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Contribution of honeybees towards the net environmental benefits of food

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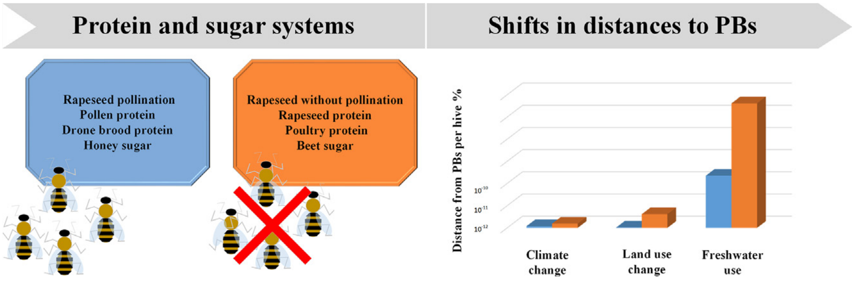
HIGHLIGHTS

- Shifts in distances to planetary boundaries were quantified using LCA.
- Beekeeping reduced environmental impacts of protein and sugar systems.
- Water use was reduced more than land use and climate change.
- Sugar use and transportation induced most beekeeping impacts.
- Including pollination revealed the net-positive impact of beekeeping.

GRAPHICAL ABSTRACT



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ABSTRACT

Beekeeping provides honey, protein-containing drone broods and pollen, and yield-increasing pollination services. This study tested the hypothesis that beekeeping can result in net-positive impacts, if pollination services and protein-containing by-products are utilised. As a case example, Finnish beekeeping practices were used. The study was performed using two different approaches. In both approaches, the evaluated impacts were related to climate change, land use, and freshwater use, and were scaled down to represent one beehive. The first approach considered honey production with pollination services and the replacement of alternative products with co-products. The impacts were normalised to correspond with planetary boundary criteria. The second approach evaluated the impacts of the different products and services of beekeeping separately. In the first approach the honey production system moved towards a safe operational space. Freshwater use was the impact category with the largest shift towards a safe operational space (39% shift). The second approach caused a global warming potential of honey production of 0.65 $\text{kg}_{\text{CO2-eq}}$ kg^{-1}, when pollen and drone broods were considered as by-products and the influence of pollination services were not included. When honey, pollen, and drone broods were considered as co-products and pollination services were included, the impacts regarding land use and climate change were net-positive. The impact of freshwater use was relatively small. For honey, the impacts on the climate change, land use, and freshwater use were -0.33 $\text{kg}_{\text{CO2-eq}}$ kg^{-1}, -7.89 m^2 kg^{-1}, and 14.01 kg kg^{-1}, respectively. The impact allocation with co-products and pollination services was conclusive. A lack of consideration for the impact reduction of pollination led to beekeeping having a negative impact on the environment. Based on these results, beekeeping enhances food security within planetary boundaries, provided that pollination services and protein-containing by-/co-products are utilised.

1. Introduction

The phenomenon of declining pollinator populations worldwide has gained awareness (e.g., Potts et al., 2010; Lebuhn et al., 2013) due to the key role of pollinators in food production. Klein et al. (2007) estimated

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that around 35% of global crop production is dependent upon animal pollinators, which also maintain the biodiversity of wild plants (Aquilar et al., 2006). The decline in pollinators is due to land use (LU) change (Hendrickx et al., 2007; Rader et al., 2014), pesticides (Brittain et al., 2014), pollution (Rortais et al., 2005), and decreased resource diversity (Biesmeijer et al., 2006). The decline is critical due to the need to provide food for a growing population with shrinking resources (FAO, 2017; Campbell et al., 2017). In addition to the pollination-induced yield increase, pollinators can provide honey and protein sources, such as drone broods (DBs) (Finke, 2005; Lindström et al., 2016). Alternative protein sources have gained increasing interest in recent years for numerous reasons, including possible sustainability advantages (e.g., Lindberg, 2016; van Huis, 2013).

Pollination increases crop yields without additional LU and resource inputs, and honeybee hives can be effectively located for this purpose (Lindström et al., 2016). The honeybee (*Apis mellifera*) is a unique pollinator as it provides multiple by-products in addition to pollination services. Honey can be used as a sweetener to replace sugars from sugarcane or sugar beet production, which require agricultural land. DBs and pollen provide protein that can replace animal or plant-based protein sources (Finke, 2005; Jensen et al., 2016; Lecocq et al., 2018; Komisinska-Vassev et al., 2015). DBs have previously been regarded as waste or not considered as a product, thus they were not collected from hives. Recently, there has been an increase in awareness concerning the potential use of DBs and pollen as a protein source and healthy food product. However, honey and DB production have environmental impacts through beekeeping, product processing, packaging, and transporting.

Life cycle assessments (LCAs) of beehives usually focus solely on honey production (e.g., Kendall et al., 2013; Mujica et al., 2016), despite the importance of pollination as an ecosystem service being well-known (Tamburini et al., 2019). There are several studies concerning the inclusion of pollination services in LCAs, but the focus is mainly on economic aspects or biodiversity impacts (e.g., Arzoumanidis et al., 2019; Crenna et al., 2017; Ulmer et al., 2020). Ulmer et al. (2020) analysed the global warming potential (GWP) of DB production with honey production. However, pollen was not considered as a by-product or co-product, and pollination services were considered using an economic allocation that transfers some of the impacts of beekeeping to pollination services. Nonetheless, the utilisation of pollination services and by-products might cause net-positive environmental impacts through increasing crop yields and replacing land-based protein production. A net-positive environmental impact refers to a situation where the impact of an activity is not negative towards the environment (e.g., Renger et al., 2014; Grönman et al., 2019; Bjørn and Hauschild, 2012). To our knowledge, the environmental impacts of honey production, such as GWP, LU, and freshwater use (FWU), with the inclusion of pollination services and by-products, such as DB and pollen protein, have not yet been evaluated.

