Life cycle assessment of a circular, urban mushroom farm

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Abstract

Modern food systems incur many environmental impacts, which can be mitigated by the application of circular economy principles, such as the closing of material and energy loops and the upcycling of waste products. Mushroom farming provides a relevant case in this direction because organic waste can be used for substrate as an input in the cultivation process, which produces valuable outputs such as edible foodstuffs and soil amendment. Few studies evaluate the actual environmental impacts of circular food production systems and assess their efficacy with respect to more linear alternatives. To address this research gap, we quantified the environmental impacts of a circular, urban mushroom farm next to Paris, France. We used life cycle assessment to study the production of 1 kg of fresh oyster mushrooms (*Pleurotus ostreatus*), from the generation of substrate materials through delivery to the distribution center. Our goals were to quantify the environmental impacts of a novel type of food production system, to find the aspects of production that contribute most to these impacts, and to assess the advantages and disadvantages of circular economy for this case study. In terms of climate change impact, the product system emitted 2.99-3.18 kg CO_2-eq./kg mushroom, and on-farm energy use was the top contributor to all impact categories except land use. Surprisingly, 31% of the climate change impacts came from transport throughout the supply chain, despite the local nature of the farm. Circular economy actions helped optimize the environmental performance by minimizing impacts from the use of materials, which were mostly upcycled. This

suggests that further improvements could be made by reducing energy consumption on the farm or by making the transport schemes more efficient, rather than continuing to focus on the type and source of materials used. This circular, urban farm had similar climate change impacts to classical, more linear systems, but these impacts could be largely reduced by implementing appropriate actions. These were identified and discussed with the farmers, factoring in their feasibility.

Keywords: life cycle assessment; mushroom; circular economy; urban agriculture; industrial ecology; sustainable food systems

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1. Introduction

The current food and agriculture system is considered by many to be environmentally unsustainable due to its substantial emissions, pollution and resource consumption (Campbell et al., 2017). Alternative food systems that ensure the well-being of people and the environment have been put forward (Kloppenburg et al., 1996), which call for improvements in the environmental sustainability compared to the mainstream systems. These can come from extensive and small scale farming, local food production, short supply chains, and circular economy (Forssell and Lankoski, 2015; Kiss et al., 2019).

The latter, circular economy, is particularly relevant in current research, practice, and policy, as evidenced by its major role in the European Green Deal and cities' action plans (European Commission, 2020; Mairie de Paris, 2017). Circular economy is a principle that comes from the discipline of industrial ecology, which generally aims to design industrial or human-made systems using principles from ecology as a means to attain sustainability (Tóth, 2019). The concept of circular economy emerged from the work of Boulding (1966) as a framework for managing limited resources in a closed system, such as the Earth, and it has gained attention in recent years from academics, policy makers, and the private sector (Merli et al., 2018). Circular economy evokes a departure from linear economies based on “take-produce-consume-discard” models, which assume unlimited resources and waste disposal facilities (Jurgilevich et al., 2016; Merli et al., 2018). Instead, circular economy focuses on closing material, energy and nutrient loops through “reducing, actively reusing, recycling and recovering materials” (Kirchherr et al., 2017). The principles of circular economy are not new, and this paradigm builds upon previous concepts relating to cleaner production, closing loops, and reduce-reuse-recycle (Tóth, 2019). Still, it goes beyond these concepts by considering them in multiple dimensions of sustainability, and by explicitly introducing the notion of full circularity. Scientific studies of circular economy have been done at the macro- (city, region, country), meso- (industrial park) and micro- (consumer, product, company) levels, and are often concerned with the environmental and/or economic sustainability of waste management and the agri-food sectors (Ghisellini et al., 2016; Kirchherr et al., 2017; Merli et al., 2018). Although circular economy can have holistic benefits to environmental, economic and socially sustainable development, we chose here to focus on the environmental dimension (Fassio and Tecco, 2019).

