

Carbon footprint and air emissions inventories for US honey production: case studies

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Abstract

Purpose The primary purpose of this study is to estimate the life cycle greenhouse gas (GHG) emissions (carbon footprint) and criteria pollutant emissions during honey production and processing for US conditions based on several case studies of different scale beekeeping and processing operations. Commercial beekeeping operations yield two coproducts, honey and pollination services. These two products present an interesting coproduct allocation problem since beekeeping operations cannot be clearly subdivided, pollination services do not have a substitutable product or service, and pollination services cannot be characterized by physical properties for value-based allocation. Thus, a secondary purpose is to identify an appropriate allocation method and to discuss how the choice of allocation strategies influences the outcomes.

Methods The commercial honey production supply chain comprises the following two primary steps: raw honey production by beekeepers and honey processing and packaging by processors. A case study approach was used based on

detailed operation data provided by several beekeepers and processors from key honey-producing regions in the USA. Process-based life cycle assessment was conducted following the ISO guidelines, and economic allocation was used as a baseline method for coproduct allocation.

Results and discussion Life cycle modeling of one complete commercial supply chain (raw honey production, transport to a processor, and processing) shows that total life cycle GHG emissions range from 0.67 to 0.92 kg CO₂ equivalent/kg of processed honey; however, outcomes show significant variability. Results show commercial honey production emits more GHGs and criteria pollutants than processing. Truck transport of bees is the dominant contributor of both GHG emissions and criteria pollutants within the life cycle of raw honey production. However, honey processing, which depends on natural gas and electricity, contributes a significant fraction of SO_x. These results are based on economic allocation among beekeeping coproducts. In addition to economic allocation, subdivision was applied to beekeeping activities. Because hive management (feed and medication) could not be further subdivided, a bounded range was generated for raw honey production, where the lower and upper bounds represent two extremes where all the environmental burdens associated with hive management were allocated to pollination or honey production.

Conclusions Economic allocation tends to fall near or below the lower bound for the subdivision method. Interestingly, some beekeepers reported that their hive management practices were driven more by demand for pollination services than honey, which seems to be reflected in the coordination of lower-bound subdivision and economic allocation results.

Keywords Beekeeping · Coproduct allocation · Food system · Hive maintenance · Life cycle assessment · Transportation

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1 Introduction

1.1 Honey production and consumption in the USA

The US Department of Agriculture's (USDA's) 2007 Census reported that there were about 2.9 million managed bee colonies in the USA, belonging to 28,000 beekeepers (USDA 2007). More than two million of these bee colonies belong to commercial beekeepers (Johnson 2010), and the rest belong to small-scale beekeepers referred to as backyard hobbyists.

Compared with other sweeteners, such as sugar and corn syrup, honey does not demand direct use of fertilizer and irrigation during production, nor does it introduce land use issues, as it is not a direct product from any cultivated crops (Melathopoulos 2006). Commercial beekeeping operations derive economic value from both honey sales and pollination services. Honeybees have become a vital part of modern agriculture due to their irreplaceable role in pollination of fruits, nuts, vegetables, and other crops. In 2000, the economic value of honeybee pollination was estimated to add \$14.6 billion to the value of US agriculture (Morse 2000). Worldwide, approximately one third of the world's food production relies on insect pollination, 80 % of which is estimated to be provided by honeybees (Pimentel et al. 1997).

A large number of crops, including almonds, apples, avocados, etc., are almost entirely dependent on honeybee pollination (Johnson 2010). Most pollination services are provided by commercial beekeepers with a rental fee, although there is a small proportion of free pollination. In order to pollinate multiple crops, beekeepers need to move bees by truck. Beekeepers may also move bees for nectar collection, for honey production, and for over-wintering locations depending on where their operation is based. Thus, transport of bee colonies is an important process in commercial beekeeping.

1.2 Previous studies on honey production and environmental effects

There have been no previous life cycle studies on US honey production and processing; however, honey has been included in a few studies focusing on the environmental impacts of food and beverage products in other countries. Two studies were identified with relevant and original analyses (Wallén et al. 2004; Rose and Grabham 2009). While both studies track food production, processing, packaging, and distribution, neither provide detailed information to break down emissions estimates by life cycle phase.