One method for approaching the evaluation of the environmental impacts of beekeeping is the planetary boundary (PB) concept (Rockström et al., 2009; Steffen et al., 2015; Kahiluoto, 2019), to which LCAs can be integrated (e.g., Uusitalo et al., 2019; Salas et al., 2016). The combined results can help address several limitations of LCA studies. For instance, the results of LCA focus on minimizing or measuring the environmental impacts of certain products and services, but LCA does not set a criterion for sustainable practices (Bjørn et al., 2015).The results of combined LCAs and PBs indicate the extent to which a certain system leaves or remains within a safe operation space. Current challenges associated with the combined approach include climate change, biogeochemical flows, biosphere integrity, FWU, and land system change, all of which impact future food security (Campbell et al., 2017; Hanjra and Qureshi, 2010; Steffen et al., 2015). There is an urgent need for solutions that help food systems to remain within or return to a safe operational space.

The aim of this study was to assess the environmental impacts of beekeeping while including pollination services and protein-containing by-products to decipher whether beekeeping can result in net-positive impacts. The assessment consisted of a system-level comparison and product-based environmental impacts with various allocation options. The investigated environmental impacts were related to the PBs of climate change, land system change, and FWU. We hypothesised that honey production would help to achieve food security within a safe operational space.

2. Materials and methods

An LCA, which was mainly based on the instructions of ISO 14040 and 14044, was used to analyse the environmental impacts of a honey production system. All modelling was carried out using GaBi 8.7 software.

2.1. Goal and scope

The function of the LCA is to estimate the environmental impacts of food products, such as rapeseed and beekeeping beekeeping-related products. Honey production has numerous side-products, such as DB, pollen, and wax, as well as providing pollination services for plants. The aim of this study was to assess the environmental impacts of honey production systems by providing information on the LU, FWU, and GWP of different products. These impacts were compared to alternative processes that serve the same function. The honey production system was located in Finland. To answer the research questions, two different analyses were carried out:

1. A system expansion assessment for a comparison of the LU, GWP, and FWU of a reference system without honey production and a new system with honey production. The system expansion was carried out specifically to study the impacts of pollination and was based on the instructions of ISO/TR 14049. The functional unit was a one-year operation related to a hive.
2. The environmental impacts of LU, GWP, and FWU were calculated for the main products of a honey production system: honey, DB protein, and pollen protein. The environmental burden was then allocated between these products. The impact analyses were based on the instructions of ISO 14067. The functional unit was the production of 1 kg of the main products.

Honey production systems consist of various life cycle stages, as presented in Fig. 1. In addition, Fig. 1 shows the system boundaries and logic for the system expansion. The main assumption for the system expansion was that the same amounts of products and services (honey, DB protein, pollen protein, and crops through pollination) were produced in the honey production and reference systems. The alternative production pathways of the reference system consisted of expanded crop production without pollination for rapeseed and alternative sugar production using sugar beet. The comparable protein source for DBs was poultry, which is relatively sustainable and a widely used animal-based protein (de Vries and de Boer, 2010), while that for pollen was rapeseed protein. In addition, rapeseed protein and sugar from sugar beets are already considered among the examined system of beekeeping. Beeswax is also a by-product of honey production. However, beeswax is used for the production of new hives and therefore is assumed to be utilised inside the system boundaries. The impact categories selected for the system expansion were GWP (CML methodology), FWU, and land occupation. The results from the system expansion comparison are presented as absolute values and normalised using the PBs framework according to the method introduced by Uusitalo et al. (2019).

The main aim for the second approach was to calculate the GWP, LU, and FWU of the main products using allocation methodology. The main product of apiaries is honey. In addition, pollen and DBs are possible co-products due to their potential economic value (e.g., Jensen et al., 2016; Lecocq et al., 2018; Komisinska-Vassev et al., 2015). However, DBs and pollen were previously not usually utilised nor collected from beehives.

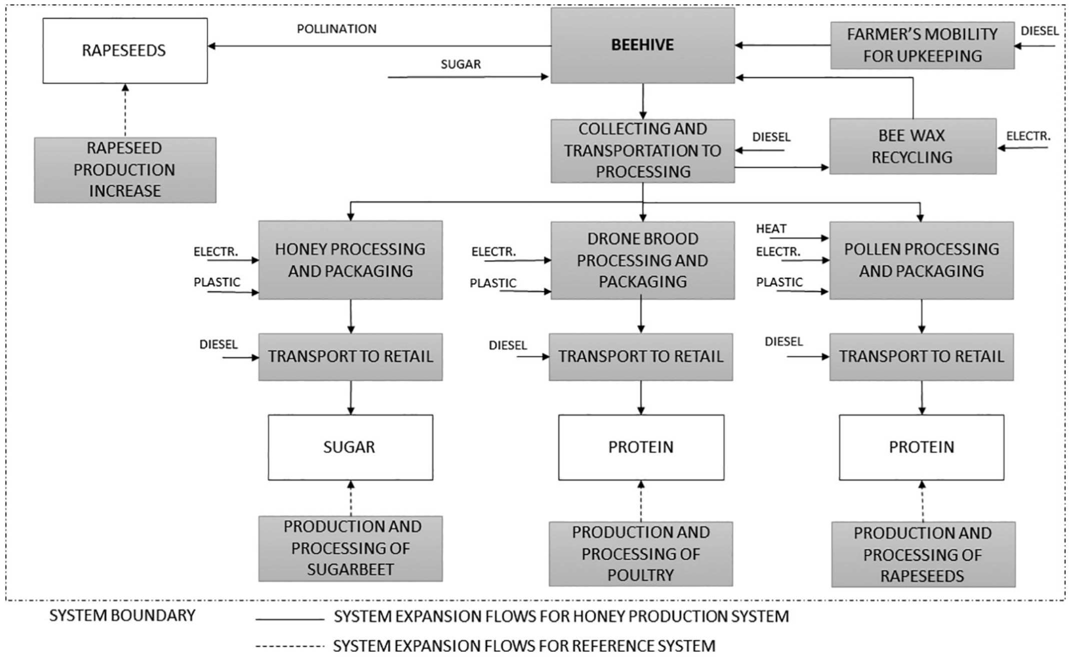

Fig. 1. System boundaries and logic for the system expansion method.

