our scenarios suggest that even net-positive impacts are possible.

However, although the data on insects used in this study is recent, it is relatively heterogeneous (Table 1). The LCA studies on insects that were selected for scenario assessments differ in the use of functional units and allocation methods. Further, the studies apply different types of LCA (attributional LCAs (A-LCA) and consequential LCAs (C-LCA), see section 2.3.), which has an impact on the way the production processes around the system are investigated, while including or excluding considerations of the avoided impacts. Thus, our study should not be understood as a comparison between systems, but rather as a cross-evaluation of the systems. Furthermore, the scenarios presented provide indicative estimates for the GWP of broiler and alternative insect protein consumption. Especially because the included peer-reviewed insect-related LCA studies are in many cases describing pilot scale, small scale, or even hypothetical insect production facilities, the results need to be interpreted with caution. On the other hand, state-of-the-art technologies for insect mass production are still in their early development stages (Cortes Ortiz et al., 2016), and therefore we could expect further considerable GWP improvements in the future.

The data sets we generated include non-ideal and ideal growing practices and processes, thus likely providing a realistic reflection of actual production practices. For instance, some of the high impacts are due to non-ideal growing conditions or due to the fact that the feed employed is not the most preferred one with respect to GHG emissions. Some studies like Bava et al. (2019) explore the production of flies by using industrial composite feed made for broiler production. In contrast, there were studies evaluating the impacts by using renewable energy sources and feed sources that are associated with low emissions (e.g., Joensuu and Silvenius, 2017; Smetana et al., 2019).

The data describing the GWP of soybean meal production is taken from studies focusing on soybean production in Southern America, which consider emissions from land use changes. By substituting non-sustainable practices with sustainable soybean production, the GWP

reduction would be lower in scenarios II and III. For instance, if certified soybean that was not farmed in tropical areas was used instead of Brazilian soybean typically farmed in such areas, then the minimum value of soybean meal would be approximately 47.0% lower (e.g., Hörtenhuber et al., 2014). Beyond such obvious GWP reductions, our analysis including the comparison of insects-based protein and soybean meal from South America adds further insight with regard to emissions from land use, considering that the increasing soybean field expansion and associated deforestation as a result of incentives to produce more food and feed is likely not going to disappear any time soon (e.g., Fehlenberg et al., 2017), considering ongoing significant social sustainability issues (e.g., Brockhaus and Di Gregorio, 2014), and considering the fact that a major part of EU imports of soybean meal continues to come from South America (van Gelder et al., 2008; Karlsson et al., 2021).

4. Conclusions, limitations and further work

This study has explored the potential of insect-based protein to reduce the carbon footprint associated with food consumption in Europe through a quantitative review, focusing on Global Warming Potentials (GWP). Overall, it supports previous research suggesting that insect protein has the greatest potential to reduce the carbon footprints of European consumers, if insects are directly consumed as food. However, the results from our scenario analyses suggest that insect proteins considered may not necessarily perform better with regard to their GWP compared to broiler proteins. Depending on location of production and insect species used, the GWP of insect protein may be larger than that of broiler protein, even if insects are used for direct human consumption. In such a context, our study reveals that current practices of insect production for feed purposes are not yet efficient enough to significantly contribute toward a GWP reduction in European food consumption. As such, the study indicates that a precondition to achieve a GWP reduction of protein consumption is that side streams will need to be shown to be safe and thus allowed to be used as insect fodder. Even if that would turn out not to be the case, a careful selection of insect species for human consumption could unleash significant environmental sustainability benefits. Besides hygiene and legislation, also technological development choices can have an important impact on the potential to which insect-based protein may reduce food-based carbon footprints. Especially the energy sources affect potential climate benefits, and efficient upscaling is required for financial affordability to consumers.

Since insect-based feed has overall been found to have a lower potential to reduce the GWP compared to direct use of insect-based protein for human food, more research on product development, consumer acceptance and legal aspects of insect-based proteins will be decisive for the exploitation of the potentials of insect proteins in the future. In spite of the recently revised regulation on novel foods which has from June 1st, 2021 authorized the placing on the market of dried yellow mealworm as a novel food, in spite of other legal challenges that are currently in place for health reasons (e.g. EU Regulation No, 2016/429 on transmissible animal diseases), and in spite of undeveloped production practices and questions related to consumer willingness to use insects, there seems to be a clear market potential, especially if stakeholders cooperate (Cortes Ortiz et al., 2016; van Huis, 2020). Considering the potential benefits with which insect-based proteins could further contribute with respect to land use, GWP, and food security (Alexander et al., 2017; van Huis, 2013; Salomone et al., 2017), and considering these in the context of the EU's Circular Economy and Green Deal strategy (Domenech and Bahn-Walkowiak, 2019; Ghinai et al., 2020; Johnson et al., 2021), it seems likely that insects will contribute more significantly with solutions for decreasing the burden of Europe's food systems on the environment. In particular, there seem large scale potentials for utilizing manure (Scarlat et al., 2018), and for utilizing biowaste from vegetable and animal sources (Lorenz et al., 2013). Both of these waste sources could be utilized as feed ingredient for insects,

Table 7

GWP (MIN., MAX., and MEAN in kg of CO₂-eq. per kg of protein) for each scenario when MIN. values of each insect species are used. Values accounting C-LCAs are given in brackets.