Rose and Grabham (2009) attempted to characterize energy use and greenhouse gas (GHG) emissions for an average Australian household or small business, which includes honey consumption. They found that 2.00–

2.85 kg carbon dioxide (CO₂) equivalent (CO₂e) is attributable to honey, with an uncertainty of ±35 %.

Wallén et al. (2004) performed a study for Sweden and estimated 4.18 kg CO₂e emissions for producing 1 kg of sweeteners, a category including sugar, honey, and treacle. Their study's scope included production and distribution to consumers. However, combining honey, sugar, and other products as members of a single class of food is problematic because sugar and honey are produced very differently and the corresponding environmental impacts are therefore likely to differ substantially from one another.

2 Methodology

This study characterizes the life cycle air emissions of honey production and processing practices at various scales for US conditions using process-based life cycle assessment (LCA) methods from cradle to processor gate. The air emissions tracked include CO₂, methane (CH₄), nitrous oxide (N₂O), carbon monoxide (CO), nitrogen oxides (NO_x), particulate matters (PM), and sulfur oxides (SO_x). Honey production practices and honey yields in the USA are highly variable over time, geographic region, and even from one producer to another. Thus, defining an average or typical production system is not possible. Instead, we take a case-study approach that evaluates the practices of specific producers at different scales of production based on surveys.

Survey methods were applied to acquire practical information from the honey industry with the cooperation of the US National Honey Board. Surveys were acquired from key honey-producing states such as California, Florida, and Montana. Commercial honey production is a two-step supply chain. First, raw honey is produced and extracted by beekeepers, and then honey is processed and packaged (either for retail sale or use by food processors) by honey processors. This case study included four commercial-scale producers, two small-scale producers referred to as hobbyists, and five processors.

Commercial beekeeping production systems generate raw honey and pollination services. These two coproducts are inextricably linked and are fundamental to a beekeeper's business model; very few commercial beekeepers only produce one of these products. Thus, pollination services must be accounted for as a coproduct.

2.1 Goal and scope definition

2.1.1 Goal and audience

The research goal of this LCA is to establish an air emissions life cycle inventory (LCI) for US honey production and processing, including GHGs and some criteria pollutant

emissions. A secondary goal is to identify emissions hotspots in the life cycle. This study’s audience is intended to include the research community, the honey industry, and consumers. It may interest researchers because a comprehensive environmental analysis of US honey has not previously been completed, and honey is a unique agricultural product not represented by other similar products. The result of this study can be used to compare with other sweeteners, such as corn syrup and sugar, despite the fact that they are not perfect substitutes. The study outcome can also help beekeepers and honey processors improve environmental performance by identifying emissions hotspots in their production process, which will allow them to target emissions reductions from the identified activities. For consumers, information on honey’s environmental impacts may help in making purchasing choices.

2.1.2 System definition, system boundary, and functional unit

The system boundary is illustrated by the flow chart in Fig. 1. The phases in a honey life cycle are summarized as hive construction, hive management, bee travel, honey extraction, and honey processing. However, beehive construction is excluded from this study since beekeeping equipment consists of a small volume of wood and a negligible amount of plastic or metal, and most bee hives are handmade. Most beekeeping gear can last for more than 20 years.

The focus of this study is on commercial-scale honey production, but results for small-scale hobbyist producers and processors are also presented. The life cycle stages “Bee Travel for Nectar and Pollen” and “Raw Honey Transport” shown in Fig. 1 do not apply to hobbyists because typical

hobbyist producers do not transport bees by truck and they process honey by themselves.

The packaging material and distribution of processed honey are not included in order to standardize the results across many different sizes and types of packaging. For example, processing facilities reported multiple packaging sizes and materials, as well as a large amount of honey sold in bulk packaging (e.g., 500 gal plastic bags) or in tankers to be packaged in other facilities or used in food processing, such as for breakfast cereal. The immense variability in how processed honey was packaged or delivered to a second site for packaging made incorporating these calculations in this study infeasible. The end-of-life (recycling, disposal, or reuse) phase of all materials is not included. The manufacturing and maintenance of machines used in the extraction and processing facility are not considered either since the average lifespan of equipment is longer than 20 years.

The functional unit is 1 kg of processed honey, and the time horizon of analysis is 1 year.