Therefore, there were two options for calculating the environmental impacts of DBs and pollen. The first was to consider them as co-products with economic value and perform an allocation procedure between honey, DBs, and pollen. The other option was to consider them as waste products without economic value and only include processes that are needed for further processing in the environmental impact assessment. In this case, the impacts from beekeeping were only allocated to honey. In general, apiaries do not get paid for pollination services in Finland, and therefore pollination services were not considered a product. However, the substituted impacts of pollination services can be allocated to the different products, which was carried out using economic allocation due to the different natures of the products. The allocation was based on the price of the product for the retailer. According to experts of Finnish honey production, the prices per kg for honey, pollen, and DBs were 13€, 65€, and 50€, respectively. To evaluate the sustainability of the selected products, the impacts were compared to those of similar products. Sensitivity analysis was performed by using one-at-a-time method.

2.2. Life cycle inventory analysis (LCIA)

The modelling of the honey, DB, and pollen production systems were based on primary data collected from Finnish producers and key informants. The initial primary data were collected via interviews with experts of the Finnish honey industry, which was supplemented with beekeeper interviews. Secondary data, e.g., related to emission factors and the reference system, were gathered from GaBi and Ecoinvent databases and literature. Finland has a relatively old fleet of vehicles (LIPASTO, 2020); thus EURO4 type vehicles were used, when transport processes were modelled. When there was uncertainty with data quality, conservative estimates were preferred. Data quality assessment based on the Greenhouse Gas Emissions Protocol (2011) can be found in the attachment.

2.2.1. Beekeeping

According to the experts and productivity survey (Finnish beekeeper's association, 2020) of beekeeping, a hive annually produces an average of 39 kg of honey, 1 kg of DB, and 5 kg of pollen. In addition, for efficient beekeeping, beehives consume approximately 20 kg of granulated sugar to feed the honeybees (Luke$_a$, 2020). Sugar was assumed to be produced from sugar beets, which was modelled using the global average sugar beet sugar production based on the Ecoinvent database. On average, a beehive annually produces 1 kg of beeswax. It was assumed that the beeswax was collected and transported to a centralised separation facility, where it was melted. The melting of the beeswax occurred in an electric oven, for which the energy consumption was estimated at 0.792 kWh kg^{-1} of beeswax.

According to Finnish statistics, the average mobility required for beekeeping throughout the season is approximately 40 km per hive (Luke$_a$, 2020). However, there can be large variation regarding the mobility. If the hives are located close to the beekeeper's home, the mobility may be marginal. However, due to long distances to the hives, small-scale apiary mobility was 375 km per hive. The beekeeper's mobility was modelled using a EURO 4 class diesel van with a 2-l engine.

Honey, DBs, beeswax, and pollen were then transported an average of 30 km for centralised separation, production, and packaging. This distance was estimated using actual apiary locations by using a database of the locations of hives (Apismap, 2020) in a region of Päijät-Häme in Finland. In this study, the centralised solution for the environmental impact evaluation was used because the distributed solution is not seen as economically feasible when large-scale production is favoured, according to the experts. Transportation was modelled based on a EURO 4 class truck with a 2.7-t payload.

2.2.2. Honey processing and packaging

Electricity consumption in honey separation is approximately 0.23 kWh $\text{kg}_{\text{honey}}^{-1}$ based on energy consumption in an example apiary. Electricity production is modelled using an average grid mix for Finland. Honey is packaged into 0.45 kg plastic containers, which is typical in Finland. Empty plastic containers weight is 0.01 kg. Manufacturing of plastic containers are modelled using GaBi database process for injection molding polypropylene part. Transportation distance for packed honey to retail is approximately 10 km based on the situation in Päijät-Häme region and it is assumed to be operated by EURO 4 class truck with 2.7 t payload.

2.2.3. Drone brood processing and packaging

DBs were frozen and separated via screening, for which the electricity consumption was estimated at 0.08 kWh kg^{-1}, based on the energy consumption of the separation device. DBs were packaged into plastic bags. Plastic bag production was modelled using the GaBi database process for plastic film production. After separation and packaging, the DBs were returned to a freezer for health and safety reasons. The electricity consumption of the cold chain was assumed to be 1.4 kWh kg^{-1}, based on the energy consumption of a freezer. Electricity production was modelled using an average grid mix for Finland. As with honey, the transportation distance to retail was 10 km, which was modelled based on a EURO 4 class truck with a 2.7-t payload. The nutritional contents of DBs are well suited for human consumption. DBs have a relatively high protein content, as well as good quality fatty acids and carbohydrates. The protein content of 100 g of fresh DBs is approximately 9.4 g (Finke, 2005). The Finnish beekeeper's association has applied for DBs to be accepted as a safe food for human consumption according to the novel food Regulation (EU) 2015/2283.