SCENARIO	PRODUCTION OF PROTEIN FOOD	MIN.	MAX.	MEAN
Scenario I	Broilers fed with soybean meal	12.50	27.60	18.50
Scenario II	Broilers fed with insects produced with industrially composite feeds	12.21	34.59	18.63
	Broilers fed with insects produced with feeds from industrial side streams (C-LCA)	10.62	20.60	12.38
		(-2.19)	(-2.19)	(-2.19)
Scenario III	Insects fed with industrially produced composite feeds	2.87	8.21	5.18
	Insects fed with feeds from industrial side streams (C-LCA)	1.38	3.40	2.56
		(-12.77)	(-12.77)	(-12.77)

such as through flies, yet hygiene and safety issues remain to be resolved. If wastes were allowed to be used in insect production, insects could enhance food security with limited environmental impacts as part of novel circular economy strategies. As our results suggest, in best-case-scenarios, insects could even provide net-positive impacts, yet future research must demonstrate that side streams are safe to use.

On top of the above issues, there are also technological and thus efficiency aspects related to upscaling to be resolved, before mass production of insects becomes feasible (e.g., Cortes Ortiz et al., 2016; van Huis, 2020; Ite et al., 2020). To anticipate some of these technological potentials and to see what kind of potentials for reducing GWP there might be in the future with regard to insect production practices, the scenarios in this paper were based on only the best results of each insect species, which showed considerably lower GWP emissions in each scenario using insects (Tables 6 and 7). The results of the best-case scenarios suggest that there is potential in all of the insect species studied, yet the variation of the GWP values among different species is large.

In spite of the above insights, our paper suffers from a number of limitations. First, and while we acknowledge the need to include a multi-indicator approach to environmental sustainability, our analysis is limited to the extent that it focuses on GWP as the single impact category. Further, the data used for this study is relatively heterogeneous, largely due to the diversity of available comparable studies underlying the analysis. Thus, the assessments presented in this study should be considered indicative (see e.g., Foster et al., 2006; Wiedemann et al., 2020; Rööß et al., 2014), although our scenario analyses aimed to contribute to the robustness of the results. In light of the above data limitations, the results presented should not be understood as a comparison between production systems but rather as an approximate cross-evaluation of the systems. This is also the case because of the significant heterogeneity underlying broiler and insect-based food production. For example, differences in chicken breed, intensity of production, feeding programs, duration of chicken's life cycle, etc. will lead to differences in the carbon footprint of the final product (Castellini et al., 2012; Williams, 2021; Pelletier, 2008; Boggia et al., 2010). Similar heterogeneities apply to the insect-based food industry (van Huis, 2016; Payne et al., 2016; Thévenot et al., 2018; Hunts et al., 2020; Pippinato et al., 2020). Furthermore, and despite their novelty, the scenarios constructed in this study need to be interpreted with caution, since they are indicative and relate to the carbon footprint of broiler and insect protein only. This is also the case because a sensitivity analysis in the form of Monte Carlo-based sensitivity analysis (e.g., Ponstein et al., 2019) could not be performed due to the nature of the underlying data. In spite of these limitations, we hope that this study's results provide a basis for an urgently needed clarification of the global warming impacts of broiler versus insect-based protein consumption and production (Ellingsen and Aanonsen, 2006; Weindl et al., 2020), for making a

contribution to transitioning toward more sustainable food systems.

CRedit authorship contribution statement

A. Vauterin: Conceptualization, Methodology, Data curation, Writing – review & editing. **B. Steiner:** Writing – review & editing, Writing – original draft, Supervision. **J. Sillman:** Formal analysis, Writing – review & editing. **H. Kahiluoto:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This paper is based on the Master of Science Thesis of Aleksis Vauterin completed at the University of Helsinki, which was done as a part of the SIRKKA (A74136) project, funded by the European Regional Development Fund.