2.1.3 Study limitations

Data were collected from beekeepers for either the 2008 or 2009 calendar year. Honey production is correlated with weather, crop conditions, and disease which may all vary from year to year and region to region; therefore, responses for any given year may not represent typical or average conditions. Due to a lack of integration in the honey supply chain, the transportation distance of raw honey from beekeepers to packing facilities is highly uncertain; beekeepers do not necessarily know where their raw honey is going to be processed, and honey processors do not always keep records about where the raw honey came from. Where possible, we have addressed this type of uncertainty using sensitivity and scenario analyses.

2.2 Data and model development

Case studies of six beekeepers from five states in the USA are included: four of them are considered commercial beekeepers, with two considered large scale and two considered medium scale for the purposes of this study based on annual honey yield. All four commercial beekeepers engage in crop pollination contracting. The two remaining beekeepers are hobbyists who do not provide paid pollination services. Information about the six honey producers is shown in Table 1.

Five processors are included, with three large-scale processors and two self-packers. Self-packers surveyed do not have dedicated facilities and consume a small amount of energy and materials during processing. The three large-scale processors (denoted as P1, P2, and P3), chosen from

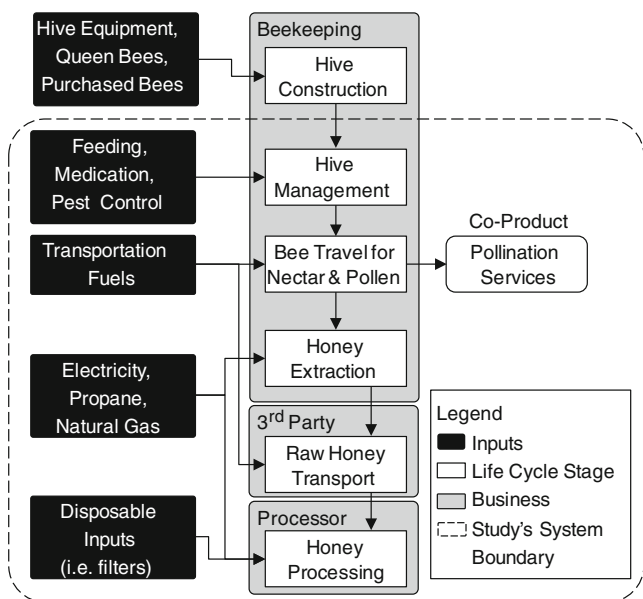


Fig. 1 LCA flow diagram for commercial honey production and processing

Table 1 Production characteristics of beekeepers

Producer	Geographic location	Number of colonies	Annual yield of honey (kg)	Supplemental feeding	Income from honey (%)	Total annual miles travel	Total annual miles for pollination
L1	Western	4,000	200,000	Low	50	70,000	16,800
L2	Mountain	5,349	180,000	Low	54	52,000	12,000
M1	Western	3,500	70,000	High	25	43,000	34,720
M2	Western	1,500	40,000	High	33	93,600	13,600
S1	Central	3	90	Low	100	0	0
S2	Southeastern	5	70	Zero	100	0	0

L1 large 1, L2 large 2, M1 medium 1, M2 medium 2, S1 small 1, S2 small 2

states in the Eastern, Western, and Mountain regions of the USA produce 18,000, 6,800, and 600 metric tons of honey annually. The two self-packers (P4 and P5), from Southeastern and Central region states, respectively produce 400 and 90 kg of honey annually. Note that processor P5 is the same entity as the producer S1.

Hive management includes supplemental feeding and medication. Supplemental feeding is necessary, especially in the winter when natural bee foods, nectar, and pollen, are not available and honey stored in the hive is inadequate. High fructose corn syrup, sugar syrup, brewer's yeast, and soybean flour are commonly used in supplemental feeding. There are many different formulas for feeding practices. For example, the weight ratio of granulated sugar to water can be 1:1 (Cornell University the Master Beekeeper Program 2006) or 2:1 (Thomas and Schumann 1993), depending on the temperature and humidity. A 1:1 ratio is used in the LCI modeling. The amount of supplemental feeding is different for each producer, with the annual mass of feed per colony ranging from 1 to 30 kg in the cases we surveyed.

Pest control and medication are an integral part of beekeeping to reduce the risk of diseases and insect invaders. The names and brands of bee treatment products were obtained from beekeeper surveys, and we obtained LCI data for the major chemical components of these products according to their chemical classes (Ministry of Agriculture and Forestry 2001). LCI datasets were obtained from the EcoInvent database accessed through SimaPro 7.1 (Ecoinvent Centre 2007; PRé Consultants 2008).