2.2.4. Pollen processing and packaging

Pollen was collected separately. For transporting, the same vehicle as that used for maintenance driving was used. According to an example beekeeper, the mobility required for 1 kg of pollen was approximately 5 km. There are several ways of drying pollen, e.g., electric-oven and air-drying. In this study, to represent a conservative estimation, it was assumed that light fuel oil was used for drying. Based on the average drying process in GaBi and applied moisture contents, drying consumes approximately 0.5 MJ of thermal energy for 1 kg of pollen. The pollen was cooled and frozen, which consumes 1.4 kWh kg^{-1} of electricity from the Finnish grid. Then, the pollen was packed into 0.25 kg plastic packages. The plastic package production was modelled similarly to that for honey. The transportation distance to retail was 10 km, which was modelled based on a EURO 4 class truck with a 2.7-t payload. Bee-collected pollen is high in nutrients and contains an average of 22.7% protein, among other nutrients (Komisinska-Vassev et al., 2015).

2.2.5. Pollination services and crop production system

Honeybees impact crop yields through pollination. The impacts of pollination on rapeseed yields have been chosen as a case example. The effects of pollination were calculated based on the results of Lindström et al. (2016), in which it was shown that rapeseed yields in the presence of approximately two hives per hectare increased by 11% compared to the control fields with no added hives. A similar crop increase (11–15%) was presented by Korpela (1988). In this study, it was assumed that there was the same number of beehives per hectare, and rapeseed production increased by 11%. The protein content of rapeseed varies between 17 and 26% (Day, 2013), with an average of 21.5%.

Rapeseed production was modelled based on the average in Finland between 2016 and 2017, which was 1400 kg ha^{-1} (The Finnish Cereal Committee, 2019). According to Farmit (2017), the average fertiliser use per hectare for oil crops in Finland is 111 kg of nitrogen, 11 kg of phosphorous, and 23 kg of potassium. Fertilising was modelled using the GaBi database processes for N-P-K, ammonium nitrate, and potassium chloride fertilisers. It was assumed that 1% of the nitrogen from fertilisers reacted to form N_2O (Brandao et al., 2011). For the rapeseed cultivation, the agricultural machinery was assumed to utilise 90 l of diesel per hectare (Uusitalo et al., 2014). Cultivation was modelled using universal tractor operations from the GaBi database. In Finland, rapeseed is not typically irrigated, thus the direct FWU was assumed to be zero.

2.2.6. Alternative sugar production system

In the system expansion approach, sugar was replaced with honey. For this, sugar was assumed to be produced from sugar beets and modelled using the global average sugar beet production based on the Ecoinvent database. Typically, honey is regarded as sweeter than sugar, with honey sweetness estimates varying from 1.0 to 1.5 times the sweetness of sugar (National Honey Board, 2011). In the model, it was assumed that 1 kg of honey can replace 1.25 kg of sugar.

2.2.7. Alternative protein production systems

DB and pollen proteins were compared to existing animal- and plant-based proteins. There is a relatively high uncertainty concerning the protein sources that are actually replaced, but for this study it was assumed that DB replaces poultry protein and pollen replaces rapeseed protein. In addition, we compared the environmental impacts of single products from honey production systems to possible alternatives. Poultry is a widely used animal-based protein source and is relatively sustainable compared to other common protein sources (Nijdam et al., 2012; Mekonnen and Hoekstra, 2012). As for insects, there are several possibilities that could be used for comparison. Mealworms are relatively well studied and an efficient protein source. Thus, mealworms were used as an insect-based protein source for comparison (e.g., Siemianowska et al., 2013; Miglietta et al., 2015). Due to a lack of studies concerning the environmental impacts of the selected products, the impacts do not necessarily represent those caused by production in Finland. Thus, all impacts should be considered as estimates. The impacts of different protein sources are presented as the impact per kg of protein. The protein content of poultry and mealworms are 20% and 18.6%, respectively (Nijdam et al., 2012; Miglietta et al., 2015). The water use was measured as the FWU per kg of protein and LU as the land occupation value per kg of protein. The averages and ranges of the impacts of the selected comparable products are listed in Table 1.

2.3. Normalising LCA results to correspond to the PB criteria

Steffen et al. (2015) defined PBs for several human impacts using absolute values. Concerning LCA studies, at least some of the results from can be modified to represent the criteria used to quantify PBs (e.g., Uusitalo et al., 2019; Salas et al., 2016). This method has also been proposed for integrating LCA and PB by Ryberg et al. (2016). These values can be normalised in relation to the safe operation zone of PBs. Uusitalo et al. (2019) used the following normalisation equation:

$$n_i = \frac{r_i}{z_i}$$

where:

n is the normalised results,
r is the modified results from the life cycle assessment,
z is the safe operational zone as an absolute value (Steffen et al., 2015), and
i is the PB category.

In this study, we focused on three PB categories, including climate change, FWU, and land system change. Regarding PBs, climate change is defined according to the CO_2 concentration in the atmosphere. The PB has been assessed to be 350 ppm (Steffen et al., 2015). Uusitalo et al. (2019) roughly calculated that one $GtCO_2$ increases the atmospheric concentration by 0.0796 ppm. The uncertainty related to this enables the modification of CO_2 emissions from an LCA to ppm in the atmosphere.

Table 1
Global warming potential, LU and freshwater consumption of poultry and mealworm proteins.

	GWP $kgCO_{2\text{-eq}}/kg_{protein}$	LU $m^2/kg_{protein}$	FWU $kg/kg_{protein}$
Poultry	15 (10–30)[a]	31.5 (23–40)[a]	742 (596–887)[b]
Mealworm	9,7 (5,3–14)[c,d,e]	13,3 (8,6–18)[c,d]	2780[f]

[a] Nijdam et al. (2012).
[b] Mekonnen and Hoekstra (2012).
[c] Thévenot et al. (2018).
[d] Oonincx and de Boer (2012).
[e] Joensuu and Silvenius (2017).
[f] Miglietta et al. (2015).

Table 2
Environmental impacts of the system expansion approach and normalised values to correspond with PB criteria.