References

- 2015/2283. Regulation (EU) 2015/2283. Regulation (EU), 2015. No 1169/2011 of the European Parliament and of the Council and Repealing Regulation (EC) No 258/97 of the European Parliament and of the Council and Commission Regulation (EC) No 1852/2001. EU, Official Journal of the European Union 22.11.201. Luxembourg. <https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2011:304:0018:0063:en:PDF>.
- Abro, Z., Kassie, M., Chrysantus, T., Beesigamukama, D., Diiri, G., 2020. Socio-economic and environmental implications of replacing conventional poultry feed with insect-based feed in Kenya. *J. Clean. Prod.* 265, 121871. <https://doi.org/10.1016/j.jclepro.2020.121871>.
- Alexander, P., Brown, C., Arneith, A., Dias, C., Finnigan, J., Moran, D., Rounsevell, M.D., 2017. Could consumption of insects, cultured meat or imitation meat reduce global agricultural land use? *Global Food Security* 15, 22–32. <https://doi.org/10.1016/j.gfs.2017.04.001>.
- Allegretti, G., Talamini, E., Schmidt, V., Bogorni, P.C., Ortega, E., 2017. Insect as feed: an energy assessment of insect meal as a sustainable protein source for the Brazilian poultry industry. *J. Clean. Prod.* 171, 403–412. <https://doi.org/10.1016/j.jclepro.2017.09.244>.
- Banszkievicz, T., 2011. Nutritional value of soybean meal. In: El-Shemy, H. (Ed.), *Soybean and Nutrition*. InTech, Rijeka, pp. 1–18.
- Barona, E., Ramankutty, N., Hyman, G., Coomes, T., 2010. The role of pasture and soybean in deforestation of the Brazilian Amazon. *Environ. Res. Lett.* 5 (2), 024002. <https://doi.org/10.1088/1748-9326/5/2/024002>.
- Bava, L., Jucker, C., Gislón, G., Lupi, D., Savoldelli, S., Zucali, M., Colombini, S., 2019. Rearing of *Hermetia illucens* on different organic by-products: influence on growth, waste reduction, and environmental impact. *Animals* 9 (6), 289. <https://doi.org/10.3390/ani9060289>.
- Blonk, H., Kool, A., Luske, B., 2008. Milieueffecten Van Nederlandse Consumptie Van Eiwitrijke Producten (Environmental Effects of Dutch Consumption of Protein-Rich Products). BMA/VROM, Gouda, Nederland (in Dutch).
- Bodenheimer, F.S., 1951. Insects as human food. In: Bodenheimer, F.S. (Ed.), *Insects as Human Food*. Springer, Dordrecht, pp. 7–38.
- Boggia, A., Paolotti, L., Castellini, C., 2010. Environmental impact evaluation of conventional, organic and organic-plus poultry production systems using life cycle assessment. *World's Poult. Sci. J.* 66 (1), 95–114. <https://doi.org/10.1017/S0043933910000103>.
- Bohnes, F.A., Laurent, A., 2021. Environmental impacts of existing and future aquaculture production: comparison of technologies and feed options in Singapore. *Aquaculture* 532, 736001. <https://doi.org/10.1016/j.aquaculture.2020.736001>.
- Bonnet, C., Bouamra-Mechemache, Z., Réquillart, V., Treich, N., 2020. Regulating meat consumption to improve health, the environment and animal welfare. *Food Pol.* 97, 101847. <https://doi.org/10.1016/j.foodpol.2020.101847>.
- Bovera, F., Piccolo, G., Gasco, L., Marono, S., Loponte, R., Vassalotti, V., Mastellone, P., Lombardi, P., Attia, Y.A., Nizza, A., 2015. Yellow mealworm larvae (*Tenebrio molitor*, L.) as a possible alternative to soybean meal in broiler diets. *Br. Poultry Sci.* 56 (5), 569–575. <https://doi.org/10.1080/00071668.2015.1080815>.
- Brockhaus, M., Di Gregorio, M., 2014. National REDD+ policy networks: from cooperation to conflict. *Ecol. Soc.* 19 (4). <https://www.jstor.org/stable/26269660>.
- Burnier, P.C., Spers, E.E., de Barcellos, M.D., 2021. Role of sustainability attributes and occasion matters in determining consumers' beef choice. *Food Qual. Prefer.* 88, 104075. <https://doi.org/10.1016/j.foodqual.2020.104075>.
- Castellini, C., Boggia, A., Paolotti, L., Thoma, G.J., Kim, D.S., 2012. Environmental impacts and life cycle analysis of organic meat production and processing. *Organic. Meat Prod. Process.* 53 (1).