Transportation includes bee travel for nectar and pollen flow and raw honey transport from producers to processors. The emissions data for transportation were based on the size of vehicle, fuel type, and fuel consumption from beekeepers' survey. Precombustion and combustion emissions for fuels are both included. The fuel efficiency is assumed constant for trips to the destination and back from the destination, because the freight weight primarily consists of the bee boxes and is only slightly affected by the honey produced after nectar collection. LCI datasets for upstream emissions and on-road emissions for road transport were

taken from the US LCI database (National Renewable Energy Laboratory 2008).

Honey extraction and processing are the two main phases where electricity, natural gas, and propane are consumed. The survey asked respondents to report electricity use as indicated on their facilities' utility bills; thus, electricity use includes lighting and climate control where applicable. Some materials used on site, such as sanitizer, soap, and other cleaning agents are not accounted for. LCI datasets for gasoline and natural gas were from the US LCI database (National Renewable Energy Laboratory 2008), a dataset for electricity from EcoInvent database (Ecoinvent Centre 2007), and a dataset for propane from the GaBi Professional database (PE International 2009). For electricity, we used the US average grid mix.

2.3 Coproduct treatment

The allocation of environmental burdens among coproducts can significantly influence the results of an LCA study, and thus the selection of an allocation procedure is critical. The ISO standard requires that, wherever possible, allocation be avoided either by division of a process into subprocesses, or through system expansion. When avoiding allocation is not possible, allocation should preferentially be conducted based on "physical relationships," such as mass or energy content, or, as a last resort, based on other measures, such as economic values (Tillman 2000; Ekvall and Finnveden 2001; International Organization for Standardization 2006).

In our study, allocation between honey and other beekeeping coproducts (pollination services) was implemented to characterize raw honey production and was only required for commercial beekeepers. While some bees kept by hobbyists may also pollinate crops because of proximity to farms, we do not consider coincidental pollination of agricultural crops as a coproduct. Thus, for hobbyists all the environmental burdens from beekeeping activities are attributed to honey production. Neither system expansion nor allocation based on physical relationship is applicable in this case, given the following two reasons: (1) pollination

services have no substitute in the market. Among various pollinators, bees are the only ones that can be easily managed and can provide on-demand, market-based pollination services. (2) Honey and pollination services are not comparable on a physical basis. Subdivision and economic allocation methods for raw honey production are explored below. No allocation is required for processing because honey processing does not produce significant coproducts.

2.3.1 Using subdivision to avoid coproduct allocation

Allocation can be avoided by subdivision, where multifunctional processes are separated and environmental flows are calculated and assigned to a particular coproduct. Beekeeping operations yield pollination services, honey, and occasionally other beekeeping products such as wax; however, the volume of these other products in the USA is minimal. Thus, for the purpose of this study, beekeeping processes are subdivided into two categories, those for pollination services and those for honey production.

Large-scale commercial beekeeping operations transport bees to different sites for pollination services and for honey production. While bees occasionally make a small amount of honey while pollinating crops that produce a large amount of nectar, such as crimson clover and hairy vetch (Morse 2000), most paid pollination services do not produce honey. For example, pollination of almond orchards, a major user of pollination services, produces no saleable honey (Sumner and Boriss 2006). Therefore, transportation can be roughly divided into two subprocesses, trips made primarily for honey production and trips made primarily for pollination.

The greatest challenge in subdivision of beekeeping is characterizing hive management, which benefits both honey production and pollination services. There are many interactions between honey production, pollination services, supplemental feeding demand, and increased exposure to disease and pests. For example, honeybees may obtain food from pollination crops and reduce total supplemental feeding demand. Conversely, honeybees can also be exhausted by pollinating some crops (Mussen (UC Davis Entomology Specialist), 2010, personal communication), thus increasing supplemental feeding demand. Furthermore, pollination may increase the chance of disease infection in the new pollination area, leading to more medication inputs and reduced honey yield. The interdependencies of feed and medication with respect to honey, pollination, and other coproducts suggest that the hive management life cycle stage cannot be reasonably subdivided.

However, we can generate a hypothetical bounded range based on the percentage of feeding and medication inputs exclusively beneficial to honey production

(as opposed to pollination). This range represents two extremes: at 0 % no hive management inputs benefit honey production, and at 100 % all inputs exclusively benefit honey production. The results of this analysis can then be compared with the results from other allocation methods.