	Honey production system (hive)	Reference system[a]
LCA results		
GWP ($kgCO_2eq$)	32	83
LU (occupation) (m^2)	13	619
FWU (kg)	937	2239
Results modified for PB normalisation		
Climate change (ppm)	2.6×10^{-9}	6.6×10^{-9}
Land system change (km^2)	1.3×10^{-5}	6.2×10^{-4}
FWU (km^3)	9.4×10^{-7}	2.2×10^{-6}
PB normalisation factors		
Normalisation factor for climate change (ppm)	350	350
Normalisation factor for land system change (km^2)	10,054,000	10,054,000
Normalisation factor for fresh water use (km^3)	4000	4000
Normalised results		
Climate change	7.4×10^{-12}	1.9×10^{-11}
Land system change	1.3×10^{-12}	6.2×10^{-11}
FWU	2.4×10^{-10}	5.6×10^{-10}

[a] Incorporates the environmental impacts of rapeseed, poultry protein, and sugar beet production without beekeeping.

Land-use change was defined by Steffen et al. (2015) as an area of forested land as a percentage of the original forest, and for boreal, temperate, and tropical forests, as a percentage of the potential forest. The current state of global forests is 62%. The boundary for boreal forests is 85% (Steffen et al., 2015). According to the Global Forest Atlas (2018), boreal forests span approximately 16,600,000 km^2.

Finally, the PB for FWU was set at 4000 $km^3\ a^{-1}$ (Steffen et al., 2015).

3. Results

3.1. Honey production system, reference system, and normalised PB values

The honey production system had a lower GWP, LU (occupation), and FWU than the reference system without honey production (Table 2). From the perspective of PBs, applying a honey production system can assist in returning an area to a safe operational zone.

The GWP of the reference system was almost three times higher than that of the honey production system. The maintenance driving for apiaries (10 $kgCO_{2eq}$), sugar production (8 $kgCO_{2eq}$) and honey/wax production (6 $kgCO_{2eq}$) contributed to a major portion (77%) of the GWP impacts of honey production. In the reference system, most of the GWP impacts were caused by rapeseed cultivation (53 $kgCO_{2eq}$) and sugar production (24 $kgCO_{2eq}$). The GWP of honey production would be significantly higher if longer maintenance driving distances were required. This could occur for various reasons, including small-scale production when the beekeeper does not live close to the hives. From the LU (occupation) perspective, honey production systems require significantly less land area. The majority of the honey production related LU was caused by sugar production (11 m^2). In the reference system, rapeseed cultivation (551 m^2), sugar production (27 m^2), and rapeseed production for proteins (39 m^2) caused the majority of the LU. The FWU of the reference system was approximately 2.4 times higher than that of the honey production system. The FWU during sugar production (890 kg) was the dominant factor in the honey production system. In the reference system, the main life cycle stage that uses freshwater was sugar production (2170 kg) (Appendix Table 1).

According to Table 2 and Fig. 2, both the honey production and reference systems impact the climate change, FWU, and land system change. From the perspective of PBs, freshwater consumption appears to be the most important aspect, followed by land-system change. Compared to the reference system, the honey production system seems to support the return of an area to a safe operational zone, as it causes net-positive impacts.

3.2. Environmental impacts of beekeeping products

Table 3 presents the GWP, LU, and FWU of honey, pollen, and DBs. For the first method, all impacts of the shared processes, such as beekeeping, sugar use, and pollination, were allocated to honey. For this, we assume that DBs were previously discarded as waste. In addition, pollen collection has just recently started, and honey production systems do not focus on their production. For the second method, the emissions from the shared processes were allocated between the products based on their economic value. The impacts of pollination were presented as negative through the increased crop production of rapeseed.

The impact depends upon the allocation method. When the impact reduction via the inclusion of pollination services was not considered in the calculations and the pollen and DBs were considered as by-

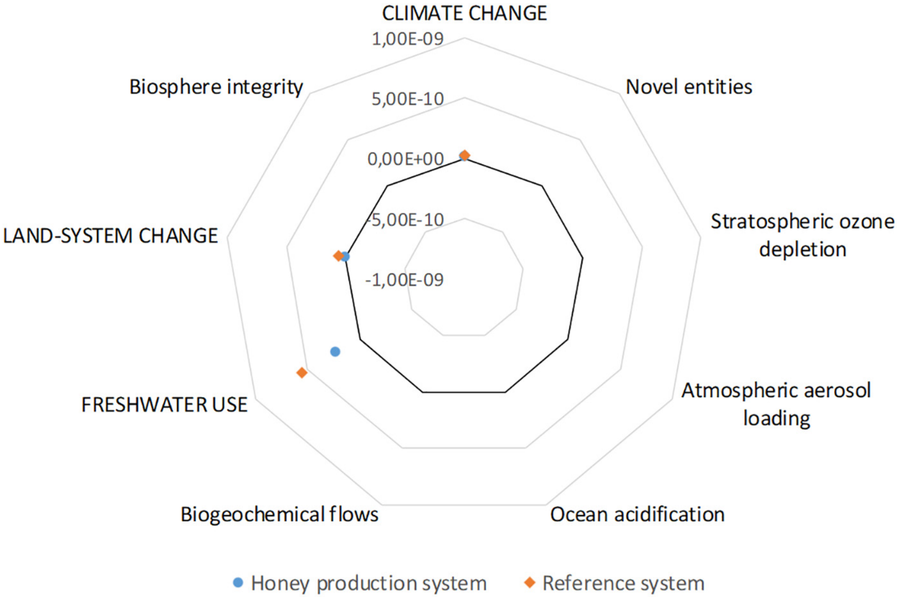

Fig. 2. Normalised impacts in the PB framework for honey production and reference systems.

Table 3
Global warming potential ($kgCO_{2eq}$), LU (m^2a), and FWU (kg) for honey, pollen, and DBs with different allocation factors for the beekeeping processes.