- Castro, D.M., Chambers IV, E., Carbonell-Barrachina, A., Noguera Artiaga, L., Vidal Quintanar, R., Burgos Hernandez, A., 2020. Consumer acceptability in the USA, Mexico, and Spain of chocolate chip cookies made with partial insect powder replacement. *J. Food Sci.* 85 (6), 1621–1628. <https://doi.org/10.1111/1750-3841.15175>.
- Cederberg, C., Stadig, M., 2003. System expansion and allocation in life cycle assessment of milk and beef production. *Int. J. Life Cycle Assess.* 8, 350–356. <https://doi.org/10.1007/BF02978508>.
- Cesari, V., Zucali, M., Sandrucci, A., Tamburini, A., Bava, L., Toschi, I., 2017. Environmental impact assessment of an Italian vertically integrated broiler system through a Life Cycle approach. *J. Clean. Prod.* 143, 904–911. <https://doi.org/10.1016/j.jclepro.2016.12.030>.
- Coletta, L.D., Pereira, A.L., Coelho, A.A.D., Savino, V.J.M., Menten, J.F.M., Correr, E., Franca, L.C., Martinelli, L.A., 2012. Barn vs. free-range chickens: differences in their diets determined by stable isotopes. *Food Chem.* 131 (1), 155–160. <https://doi.org/10.1016/j.foodchem.2011.08.051>.
- Cortes Ortiz, J.A., Ruiz, A.T., Morales-Ramon, J.A., Thomas, M., Rojas, M.G., Tomberlin, J.K., Yi, L., Han, R., Giroud, L., Jullien, R.L., 2016. Chapter 6 - insect mass production technologies. In: Dossey, A., Morales-Ramon, J.A., Guadalupe Rojas, M. (Eds.), *Insects as Sustainable Food Ingredients*. Elsevier, Amsterdam, pp. 153–201.
- Curran, M.A., Mann, M., Norris, G., 2005. The international workshop on electricity data for life cycle inventories. *J. Clean. Prod.* 13 (8), 853–862. <https://doi.org/10.1016/j.jclepro.2002.03.001>.
- Dei, H.K., 2011. Soybean as a feed ingredient for livestock and poultry. In: Krezhova, D. (Ed.), *Recent Trends for Enhancing the Diversity and Quality of Soybean Products*. IntechOpen (chapter 10).
- Domenech, T., Bahn-Walkowiak, B., 2019. Transition towards a resource efficient circular economy in Europe: policy lessons from the EU and the member states. *Ecol. Econ.* 155, 7–19. <https://doi.org/10.1016/j.ecolecon.2017.11.001>.
- Dyer, J.A., Worth, D.E., Vergé, X.P.C., Desjardins, R.L., 2020. Impact of recommended red meat consumption in Canada on the carbon footprint of Canadian livestock production. *J. Clean. Prod.* 266, 121785. <https://doi.org/10.1016/j.jclepro.2020.121785>.
- Ekvall, T., Finnveden, G., 2001. Allocation in ISO 14041 – a critical review. *J. Clean. Prod.* 9 (3), 197–208. [https://doi.org/10.1016/S0959-6526\(00\)00052-4](https://doi.org/10.1016/S0959-6526(00)00052-4).
- Ellingsen, H., & Aanonsen, S. A. 2006. Environmental impacts of wild caught cod and farmed Salmon—a comparison with chicken (7 pp). *Int. J. Life Cycle Assess.*, 11(1), 60–65.
- Fearnside, P.M., 2001. Soybean cultivation as a threat to the environment in Brazil. *Environ. Conserv.* 28 (1), 23–38. <https://doi.org/10.1017/S0376892901000030>.
- Fehlenberg, V., Baumann, M., Gasparri, N.I., Piquer-Rodríguez, M., Gaviera-Pizarro, G., Kuemmerle, T., 2017. The role of soybean production as an underlying driver of deforestation in the South American Chaco. *Global Environ. Change* 45, 24–34. <https://doi.org/10.1016/j.gloenvcha.2017.05.001>.
- Finke, M.D., Rojo, S., Roos, N., van Huis, A., Yen, A.L., 2015. The European Food Safety Authority scientific opinion on a risk profile related to production and consumption of insects as food and feed. *J. Insects as Food Feed* 1 (4), 245–247. <https://doi.org/10.3920/JIFF2015.x006>.
- Florou-Paneri, P., Christaki, E., Giannenas, I., Bonos, E., Skoufos, I., Tsinas, A., et al., 2014. Alternative protein sources to soybean meal in pig diets. *J. Food Agric. Environ.* 12, 655–660.
- Foster, C., Green, K., Bleda, M., Dewick, P., Evans, B., Flynn, A., Mylan, J., 2006. Environmental impacts of food production and consumption. A Final Report to the Department for Environment, Food and Rural Affairs. Manchester Business School, Defra, London.
- Fowles, T.M., Nansen, C., 2020. Insect-based bioconversion: value from food waste. In: Närvalen, E., Mesiranta, N., Mattila, M., Heikkinen, A. (Eds.), *Food Waste Management*. Palgrave Macmillan, Cham. https://doi.org/10.1007/978-3-030-20561-4_12.
- Frigerio, J., Agostinetto, G., Galimberti, A., De Mattia, F., Labra, M., Bruno, A., 2020. Tasting the differences: microbiota analysis of different insect-based novel food. *Food Res. Int.* 137, 109426. <https://doi.org/10.1016/j.foodres.2020.109426>.
- Gelder, van J.W., Kammeraat, K., Kroes, H., 2008. Soy Consumption for Feed and Fuel in the European Union: A Research Paper Prepared for Milieufdefensie (Friends of the Earth Netherlands). Netherlands. <http://www.foeeurope.org/agrofuels/FFE/Profund%20report%20final.pdf>. (Accessed 1 November 2020). accessed.
- Ghini, S., Silvestri, F., Steiner, B., 2020. The role of local stakeholders in disseminating knowledge for supporting the Circular Economy: a network analysis approach. *Ecol. Econ.* 169 <https://doi.org/10.1016/j.ecolecon.2019.106446>.
- González, N., Marqués, M., Nadal, M., Domingo, J.L., 2020. Meat consumption: which are the current global risks? A review of recent (2010–2020) evidences. *Food Res. Int.*, 109341 <https://doi.org/10.1016/j.foodres.2020.109341>.
- González-García, S., Gómez-Fernández, Z., Dias, A.C., Feijoo, G., Moreira, M.T., Arroja, L., 2014. Life Cycle Assessment of broiler chicken production: a Portuguese case study. *J. Clean. Prod.* 74, 125–134. <https://doi.org/10.1016/j.jclepro.2014.03.067>.
- Greibitus, C., Steiner, B., Veeman, M.M., 2016. Paying for sustainability: a cross-cultural analysis of consumers' valuations of food and non-food products labeled for carbon and water footprints. *J. Behav. Exp.* 63, 50–58. <https://doi.org/10.1016/j.socce.2016.05.003>.
- Grunert, K.G., Sonntag, W.I., Glanz-Chanos, V., Forum, S., 2018. Consumer interest in environmental impact, safety, health and animal welfare aspects of modern pig production: results of a cross-national choice experiment. *Meat Sci.* 137, 123–129. <https://doi.org/10.1016/j.meatsci.2017.11.022>.