2.3.2 Economic allocation

A partitioning factor reflecting physical properties of coproducts from beekeeping could not be identified, so the only property used for allocation calculations was the economic value. Some have argued that economic allocation may be preferable for LCAs of food production. For example, Ziegler and Hansson (2003) suggest that an allocation based on gross market value reflects the causes or drivers of environmental burdens in food production systems and is thus the best-suited property for allocation calculations.

In this study, economic allocation was conducted based on survey respondents' reports about the percentage of their total beekeeping-related income that is derived from raw honey sales. This percentage ranged from 25 to 54 % for surveyed commercial beekeepers, as given in Table 1, and we used this percentage as an allocation coefficient and calculated the emissions for each individual beekeeper. The rationale to use income share as the allocation coefficient is that the economic value of the product is the driving force of the production system.

All the results presented below are based on economic allocation, except those in Section 3.4 where results from two allocation methods are compared.

2.4 Life cycle impact assessment

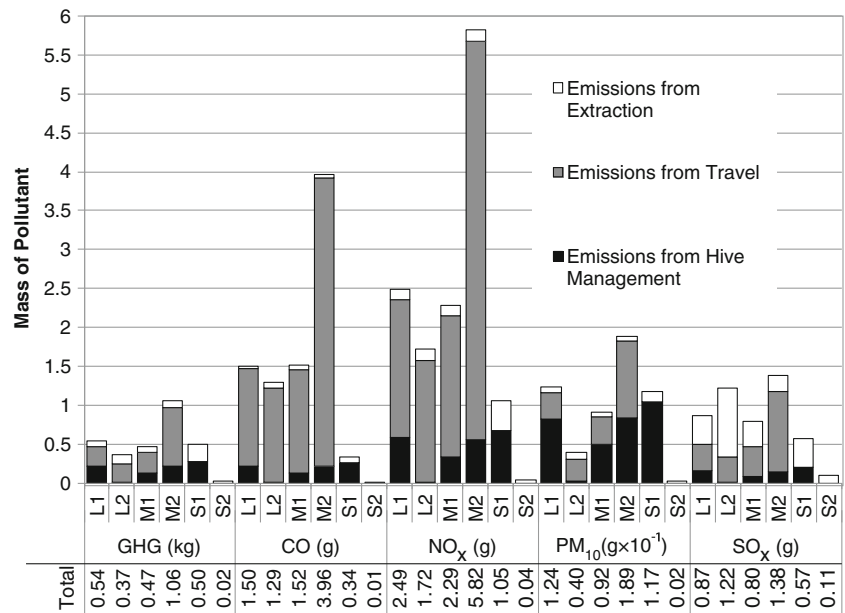
Since our primary purpose was to provide LCI data for honey production and processing, impact assessment is not further discussed. CO_{2e} emissions were calculated based on the Intergovernmental Panel on Climate Change's 100-year global warming potentials for N₂O and CH₄ (Intergovernmental Panel on Climate Change 2007).

3 Results and discussion

3.1 Emissions from raw honey production

GHG and criteria pollutant emissions were calculated for 1 kg of processed honey. Since 1.5 % by mass of raw honey is lost during processing according to processors' surveys, 1.015 kg of extracted, unprocessed honey will yield 1 kg of processed honey. Air emissions for 1.015 kg of unprocessed honey for six producers are shown in Fig. 2. Note that all the

Fig. 2 Air emissions from commercial honey production per 1.015 kg of unprocessed honey (will yield 1 kg of processed honey)



results below are calculated using the baseline method, economic allocation, except for the results in Section 3.4.

Figure 2 shows that the air emissions associated with commercial honey production are significantly higher than the emissions from hobbyist honey production, especially for CO, NO_x, and SO_x emissions, due to the fact that commercial beekeepers heavily depend on truck transport whereas hobbyists do not. The producer M2 has the highest amount of emissions for all pollutants due to lower yields on a per-colony basis and particularly high transportation emissions. The hobbyist S2 has the lowest emissions for all categories due to zero supplemental feeding and low energy use in extraction. S1's emissions are higher due to the provision of 90 kg of supplemental feed in the winter. The difference in the quantities of supplemental feeding may be related to differences in climate conditions.