1 kg of honey						
Allocation of beekeeping processes	100%			57%		
	GWP	LU	FWU	GWP	LU	FWU
Maintenance driving by a farmer, hives, and wax	0.23	0.02	0.00	0.13	0.01	0.00
Sugar production	0.27	0.29	22.82	0.15	0.16	13.01
Honey transportation for processing	0.01	0.00	0.00	0.01	0.00	0.00
Honey processing	0.15	0.02	1.00	0.15	0.02	1.00
Honey transportation for retail	0.00	0.00	0.00	0.00	0.00	0.00
Total without pollination	0.65	0.32	23.82	0.44	0.19	14.01
Pollination	−1.35	−14.13	0.00	−0.77	−8.06	0.00
Total	−0.70	−13.81	23.82	−0.33	−7.86	14.01
1 kg of pollen protein						
Allocation of beekeeping processes	0%			37%		
	GWP	LU	FWU	GWP	LU	FWU
Maintenance driving by a farmer, hives, and wax	0.00	0.00	0.00	2.87	0.23	0.00
Sugar production	0.00	0.00	0.00	3.40	3.66	290.13
Pollen collecting and transportation for processing	3.93	0.30	0.00	3.93	0.30	0.00
Pollen processing	1.99	0.37	6.51	1.99	0.37	6.51
Pollen transportation for retail	0.01	0.00	0.00	0.01	0.00	0.00
Total without pollination	5.93	0.67	6.51	12.20	4.56	296.64
Pollination	0.00	0.00	0.00	−17.21	−179.70	0.00
Total	5.93	0.67	6.51	−5.01	−175.14	296.64
1 kg of drone brood protein						
Allocation of beekeeping processes	0%			6%		
	GWP	LU	FWU	GWP	LU	FWU
Maintenance driving by a farmer, hives, and wax	0.00	0.00	0.00	5.62	0.45	0.00
Sugar production	0.00	0.00	0.00	6.65	7.17	568.09
Drone brood transportation for processing	0.09	0.01	0.00	0.09	0.01	0.00
Drone brood processing	3.35	1.15	0.00	3.35	1.15	0.00
Drone brood transportation for retail	0.02	0.00	0.00	0.02	0.00	0.00
Total without pollination	3.46	1.16	0.00	15.73	8.78	568.09
Pollination	0.00	0.00	0.00	−33.70	−351.86	0.00
Total	3.46	1.16	0.00	−17.97	−343.08	568.09

products, the GWP of 1 kg of honey production was approximately 0.65 $kgCO_{2eq}$. However, when DBs and pollen were considered as co-products, the GWP reduced by 32%. Furthermore, the inclusion of pollination services caused a further reduction in the GWP. For these cases, the impacts became net-positive. Therefore, honey production can help an area to stay within the PBs. Compared to by-products, the GWP was reduced by approximately 50% for pollen and 75% for DBs when allocated as co-products. When pollination services were included in the calculations, the impact became net-positive. Similar shifts occur for other impact categories of different products when different methods of impact distribution are performed.

When the sustainability was evaluated via environmental impacts without pollination services, by-products containing protein compared well with the alternative products (Tables 1 and 3; Appendix Table 1). The impacts of DBs on the GWP, LU, and FWU were minimal compared to those of poultry production. When the impacts were allocated to DBs, the difference becomes moderate. However, the DBs are still the most sustainable alternative in all studied impact categories. Notably, the difference between the FWUs was significant. When comparing the sustainability of DBs and mealworms, DBs were favoured when considered a by-product. When DBs were considered a co-product, the GWP and LU impacts were very similar. However, the impact of DBs on the FWU was significantly lower than that of mealworms. When the impact reduction of pollination services was included, the impact of DBs was net-positive, making DBs superior compared to poultry or mealworms regarding sustainability.

3.3. Sensitivity analysis

Maintenance driving and sugar consumption cause significant shares of emissions for different beekeeping products. In addition, both factors have a relatively large range of values, of which the average estimate was used in the GaBi model. Hence, the sensitivities of these variables were investigated. Maintenance driving and the amount of sugar have both good data quality (attachment).

Sugar for feeding bees is responsible for 32% of GWP, 83% of LU and 95% of FWU of beekeeping, when 20 kg sugar is needed per hive. This leads to 10.4 kg $kgCO_{2eq}$, 11.2 m^2 LU and 890 kg FWU. If varying sugar use from 15 to 25 kg per hive the results would vary for GWP 7.8–13.0 $kgCO_{2eq}$, for LU 8.4–14.0 m^2 and for FWU 667.5–1112.5 kg.

Maintenance driving is one of the key factors in GWP but it does not have a significant impact on LU or FWU. The basic assumption was that total maintenance driving is 40 km per hive which leads to 8.6 $kgCO_{2eq}$. If hives are close to the farmer's home and the required driving is only 5 km then GWP is only 1.1 $kgCO_{2eq}$. With some of the small-scale apiaries that are located far from farmers' home driving can be 375 km which would lead to 80.6 $kgCO_{2eq}$. However, this can be considered not as a typical case.

4. Discussion

4.1. Sustainability and validity of the findings

The results show clear environmental benefits from the perspectives of GWP, LU, and FWU, when comparing food production with beekeeping to food production without beekeeping. When only the impacts of beekeeping were considered, the GWP, LU, and FWU were impacted. However, when considering systemic benefits, e.g., pollinating services or product replacement, the impact reductions were significant. In fact, beekeeping can have a net-positive impact on the system. Including the impact reduction of pollination services with beekeeping causes less land occupation and greenhouse gas emissions than the beekeeping alone. Regarding water use, the studied system caused FWU impacts despite the inclusion of pollination services. However, rapeseed farming does not typically require irrigation in Finland, thus an increase in the rapeseed yield was not apparent in the FWU value. If the studied system requires irrigation, the FWU can also become net-positive.