- Guo, H., Jiang, C., Zhang, Z., Lu, W., Wang, H., 2020. Material flow analysis and life cycle assessment of food waste bioconversion by black soldier fly larvae (*Hermetia illucens* L.). *Sci. Total Environ.* 750, 141656. <https://doi.org/10.1016/j.scitotenv.2020.141656>.
- Halloran, A., Hanboongsong, Y., Roos, Y., Bruun, S., 2017. Life cycle assessment of cricket farming in north-eastern Thailand. *J. Clean. Prod.* 156, 83–94. <https://doi.org/10.1016/j.jclepro.2017.04.017>.
- Hawkey, K.J., Lopez-Viso, C., Brameld, J.M., Parr, T., Salter, A.M., 2021. Insects: a potential source of protein and other nutrients for feed and food. *Annual Review of Animal Biosciences* 9. <https://doi.org/10.1146/annurev-animal-021419-083930>.
- He, J., Evans, N.M., Liu, H., Shao, S., 2020. A review of research on plant-based meat alternatives: driving forces, history, manufacturing, and consumer attitudes. *Compr. Rev. Food Sci. Food Saf.* 19 (5), 2639–2656. <https://doi.org/10.1111/1541-4337.12610>.
- Hellweg, S., i Canals, L.M., 2014. Emerging approaches, challenges and opportunities in life cycle assessment. *Science* 344 (6188), 1109–1113. <https://doi.org/10.1126/science.1248361>.
- Hörtenhuber, S., Piring, G., Zollitsch, W., Lindethal, T., Winiwarter, W., 2014. Land use and land use change in agricultural life cycle assessments and carbon footprints - the case for regionally specific land use change versus other methods. *J. Clean. Prod.* 73, 31–39. <https://doi.org/10.1016/j.jclepro.2013.12.027>.
- van Huis, A., 2013. Potential of insects as food and feed in assuring food security. *Annu. Rev. Entomol.* 58, 563–583. <https://doi.org/10.1146/annurev-ento-120811-153704>.
- van Huis, A., 2016. Edible insects are the future? *Proceedings of the Nutrition Society* 75 (3), 294–305. <https://doi.org/10.1017/S0029665116000069>.
- van Huis, A., 2020. Prospects of insects as food and feed. *Org. Agr.* <https://doi.org/10.1007/s13165-020-00290-7>.
- van Huis, A., van Isterbeek, J., Klunder, H., Mertens, E., Halloran, A., Muir, G., Vantomme, P., 2013. *Edible Insects: Future Prospects for Food and Feed Security*. FAO, Rome.
- Hunts, H.J., Dunkel, F.V., Thienes, M.J., Carnegie, N.B., 2020. Gatekeepers in the food industry: acceptability of edible insects. *J. Insects. Food. Feed* 6 (3), 231–243.
- Ikiamba, L.M., Nene, W., Mugambi, M., 2021. Growth performance of broilers fed on processed *Acacia tortilis* seed meal as a replacement of soya bean meal. *International Journal of Professional Practice* 9 (1), 100–115. <https://doi.org/10.1234/ijpp.v9i1.77>.
- ISO 14040. International Organization for Standardization. EN ISO 14040:2006. Environmental management. Life cycle assessment. Principles and framework. <https://www.iso.org/standard/38498.html>, <https://www.iso.org/standard/37456.html>.
- Ites, S., Smetana, S., Toepfl, S., Heinz, V., 2020. Modularity of insect production and processing as a path to efficient and sustainable food waste treatment. *J. Clean. Prod.* 248, 119248. <https://doi.org/10.1016/j.jclepro.2019.119248>.
- Jia, F., Peng, S., Green, J., Koh, L., Chen, X., 2020. Soybean supply chain management and sustainability: a systematic literature review. *J. Clean. Prod.* 255, 120254. <https://doi.org/10.1016/j.jclepro.2020.120254>.
- Joensuu, K., Silvenius, F., 2017. Production of mealworms for human consumption in Finland: a preliminary life cycle assessment. *J. Insects as Food Feed* 3 (3), 211–216. <https://doi.org/10.3920/JIFF2016.0029>.
- Johnson, C., Sierra, A.R., Dettmer, J., Sidiropoulou, K., Zicmane, E., Puzzolo, V., et al., 2021. The bio-based industries joint undertaking as a catalyst for a green transition in Europe under the European green deal. *EFB Bioeconomy Journal*, 100014. <https://doi.org/10.1016/j.bioeco.2021.100014>.
- Józefiak, D., Józefiak, A., Kierńczyk, B., Rawski, M., Świątkiewicz, S., Długosz, J., Engberg, R.M., 2016. Insects – a natural nutrient source for poultry – a review. *Ann. Anim. Sci.* 16 (2), 297–313. <https://doi.org/10.1515/aas-2016-0010>.
- Karlsson, J.O., Parodi, A., Van Zanten, H.H., Hansson, P.A., Röös, E., 2021. Halting European Union soybean feed imports favours ruminants over pigs and poultry. *Nature Food* 2 (1), 38–46. <https://doi.org/10.1038/s43016-020-00203-7>.
- Katajajuri, J.-H., Grönroos, J., Usva, K., 2014. Energy use and greenhouse gas emissions and related improvement options of the broiler chicken meat supply chain. *Int. J. Sustain. Dev.* 17 (1), 49–61. <https://doi.org/10.1504/IJSD.2014.058433>.
- Kearney, J., 2010. Food consumption trends and drivers. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* 365 (1554), 2793–2807. <https://doi.org/10.1098/rstb.2010.0149>.
- Khusro, M., Andrew, N.R., Nicholas, A., 2012. Insects as poultry feed: a scoping study for poultry production systems in Australia. *World's Poult. Sci. J.* 68 (3), 435–446. <https://doi.org/10.1017/S0043933912000554>.
- Kouřimská, L., Adámková, A., 2016. Nutritional and sensory quality of edible insects. *NFS Journal* 4, 22–26. <https://doi.org/10.1016/j.nfs.2016.07.001>.
- Kyriakopoulou, K., Keppler, J.K., van der Goot, A.J., Boom, R.M., 2021. Alternatives to meat and dairy. *Annual Review of Food Science and Technology* 12. <https://doi.org/10.1146/annurev-food-062520-101850>.
- Lähteenmäki-Uutela, A., Grmelová, N., 2016. European Law on Insects in Food and Feed. *European Food and Feed Law Review* 11 (1), 2–8. <http://www.jstor.org/stable/43958606>.
- Leinonen, I., Kyriazakis, I., 2016. How can we improve the environmental sustainability of poultry production? *Proc. Nutr. Soc.* 75 (3), 265–273. <https://doi.org/10.1017/S0029665116000094>.
- Leinonen, I., Williams, A.G., Wiseman, J., Guy, J., Kyriazakis, I., 2012. Predicting the environmental impacts of chicken systems in the United Kingdom through a life cycle assessment: broiler production systems. *Poultry Sci.* 91 (1), 8–25. <https://doi.org/10.3382/ps.2011-01634>.
- Lima, A., Nääs, I.A., 2005. Evaluating two systems of chicken production: conventional and free-range. *Rev. Bras. Ciência Avícola* 7 (4). <https://doi.org/10.1590/S1516-635X2005000400004>.