Figure 2 also shows that the transport of honeybees (the travel phase), is the largest contributor to CO₂e, CO, NO_x, and PM₁₀ emissions. Travel and extraction are the primary contributors to SO_x emissions. SO_x emissions from travel are due to diesel emissions, and those from extraction result from electricity and natural gas consumption. SO_x emissions occur during electricity generation (e.g., coal-fired power plants), and during the precombustion phases for natural gas.

3.2 Emissions from honey processing

GHG and criteria pollutant emissions are calculated for five processors. Notably, neither of the small processors (P4 and P5) used any fuels or electricity during processing. Whenever needed, they used waste heat from other domestic activities such as cooking or running appliances that generate heat. The only emissions source was water consumption. GHG emissions for these processors were 0.76 g CO₂e (for P4) and 3.0 g

CO₂e (for P5)/kg of honey, compared with an average of 120 g CO₂e/kg of honey for commercial processors. The other air pollutants are similarly much lower for small processors. Figure 3 shows emissions from the three large, commercial-scale facilities (P1, P2, and P3) broken down by the fuel or material flow contributing the emissions.

Figure 3 suggests that economies of scale are realized as commercial processors increase in size (P1 is the largest and P3 the smallest in size). In other words, larger-scale operations seem to operate more efficiently, demanding less energy and material inputs per unit of honey output. However, one should be cautious in drawing any general conclusions about this due to the limitation of the sample size.

The results in Fig. 3 do not include transport of raw honey from beekeepers to a processor's site. Adding this parameter to the assessment could reverse the trend of larger facilities and greater efficiency, as larger facilities may require greater distances for honey transport to realize

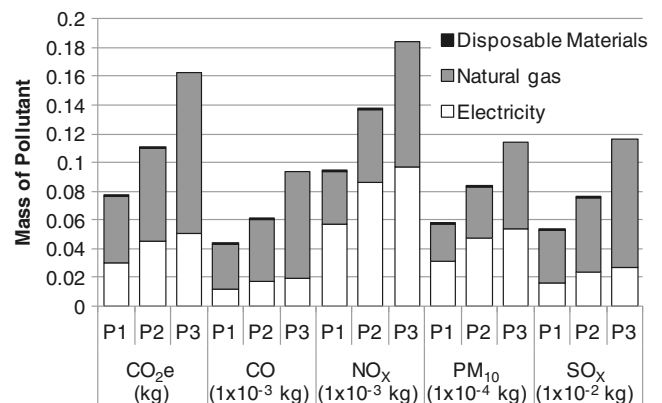


Fig. 3 Air emissions per kilogram of processed honey for commercial-scale processors

capacity. Thus, we cannot conclude that a larger processing operation will result in lower emissions from a life cycle perspective.

3.3 Emissions from the full honey production and processing life cycle

To quantify and assess the air emissions from the life cycle of 1 kg of processed honey, the transport between the facilities of honey production and processing has to be included. However, for commercial operations, the transport of raw honey is usually performed by a third party. Estimating an average distance is not possible due to the lack of integration in the supply chain and the large diversity of producer and processor locations across the country. Therefore, we created example scenarios based on plausible combinations of producers and processors to demonstrate the contribution of raw honey transport to total life cycle air emissions.

Producer L1 and processor P2 are chosen as an example supply chain, which means that the selected producer sells its raw honey to the selected processor. Raw honey is transported in heavy-duty trucks with a capacity of 64 steel drums for a distance of 225 km. This is shown as the *Transport (low)* scenario in Fig. 4. In this scenario, 80–90 % of emissions of GHGs, CO, NO_x, and PM₁₀, and about 50 % of SO_x emissions are attributable to raw honey production.

To deal with the uncertainty associated with raw honey transport, a sensitivity analysis is used to evaluate the effect of transportation distance on life cycle emissions. The distance of raw honey transport to processors ranges from 225 (140 mi) to 2,897 km (1,800 mi) in our analysis; 2,897 km was selected as the upper bound based on the maximum transport distance reported by the surveyed processors. Truck transport was assumed to be the only mode. In the