To decipher the validity of the impact evaluation, the results of this study were compared to those of other studies. Provided that the impacts of shared processes were solely allocated to honey and the benefits of pollination were not considered, the carbon footprint of honey was 0.65 $kgCO_{2eq}\ kg^{-1}$. Kendall et al. (2013) calculated that the carbon footprint of honey produced in the U.S. was 0.67–0.92 $kgCO_{2eq}\ kg^{-1}$, for which the main contributor was the transportation of beehives. Mujica et al. (2016) calculated the carbon footprint of honey production in Argentina. According to their study, the carbon footprint of honey production was approximately 2.5 $kgCO_{2eq}\ kg^{-1}$, of which honey extraction was responsible for 90.7%. In our study, unlike in the U.S., honeybees and hives were not transported. In addition, the honey extraction emissions in this study were significantly lower than those presented by Mujica et al. (2016) due to the significantly lower electricity consumption during the extraction process. The demand for electricity as well as the amount of sugar consumed per hive as assumed in this study, was similar to that presented by Ulmer et al. (2020) for two example cases in Germany.

The impact evaluation of the comparison between the honey production and reference systems includes high uncertainty related to the products that were replaced with pollen and DB. In addition, it is possible that because pollen and DBs are new products, there are no appropriate direct replacements. This uncertainty was also raised by Ulmer et al. (2020). However, our results show that the replacement of poultry and rapeseed proteins has a marginal impact on the results compared to sugar replacement and the advantages of pollination services. Therefore, changes in the assumptions related to crop productivity with rapeseed pollination, sugar required for beekeeping, and sugar replacement by honey may have considerable impacts on the results. In addition, when investigating the impact reduction of pollination services, the reduction differs greatly depending upon the crop, fruit, or berries that are used. Therefore, when using the approach presented in this study to investigate the possible net-positive impacts of other food production systems with beekeeping, impact reduction should be evaluated case by case depending upon the target of the pollination services. In addition, the focus of this study was beekeeping in Finland. Different locations have specific climatic conditions that influence crop yields and beekeeping. For these reasons, the results cannot be used to estimate the impact of beekeeping in countries with different climatic and ecological conditions. To estimate the exact environmental impacts of beekeeping in other countries, the effects of pollination services and other factors should be estimated according to those countries. Despite these uncertainties, the results show clear environmental benefits. Thus, it can be argued that beekeeping should be maintained or improved in areas with crops requiring pollination, which could result in net-positive environmental impacts.

The impacts of the different products became more case dependent after system expansion, when using different allocation methods, and after product replacement. By using different allocation methods, the assessment can be modified to achieve the wanted values. Thus, the allocation method should be standardised for LCAs considering beekeeping. For instance, the variation in the environmental values of DBs is greatly dependent upon how the impacts are allocated and whether the DBs are considered by-products or co-products (Table 3). When the impact reduction of the pollination services was included in the calculations, the results provided a more systematic evaluation of the impacts of beekeeping. Without beekeeping, no benefits can be gained from pollination services. With this in mind, the situation for beekeepers is unfavourable, if the impact reduction of pollination services is given to crop farmers or not considered at all.

In Finland, the most important product from beekeeping is honey. However, DBs and pollen have higher economic values per kg of the product. The amount of DBs and pollen produced is over ten times less than that of honey and their use is still marginal. Considering the bulk prices of the products in Finland, honey accounts for over 57% of the economic value of the products from beekeeping, if DBs and pollen are utilised. However, life cycle cost analysis was not performed in this study. Thus, more detailed research is required to investigate whether it is economically feasible to produce DBs and pollen as protein sources along with honey. Considering how the impacts are divided among different products of beekeeping, the situation becomes different for honey production in other countries where pollination services account for a major portion of the economic value (e.g., Ulmer et al., 2020). In these cases, the economic allocation should be conducted differently (e.g., Arzoumanidis et al., 2019). Furthermore, future variation in the prices of pollen and DBs due to changes in the supply and demand will have an influence on how the impacts are distributed among the products.

4.2. Limitations of the LCA PB approach

The conversion of the LCA results to the absolute values of PBs produces some shortcomings (e.g., Bjørn et al., 2019; Ryberg et al., 2016). For instance, this study did not consider local water scarcity issues and the LU was estimated based on the occupied area. In this study, it was assumed that the unused land area was boreal forest, which is not necessarily the case. In addition, the occupied boreal forest does not influence the climate change values in this study. Another limitation of the method used in this study is how companies, organisations, or institutions understand their roles in comparison to others, especially others operating in the same market segments, when considering safe operational space. Despite these uncertainties, this study shows that it is possible to use the methodology developed by Uusitalo et al. (2019) to other kinds of systems than their example in a flexible manner. This study integrated LCA and PB to a system with different kinds of products and services and compared them with other similar systems. However, further research is required to overcome the shortcomings related to the methodology of combined LCAs and PBs.

Biodiversity is a PB that has exceeded the safe operation space (Campbell et al., 2017; Steffen et al., 2015). However, this impact category was not modelled in this study. The impacts on biodiversity are complex and there are several influencing factors regarding pollinators, such as climate change, LU, pesticides, pollination services, and local conditions (Biesmeijer et al., 2006; Brittain et al., 2014; Hendrickx et al., 2007; Rader et al., 2014; Rortais et al., 2005). Methods incorporating LCAs to evaluate the biodiversity impacts of pollinators are still being developed (Crenna et al., 2017), which is why the impacts on biodiversity were not included in this study. However, the results of decreased greenhouse gas emissions and LU indicates that honey production can have a positive influence on biodiversity. In addition, beekeeping can be seen to have positive impacts on biodiversity, for instance by increasing the pollination services for wild plants (Potts et al., 2010).