Agriculture has been identified as a relevant topic for implementation of circular economy due to its environmental sustainability issues, large amount of waste production, and important nutrient flows (Fassio and Tecco, 2019). A review of 40 circular practices from case studies in the agro-food sector found that the main circular practices employed relate to optimization, looping, and regeneration (Fassio and Tecco, 2019). Here, optimization focuses on removing waste from production systems by transforming materials regularly considered as waste into valuable inputs to another system without losing value, otherwise known as upcycling. Regeneration refers to a shift to renewable energy and materials, and looping aims to keep materials in closed loops (MacArthur et al., 2015). Within the food system, this can be implemented by utilizing food byproducts and waste to recycle nutrients, avoiding generation of waste altogether, and shifting diets towards foods that can be produced with minimum inputs (Jurgilevich et al., 2016). Collaboration between the food production and waste management sectors is especially important to keep nutrients and organic matter in productive loops rather than discard them as waste through landfilling or incineration.

Mushroom farming is a particularly appropriate activity to demonstrate the potential symbioses of circular economy. Many cultivated fungi naturally cycle organic matter and nutrients by decomposing organic waste and yielding edible mushrooms. The organic waste that mushrooms are grown on is transformed into a nutrient rich soil amendment that is rich in organic carbon, called spent mushroom substrate (SMS) (Grimm and Wösten, 2018; Stamets, 2000). This allows for symbioses in the inputs to the system, whereby mushroom farms can take up waste streams of materials such as straw and manure to give value to the waste and extract their remaining nutrients and organic matter (Sánchez, 2010). For example, Chance et al. (2018) present a mushroom farm that is highly symbiotic with other businesses in an industrial park, through upcycling waste products from beer brewing and coffee roasting. On the output side, SMS, which is essentially composted waste, has many uses as soil amendment, animal feed, biofuel material, wastewater treatment, and packaging material (Grimm and Wösten, 2018; Mohd Hanafi et al., 2018). Oyster mushrooms (*Pleurotus spp.*) have been shown to successfully grow on waste substrates that do not have other common recycling paths, including grape marc from wineries, waste from olive oil mills, and coffee ground waste recovered after the brewing phase (Koutrotsios et al., 2018; Murthy and Madhava Naidu, 2012). Spent coffee ground (SCG) use is unique because it is an urban waste. Its upcycling by urban and peri-urban mushroom farms would allow for a closed loop system with minimal distance between collaborating actors (waste collection, mushroom production and consumption points), and could place the production near the consumers. Furthermore, an estimated six million tons of SCGs are generated annually worldwide, making up between 16-35% of the food waste from restaurants, cafes and gas stations (Silvennoinen et al., 2015; Tokimoto et al., 2005). Although they can be upcycled by other methods, such as for animal feed, antioxidant extraction, and biofuel, they are typically not valorized and are treated in the regular waste stream (Kovalcik et al., 2018).

Evaluations of circular economy food production are necessary to test the actual environmental advantages of circularity, and to help design optimally sustainable systems. In a review of performance evaluations in this context, Sassanelli et al. (2019) found that life cycle assessment (LCA) was the most commonly used method. LCA is a standardized methodology and tool that models and evaluates systems through their entire life cycle, from extraction of raw materials through disposal (ISO 14040, 2006). Environmental LCA considers the outputs associated with the flows of material and energy in the life cycle of a product, and quantifies the related environmental impacts. Several LCAs of circular food production systems focus on using waste as an input (Dorr et al., 2017; Llorach-Massana et al., 2017), but to the best of our knowledge, no studies focus on mushroom production. Several studies perform LCAs for current food systems and, based on the outcomes, make recommendations for implementing circular strategies to reduce environmental impacts (Krishnan et al., 2020; Pagotto and Halog, 2016). Comparison between circular and conventional, linear systems points to mixed results, indicating that circular systems should not be considered better by default. For example, Fan et al. (2018) assessed pig farming in a circular agriculture system that also included hay, fish, dragon fruit, mushroom, biogas, and compost production. They found that environmental impacts were higher in the circular system than the traditional system by an average of 43% across 11 impact categories, and that removing some actors from the large network could improve environmental sustainability. Strazza et al. (2015) compared the production of conventional fish feed for aquaculture, made with crops and fish, with a circular option of fish feed derived from food waste, and found that the circular option had lower climate change impacts and energy and water demand by an average of approximately 60%. Also assessing the upcycling of food waste to agriculture, Oldfield et al. (2017) studied the valorization of tomato processing waste for annual preparation of agricultural soils (in a process called biosolarization), and found this circular option to be less environmentally impactful than the business-as-usual system by 20-23%. More LCA case studies in different contexts are needed to evaluate the actual contributions of circular economy agriculture to environmental sustainability.