- Llagostera, P.F., Kallas, Z., Reig, L., de Gea, D.A., 2019. The use of insect meal as a sustainable feeding alternative in aquaculture: current situation, Spanish consumers' perceptions and willingness to pay. *J. Clean. Prod.* 229, 10–21. <https://doi.org/10.1016/j.jclepro.2019.05.012>.
- Lorenz, H., Fischer, P., Schumacher, B., Adler, P., 2013. Current EU-27 technical potential of organic waste streams for biogas and energy production. *Waste Manag.* 33 (11), 2434–2448. <https://doi.org/10.1016/j.wasman.2013.06.018>.
- Lu, R., Chen, Y., Yu, W., Lin, M., Yang, G., Qin, C., Nie, G., 2020. Defatted black soldier fly (*Hermetia illucens*) larvae meal can replace soybean meal in juvenile grass carp (*Ctenopharyngodon idellus*) diets. *Aquaculture Reports* 18, 100520. <https://doi.org/10.1016/j.aqrep.2020.100520>.
- Makkar, H.P.S., Tran, G., Heuzé, V., Ankers, P., 2014. State-of-the-art on use of insects as animal feed. *Anim. Feed Sci. Technol.* 197, 1–33. <https://doi.org/10.1016/j.anifeedsci.2014.07.008>.
- Myhre, G., Shindell, D., Bréon, F.M., Collins, W., Fuglestad, J., Huang, J., Koch, D., Lamarque, J.F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., Zhang, H., 2013. Anthropogenic and natural radiative forcing. In: Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), *Climate Change 2013: the Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Nijdam, D., Rood, T., Westhoek, H., 2012. The price of protein: review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes. *Food Pol.* 37 (6), 760–770. <https://doi.org/10.1016/j.foodpol.2012.08.002>.
- Ojha, S., Bußler, S., Schlüter, O.K., 2020. Food waste valorisation and circular economy concepts in insect production and processing. *Waste Manage* 118, 600–609.
- Ooninx, D.G.A.B., de Boer, L.J.M., 2012. Environmental impact of the production of mealworms as a protein source for humans – a life cycle assessment. *PLoS One* 7 (12), e51145. <https://doi.org/10.1371/journal.pone.0051145>.
- Painter, J., Brennen, J.S., Kristiansen, S., 2020. The coverage of cultured meat in the US and UK traditional media, 2013–2019: drivers, sources, and competing narratives. *Climatic Change* 162 (4), 2379–2396. <https://doi.org/10.1007/s10584-020-02813-3>.
- Payne, C.L., Dobermann, D., Forkes, A., House, J., Josephs, J., McBride, A., Soares, S., 2016. Insects as food and feed: European perspectives on recent research and future priorities. *J. Insects. Food. Feed* 2 (4), 269–276.
- Pelletier, N., 2008. Environmental performance in the US broiler poultry sector: Life cycle energy use and greenhouse gas, ozone depleting, acidifying and eutrophying emissions. *Agri. Sys.* 98 (2), 67–73.
- Pippinato, L., Gasco, L., Di Vita, Mancuso, T., 2020. Current scenario in the European edible-insect industry: a preliminary study. *J. Insect. Food. Feed* 6 (4), 371–381.
- Ponstein, H., Ghinai, S., Steiner, B., 2019. How to increase sustainability in the Finnish wine supply chain? Insights from a country of origin-based greenhouse gas emissions analysis. *J. Clean. Prod.* 226, 768–780.
- Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. *Science* 360 (6392), 987–992. <https://doi.org/10.1126/science.aqa0216>.
- Poveda, J., 2021. Insect frass in the development of sustainable agriculture. A review. *Agron. Sustain. Dev.* 41 (1), 1–10. <https://doi.org/10.1007/s13593-020-00656-x>.
- Raven, P.H., Wagner, D.L., 2021. Agricultural intensification and climate change are rapidly decreasing insect biodiversity. *Proc. Natl. Acad. Sci. Unit. States Am.* 118 (2), e2002548117. <https://doi.org/10.1073/pnas.2002548117>.
- Riddick, E.W., 2014. Insect protein as a partial replacement for fishmeal in the diets of juvenile fish and crustaceans. In: Morales-Ramos, J., Shapiro-Ilan, D., Rojas, G.M. (Eds.), *Mass Production of Beneficial Organisms*. Academic Press, pp. 565–582.
- Roffeis, M., Wakefield, M.E., Almeida, J., Valada, T.R.A., Devic, E., Kenis, M., et al., 2018. Life cycle cost assessment of insect based feed production in West Africa. *J. Clean. Prod.* 199, 792–806. <https://doi.org/10.1016/j.jclepro.2018.07.179>.