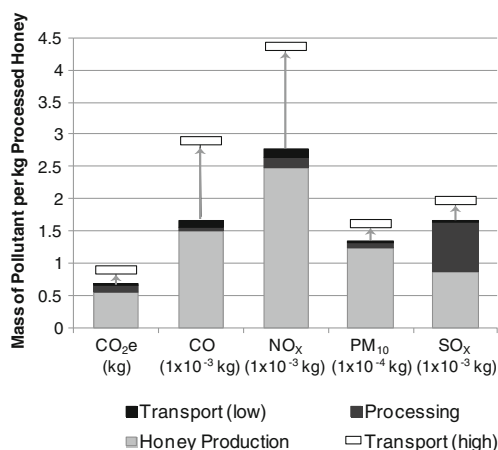


Fig. 4 Life cycle emissions per kilogram of processed honey for a supply chain scenario (producer L1 to processor P2)

Transport (low) scenario, the contribution of the raw honey transport phase is approximately 2–6 % for all types of emissions. When the transport distance is increased to 2,897 km, the transport phase contributes 29 % of the total GHG emissions, and 47, 40, 19, and 19 % of the total emissions of CO, NO_x, PM, and SO_x, respectively.

Additional scenarios are shown in Fig. 5 but only for GHG emissions. These scenarios represent possible combinations of honey producers and processors in our study; not all combinations are included because we assumed that the maximum distance between producer and processor is 2,897 km. S1 and P5 are actually the same entity, representing an integrated, hobbyist operation, shown as S1 in Fig. 5. The other hobbyist scale producer (S2) and processor (P5) were not included because of incomplete data.

Figure 5 shows a large range of potential GHG emissions from honey production, from just over 0.4 kg CO₂e/kg of honey for small-scale producers who do not transport bees or honey to nearly 1.4 kg CO₂e/kg of honey for a commercial honey production supply chain. However, most of the commercial production supply chain scenarios fall within 0.6–0.9 kg CO₂e/kg of processed honey. Raw honey production is the dominant contributor to GHG emissions. Transport of raw honey and honey processing together contributes 0–50 % of total GHG emissions depending on the supply chain.

3.4 Coproduct allocation

Subdivision could not be used to generate a point estimate for raw honey production because hive management cannot be reasonably separated. However, the subdivision method was applied to generate a bounded range of 0 to 100 % of hive management inputs specifically benefitting honey production. Travel of bees is subdivided by the primary

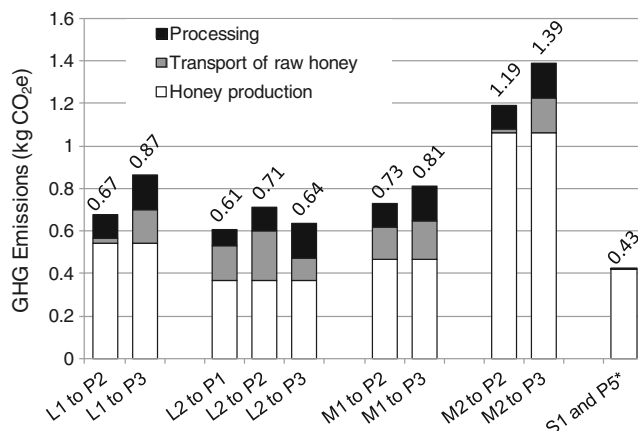


Fig. 5 Life cycle greenhouse gas emissions (in kilograms CO₂ equivalent per kilogram of honey) for potential honey production supply chains

purposes of trips reported by beekeepers. GHG emissions from commercial raw honey production calculated using the subdivision method versus using economic allocation are compared in Fig. 6.

Figure 6 demonstrates that GHG emissions calculated by economic allocation are lower than the lower-bound results produced using the subdivision method for honey producers L2 and M2. Beekeeper M2 traveled much greater distances and had lower yields than the other surveyed beekeepers, which explains, at least in part, the significant difference in the magnitude of emissions and the spread between the subdivision and economic allocation outcomes.

In the other two cases, L1 and M1, results estimated by economic allocation are almost perfectly aligned with (just slightly higher than) the lower bound of the range calculated by the subdivision method. Anecdotally, some beekeepers reported that their hive management decisions were dictated mostly by demand for pollination services; not honey production. This may explain why the results for economic allocation and the lower bound of subdivision are well aligned in these two cases.

Similar analyses for criteria pollutants were also conducted. In nearly all cases, results for economic allocation are lower than for subdivision. In particular, SO_x emissions for all producers by economic allocation are significantly lower than the results by the subdivision method. Given that the dominant contributor of SO_x emissions is electricity used for honey extraction, this result is not surprising. The overall outcome implies that honey production is more emissions intensive than pollination services on a per-dollar basis. Comparison between subdivision and economic allocation procedures also shows that a proportion of emissions, such as those from honey extraction, almost exclusively from raw honey production, are discounted under economic allocation, which makes this method favorable to honey production.