4.3. Honey production can enhance food security without the additional use of resources

Regarding the DB and pollen production capacity, the production is relatively minor, with approximately 1 kg of DBs and 5 kg of pollen per hive per year. According to the Finnish beekeeper's association (2020), there are approximately 70,000 active hives in Finland. Therefore, theoretically, the maximum production capacities of DBs and pollen are 70 and 350 tons, respectively. This corresponds to 6.6 tons of protein from DBs and 79.5 tons of protein from pollen. Regarding honey, the annual production is approximately 2730 tons per year. However, the annual increase in the yields of crops, fruits, and berries due to pollination services might be more significant than the honey production itself, as is shown in the case of rapeseed production. For instance, the production capacity of rape and rapeseed in Finland was approximately 71 thousand tons in 2018 (Luke_b, 2020). If all cultivation areas of rape and rapeseed have at least two bee hives per hectare, which increases the yield by 11%, this would mean that approximately 7036 tons of rapeseed are annually produced due to bee farming. Assuming that the average protein content is 21.5%, this corresponds to a production of 1512 tons of plant-based protein per year. Based on these assumptions, beekeeping can have a positive impact on food security through increased protein and sweetener production with reduced environmental impacts. However, these values are based on assumptions. Therefore, more research is required concerning the influence of honeybees on the pollination of crop yields in large-scale.

Given that similar net-positive impacts are possible for other food systems, the phenomenon of decreasing pollinator populations is severe in the context of sustainability goals and food security issues, as approximately 35% of cultivated crops are dependent upon pollinators. In an economical manner pollination has a huge impact on agriculture. For instance, it has been estimated that pollination has a direct economic benefit of approximately 585€ per hectare for oilseed rape farming in Ireland (Stanley et al., 2013; Breeze et al., 2016). Globally, the value of pollination has been evaluated at 153 € billion in 2005 (Gallai et al., 2009). If the phenomenon of decreasing populations is not halted, an alternative method for influencing food production is required. Otherwise, food security is in danger of being compromised due to decreased crop yields and the loss of products from honey production. However, the results of this study show that it is possible to increase food production without the additional use of resources in areas without proper beekeeping practices. To create the possibility of net-positive impacts and increase food security by increasing the yields of some crops and co-products of beekeeping, beekeeping with crops requiring pollination services should be maintained and possibly even improved. For instance, the balance between a suitable amount of pesticides and beehives in different crop production areas should be investigated, as the use of pesticides contributes towards the declining pollinator populations (Brittain et al., 2014).

5. Conclusions

In this study, a novel approach was used to estimate environmental impacts of beekeeping. The results of LCA were converted to represent PB criteria and consider the impact of pollination services, which has previously not been done. The results show that beekeeping can help the food sector to remain within safe operation spaces concerning three impact categories. The impact categories were GWP, LU, and FWU. From the perspective of PBs, the biggest impact reduction was FWU. When the impacts were considered as product-based, the GWP and LU impacts were net-positive, given that pollination services were included in the calculations. Based on the impact values of the assessment, it is strongly recommended that beekeeping is increased in areas where possible, as there are clear benefits regarding sustainability and food security. The knowledge can help decision makers plan more sustainable food systems and aid beekeepers in estimating their positive influence on food systems and marketing their pollination services. However, more research is required concerning different systems with different crops to show how beekeeping affects overall food systems and their environmental impacts.

CRediT authorship contribution statement

Conceptualization	Ideas; formulation or evolution of overarching research goals and aims
Methodology	Development or design of methodology; creation of models
Software	Programming, software development; designing computer programs; implementation of the computer code and supporting algorithms; testing of existing code components
Validation	Verification, whether as a part of the activity or separate, of the overall replication/reproducibility of results/experiments and other research outputs
Formal analysis	Application of statistical, mathematical, computational, or other formal techniques to analyse or synthesize study data
Investigation	Conducting a research and investigation process, specifically performing the experiments, or data/evidence collection
Resources	Provision of study materials, reagents, materials, patients, laboratory samples, animals, instrumentation, computing resources, or other analysis tools
Data curation	Management activities to annotate (produce metadata), scrub data and maintain research data (including software code, where it is necessary for interpreting the data itself) for initial use and later reuse
Writing - Original draft	Preparation, creation and/or presentation of the published work, specifically writing the initial draft (including substantive translation)
Writing - Review & editing	Preparation, creation and/or presentation of the published work by those from the original research group, specifically critical review, commentary or revision – including pre-or postpublication stages
Visualization	Preparation, creation and/or presentation of the published work, specifically visualization/data presentation
Supervision	Oversight and leadership responsibility for the research activity planning and execution, including mentorship external to the core team
Project administration	Management and coordination responsibility for the research activity planning and execution
Funding acquisition	Acquisition of the financial support for the project leading to this publication

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.

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Appendix A

Appendix Table 1
Environmental impacts of the system expansion approach.

	Honey production system		
	GWP	LU (occupation)	FWU
	$kgCO_2eq$	m^2	kg
Maintenance driving by a farmer and hives	8.6	0.6	0.0
Sugar production	10.4	11.2	890.0
Transportation for processing	0.4	0.0	0.0
Honey and wax processing	6.0	0.7	39.2
Pollen processing	2.3	0.4	7.4
Drone brood processing	0.3	0.1	0.0
Pollen collecting	4.4	0.3	0.0
Transportation for retail	0.1	0.0	0.0
Total	32.6	13.5	936.5
	Reference system		
	GPW	LU (occupation)	FWU
	$kgCO_2eq$	m^2	kg
Rapeseed cultivation	52.8	551.2	0.0
Poultry protein production	1.4	3.0	69.7
Sugar production	24.3	27.4	2169.4
Rapeseed protein production	3.6	37.8	0.0
Transportation	0.4	0.0	0.0
Total	82.5	619.4	2239.1

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.143880.

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