- Röös, E., Ekelund, L., Tjärnemo, H., 2014. Communicating the environmental impact of meat production: challenges in the development of a Swedish meat guide. *J. Clean. Prod.* 73, 154–164. <https://doi.org/10.1016/j.jclepro.2013.10.037>.
- Roy, P., Nei, D., Orisaka, T., Xu, Q., Okadome, H., Nakamura, N., Shiina, T., 2009. A review of life cycle assessment (LCA) on some food products. *J. Food Eng.* 90 (1), 1–10. <https://doi.org/10.1016/j.jfoodeng.2008.06.016>.
- Salomone, R., Saija, G., Mondello, G., Giannetto, A., Fasulo, S., Savastano, D., 2017. Environmental impact of food waste bioconversion by insects: application of Life Cycle Assessment to process using *Hermetia illucens*. *J. Clean. Prod.* 140, 890–905. <https://doi.org/10.1016/j.jclepro.2016.06.154>.
- Sánchez-Muros, M.J., Barroso, F.G., Manzano-Agugliaro, F., 2014. Insect meal as renewable source of food for animal feeding: a review. *J. Clean. Prod.* 65, 16–27. <https://doi.org/10.1016/j.jclepro.2013.11.068>.
- Santo, R.E., Kim, B.F., Goldman, S.E., Dutkiewicz, J., Biehle, E., Bloem, M.W., et al., 2020. Considering plant-based meat substitutes and cell-based meats: a public health and food systems perspective. *Front. Sustain. Food Syst.* 4, 134. <https://doi.org/10.3389/fsufs.2020.00134>.
- Scarlat, N., Fahl, F., Dallemand, J.-F., Monforti, F., Motola, V., 2018. A spatial analysis of biogas potential from manure in Europe. *Renew. Sustain. Energy Rev.* 94, 915–930. <https://doi.org/10.1016/j.rser.2018.06.035>.
- Sillman, J., Uusitalo, V., Tapanen, T., Salonen, A., Soukka, R., Kahiluoto, H., 2020. Contribution of honeybees towards the net environmental benefits of food. *Sci. Total Environ.* 756, 143880. <https://doi.org/10.1016/j.scitotenv.2020.143880>.
- da Silva, R., Bach-Faig, A., Raidó Quintana, B., Buckland, G., Vaz de Almeida, M.D., Serra-Majem, L., 2009. Worldwide variation of adherence to the Mediterranean diet, in 1961–1965 and 2000–2003. *Publ. Health Nutr.* 12 (9A), 1676–1684. <https://doi.org/10.1017/S1368980009990541>.
- da Silva, J.V.P., Cherubini, E., Soares, S.R., 2012. Comparison of two production scenarios of chickens consumed in France. In: 8th International Conference on LCA in the Agri-Food Sector. Saint-Malo, France, pp. 546–551. <https://doi.org/10.13140/2.1.2044.5769>.
- da Silva, V.P., van der Werf, H.M.G., Soares, S.R., Corson, M.S., 2014. Environmental impacts of French and Brazilian broiler chicken production scenarios: an LCA approach. *J. Environ. Manag.* 133, 222–231. <https://doi.org/10.1016/j.jenvman.2013.12.011>.
- Smetana, S., Palanisamy, M., Mathys, A., Heinz, V., 2016. Sustainability of insect use for feed and food: life Cycle Assessment perspective. *J. Clean. Prod.* 137, 741–751. <https://doi.org/10.1016/j.jclepro.2016.07.148>.
- Smetana, S., Schmitt, E., Mathys, A., 2019. Sustainable use of *Hermetia illucens* insect biomass for feed and food: attributional and consequential life cycle assessment. *Resour. Conserv. Recycl.* 144, 285–296. <https://doi.org/10.1016/j.resconrec.2019.01.042>.
- Spiegel, M., Noordam, M.Y., Fels-Klerx, H.J., 2013. Safety of novel protein sources (insects, microalgae, seaweed, duckweed, and rapeseed) and legislative aspects for their application in food and feed production. *Compr. Rev. Food Sci. Food Saf.* 12 (6), 662–678. <https://doi.org/10.1111/1541-4337.12032>.
- Steiner, B.E., Peschel, A.O., Grebitus, C., 2017. Multi-product category choices labeled for ecological footprints: exploring psychographics and evolved psychological biases for characterizing latent consumer classes. *Ecol. Econ.* 140, 251–264. <https://doi.org/10.1016/j.ecolecon.2017.05.009>.
- Suckling, J., Druckman, A., Moore, C.D., Driscoll, D., 2020. The environmental impact of rearing crickets for live pet food in the UK, and implications of a transition to a hybrid business model combining production for live pet food with production for human consumption. *Int. J. LCA.* 25, 1693–1709. <https://doi.org/10.1007/s11367-020-01778-w>.
- Swane, E., Vold, M., Hanssen, O.J., 2011. Effect of different allocation methods on LCA results of products from wild-caught fish and on the use of such results. *Int. J. Life Cycle Assess.* 16, 512–521. <https://doi.org/10.1007/s11367-011-0288-4>.