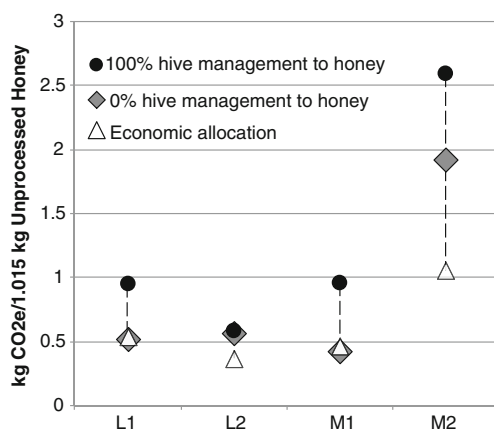


Fig. 6 Comparison of GHG emissions per 1.015 kg of unprocessed honey calculated by subdivision method and by economic allocation method

3.5 Economic benefits of pollination for agriculture

Pollination is a special “coproduct.” On the one hand, pollination activities consume energy and emit air pollutants; thus, it is treated as a usual coproduct associated with negative environmental impacts; on the other hand, pollination activities provide services which benefit agriculture and the ecosystem. These two aspects can give rise to trade-offs in the sense that more energy and material inputs are required to provide more pollination services, but pollination services may have economic and environmental benefits well beyond the increased amounts of supplemental feed and mileage required to fulfill more pollination contracts.

Our economic allocation method was based on the income received by beekeepers; we did not account for the substantial economic value pollination provides to agricultural producers. In fact, evidence suggests that the economic costs of pollination contracts may be significantly lower than the economic value of pollination services to crop producers (Allsopp et al. 2008). Accounting for these crop production benefits from pollination across multiple US crops and regions, with different degrees of dependence on managed honeybees versus wild pollinators (Kremen et al. 2002), would be challenging. Given that the goal of this study is to characterize the GHG and criteria pollutants emissions of honey production and processing, assessing the benefits provided by pollination services to processes outside of the beekeeping production system were beyond the scope of this study.

4 Conclusions

GHG emissions from honey production and processing range from approximately 0.4 to 1.4 kg $\text{CO}_2\text{e}/\text{kg}$ of processed honey in our case study. Small-scale beekeepers may achieve significantly lower emissions because they generally do not transport hives for nectar collection or for pollination. For large-scale honey processors, the GHG emissions from honey processing range from 0.08 to 0.16 kg $\text{CO}_2\text{e}/\text{kg}$ of processed honey and may be near zero for hobbyists who process their own honey.

A few conclusions can be drawn based on this case study. First, small-scale producers and self processors may have the least environmental impacts due to their near-zero transportation needs and low energy use, with the caveat that it is important to note that emissions associated with packaging and transporting honey for retail sale are not included here. Second, transporting bees to collect nectar is the largest contributor to air emissions among the life stages of commercial raw honey production. One potential method to reduce emissions and energy consumption is to minimize transport distance and to use more efficient transport modes.

Finally, identifying a processor close to the beekeeper's extraction site can be a straightforward way to minimize life cycle emissions.

Coproduct treatment is a challenge because of the interdependent production system yielding both honey and pollination services. A sensitivity analysis exploring the effect of applying subdivision and economic allocation showed that economic allocation generally resulted in emissions at or below the lower bound range generated using subdivision. This exercise showed that the choice of coproduct treatment method in LCA may significantly influence results. It is inappropriate to argue which method is better or more reasonable; in fact any coproduct treatment method, which attempts to simplify complicated multifunctional systems, would result in some bias to some extent. In the case of honey, given that honey production accounts for less than half of the annual beekeeping income, using economic allocation might favor honey production because emissions resulting exclusively from honey-related activities, such as extraction, are discounted, whereas they would be allocated 100 % to honey production when using subdivision. As an LCA practitioner, presenting the results based on multiple allocation methods is a good way to help understand the complexity of the system and test the robustness of the LCA analysis. This challenge of coproduct treatment in complex systems, where some coproducts may actually be ecosystem services rather than products, also suggests that more sophisticated methods to account for ecosystem services within an LCA framework could be explored in future work.

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