In parallel, a number LCAs of typical mushroom production have been performed. Gunady et al. (2012) evaluated button mushroom (*Agaricus bisporus*), strawberry, and lettuce production using survey data from farmers in Australia, with a cradle-to-market scope. They found that most climate change impacts in the mushroom systems came from the pre-farm stage, from deliveries of materials for substrate including compost and peat (common substrate materials for button mushroom farming, as opposed to oyster mushrooms which can grow on organic waste). Leiva et al. (2015a) collected data from a button mushroom farm in Spain and performed a cradle-to-farm gate LCA. They found that on-farm energy use was the main driver for all impact categories. Specifically, this was from indoor climate control for most impacts, and from application of compost for climate change impacts. Robinson et al. (2018) performed a cradle-to-farm gate LCA of button mushroom production in the USA. They modeled a typical farm using survey responses from 22 mushroom farmers. They also found that on-farm energy use was the major contributor to several impact categories, and cited use for climate control, trucks, and machinery. Unlike the first two studies mentioned, Robinson et al. (2018) included emissions from the composting process that created substrate to cultivate mushrooms on, and found that it had an important contribution to climate change impacts (23%). The only LCA we found of oyster mushroom production was by Ueawiwatsakul et al. (2014), who collected data from 31 farms in Thailand and used a cradle-to-farm gate scope. The most impactful processes were emissions from burning firewood and fuel to sterilize the substrate, and transport of substrate materials (rice bran and sawdust). The small set of mushroom LCAs show variable CC results, from 2.13-5.0 kg CO_2 eq. / kg mushroom, suggesting the need for further research into this type of farming.

To help fill the knowledge gaps in circular agriculture and mushroom farming environmental impacts, we conducted an environmental LCA of a circular, urban oyster mushroom farm in a town neighboring Paris, France. Our goals were first to quantify the environmental impacts of this type of farm and find the most impactful phases of production. Our second goal was to investigate explicitly the circular economy aspects of the farm to understand their positive and negative contributions to environmental impacts. The farm case study grows oyster mushrooms (*Pleurotus ostreatus*) using SCGs collected from Paris as the bulk material for the substrate, in the place of typical substrate materials consisting of agricultural co-products such as straw (Sánchez, 2010). The waste product SMS is sold to local farmers who use it as a substrate amendment, and the mushrooms are delivered to a nearby distribution center in the wholesale market of Rungis and consumed mostly in Paris.

2. Methods

2.1. Case study description

The mushroom farm is situated on 1000 m^2 of land next to Paris in the Yvelines administrative department in France, and sources many materials from and delivers all of its product to the Paris region. Maintaining short supply chains and reusing urban waste to promote a circular economy are important to the farm's mission. This is evidenced first by the upcycling of SCGs. In 2018 alone the farm used approximately 30 tonnes of SCGs, diverting them from the municipal waste stream of Paris while extracting their remaining organic matter and nutrient contents. The farm's second main contribution to a circular economy comes from waste management, whereby SMS is sold to local farmers who pick it up from the farm and either compost it or directly spread it to agricultural fields as both an organic amendment and a fertilizer. It has even been used by farmers in the urban agriculture network of Paris and shown to be a soil amendment high in organic matter and nutrients (Grard et al., 2015).

The mushroom farm represents a short food supply chain because the major input material (SCGs) is sourced locally (about 35 km. away), the product is sold and consumed locally (about 45 km. away), and there are a reduced number of intermediaries between producer and consumer. The delivery of mushrooms is done daily by an employee who passes near the market every day on his commute home, and so involves frequent deliveries and small volumes. SCGs are delivered to the farm weekly, with the delivery truck returning empty and the frequency of deliveries limited by the amount that they can store, and the risk that large stocks of SCGs sitting on the farm are prone to fungal contamination. Frequent trips with low volumes of material is a regular characteristic of short supply chains, and can be economically and environmentally inefficient (Brunori et al., 2016; Schlich and Fleissner, 2005).