- Tallentire, C.W., Mackenzie, S.G., Kyriazakis, I., 2018. Can novel ingredients replace soybeans and reduce the environmental burdens of European livestock systems in the future? *J. Clean. Prod.* 187, 338–347. <https://doi.org/10.1016/j.jclepro.2018.03.212>.
- Tedesco, D.E.A., Conti, C., Lovarelli, D., Biazzi, E., Bacenetti, J., 2019. Bioconversion of fruit and vegetable waste into earthworms as a new protein source: the environmental impact of earthworm meal production. *Sci. Total Environ.* 683, 690–698. <https://doi.org/10.1016/j.scitotenv.2019.05.226>.
- Thévenot, A., Aubin, J., Tillard, E., Vayssières, J., 2013. Accounting for farm diversity in life cycle assessment studies – the case of poultry production in a tropical island. *J. Clean. Prod.* 57, 280–292. <https://doi.org/10.1016/j.jclepro.2013.05.027>.
- Thévenot, A., Rivera, J.L., Wilfert, A., Maillard, F., Hassouna, M., Senga-Kiesse, T., Féon, S.L., Aubin, J., 2018. Mealworm meal for animal feed: environmental assessment and sensitivity analysis to guide future prospects. *J. Clean. Prod.* 170, 1260–1267. <https://doi.org/10.1016/j.jclepro.2017.09.054>.
- Thomas, C., Grémy-Gros, C., Perrin, A., Symoneux, R., Maitre, I., 2020. Implementing LCA early in food innovation processes: study on spirulina-based food products. *J. Clean. Prod.* 268, 121793. <https://doi.org/10.1016/j.jclepro.2020.121793>.
- Tillman, A.M., Ekvall, T., Baumann, H., Rydberg, T., 1994. Choice of system boundaries in life cycle assessment. *J. Clean. Prod.* 2 (1), 21–29.
- Toviho, O., Bárony, P., 2020. Insect base-protein: a new opportunity in animal nutrition. *Acta Agraria Debreceniensis* 1, 129–138. <https://doi.org/10.34101/actaagrar/1/3744>.
- Tuomisto, H.L., 2019. The eco-friendly burger: could cultured meat improve the environmental sustainability of meat products? *EMBO Rep.* 20 (1), e47395. <https://doi.org/10.15252/embr.201847395>, 10.15252/embr.202152698.
- Voora, V., Larrea, C., Bermudez, S., 2020. Global Market Report: Soybeans. International Institute for Sustainable Development. <https://www.iisd.org/stable/pdf/resrep/26554.pdf>.
- Westhoek, H.J., Rood, G.A., van der Berg, M., Janse, J.H., Nijdam, D.S., Reudink, M.A., Stehfest, E.E., 2011. The protein puzzle: the consumption and production of meat, dairy and fish in the European union. *European j. nutr. food saf.* 1 (3), 123–144. Retrieved from. <http://www.journalejnfs.com/index.php/EJNFS/article/view/30006>.
- Weindl, I., Ost, M., Wiedmer, P., Schreiner, M., Neugart, S., Klopsch, R., Klaus, S., 2020. Sustainable food protein supply reconciling human and ecosystem health: A Leibniz Position. *Global. Food. Secure.* 25, 100367.
- Westhoek, H., Lesschen, J.P., Rood, T., Wagner, S., De Marco, A., Murphy-Bokern, D., Leip, A., van Grinsven, H., Sutton, M.A., Oenema, O., 2014. Food choices, health and environment: effects of cutting Europe's meat and dairy intake. *Global Environ. Change* 26, 196–205. <https://doi.org/10.1016/j.gloenvcha.2014.02.004>.
- Wiedemann, S.G., Biggs, L., Nebel, B., Bauch, K., Laitala, K., Klepp, I.G., Watson, K., 2020. Environmental impacts associated with the production, use, and end-of-life of a woollen garment. *Int. J. Life Cycle Assess.* 25, 1486–1499.
- Williams, R.A., 2021. Opportunities and challenges for the introduction of new food proteins. *Annual Review of Food Science and Technology* 12. <https://doi.org/10.1146/annurev-food-061220-012838>.

- Yang, Y., 2016. Two sides of the same coin: consequential life cycle assessment based on the attributional framework. *J. Clean. Prod.* 127, 274–281. <https://doi.org/10.1016/j.jclepro.2016.03.089>.
- Yang, X., Chen, Q., Xu, Z., Zheng, Q., Zhao, R., Yang, H., et al., 2021. Consumers' preferences for health-related and low-carbon attributes of rice: a choice experiment. *J. Clean. Prod.* 126443.
- van Zanten, H.H.E., Mollenhorst, H., Oonincx, D.G.A.B., Bikker, P., Meerburg, B.G., de Boer, I.J.M., 2015. From environmental nuisance to environmental opportunity: housefly larvae convert waste to livestock feed. *J. Clean. Prod.* 102, 362–369. <https://doi.org/10.1016/j.jclepro.2015.04.106>.