The cultivation of mushrooms follows typical growing practices, requiring approximately 2 months to fruit after being inoculated with mycelium (Sánchez, 2010). The substrate is made up mostly of SCGs, along with wood chips, agricultural lime, mycelium-inoculated rye seeds, and municipal tap water. The substrate materials are mixed, pasteurized using a large autoclave, and inoculated with mycelium, after which the mix is placed in 32 L plastic bags. Next, in the cultivation stage, bags are incubated for about 2 weeks at 70% relative humidity and 17°C and then spend 7 weeks at 93% relative humidity and 16.5°C. During this stage, contamination by competing fungi and bacteria is a major problem, leading to losses of nearly 25% of the bags of substrate prepared. Harvest is done manually throughout these 7 weeks, and occurs several times before the substrate is considered spent. In 2018 a total 8,728 kg of mushrooms were harvested, and during the study period the harvest was 1,253 kg of mushrooms. The mushrooms are packaged in small wooden crates (2 kg per crate) and delivered to the Rungis wholesale food market south of Paris, where they can be sold to local grocery stores and restaurants. The Rungis market is an essential food distribution source for Paris, with 40% of all food consumed in the city passing through Rungis (Mairie de Paris, 2016). The SMS is sold to local farmers who pick it up at the mushroom farm and apply it as a soil amendment.

2.2. Life cycle assessment

2.2.1. Goals and scope

The main goals of this LCA were to assess several environmental impacts of circular, urban mushroom cultivation, identify the aspects of the system that contribute the largest impacts, and evaluate the role of circular practices in the environmental performance. Comparisons to other mushroom LCAs are also presented. The functional unit was 1 kg fresh weight of oyster mushrooms, produced over a 2-month period at the end of 2018. Use of data from a 2 month period was justified because, although there are annual variations in production, they are related to holidays and social factors that affect resource use and food production, rather than climatic conditions. For example, there is lower mushroom production in July and August because of summer holidays, but there is proportionally lower energy and water consumption because of the decision to reduce production. A process-based, attributional LCA was performed, with a cradle-to-market scope. The system boundary is illustrated in Figure 1 and includes the extraction of raw materials and energy use used in the foreground and background of mushroom growing, delivery to the distribution center, and the waste treatment of consumed materials. Construction and waste treatment of machinery and infrastructure were excluded due to their assumed longevity and relatively small impacts (Martin and Molin, 2019).

Delivery from the distribution center to the final consumer was excluded due to constraints on data collection.

2.2.2. Life cycle inventory

Background processes were modelled using the Ecoinvent v3.5 database using the recycled content system model (Ecoinvent, 2018). Electricity use was modeled using the French grid. Information about foreground processes was collected from farm records, interviews about farm practices, water and energy bills, and technical specifications documents for machinery and purchased supplies. The life cycle inventory for mycelium production was taken from Leiva et al. (2015b), using Swiss integrated rye production. The life cycle inventory, showing inputs attributed per kilogram of mushroom, is compiled in Table 1, and a more detailed inventory with corresponding Ecoinvent process names is included in Table A1 in the Appendix.

To facilitate interpretation of the results, the production system was delineated chronologically into 4 life cycle stages, shown in Figure 1. The first stage was "Substrate materials" and included the production and acquisition of materials to compose the substrate on which mushrooms were cultivated, along with electricity from a refrigerator used to store mycelium. Next, the "Substrate preparation" stage involved preparing the substrate materials through mixing, gas-powered pasteurizing, and bagging, along with the plastic bags themselves. The "Cultivation" stage consisted of the inputs used during the 2 month period from inoculation to fruiting and harvest, such as water for cleaning rooms and maintaining humidity, and electricity from LED lights and air heating/cooling. Sanitary materials were counted, including lab coats that were washed and reused 5 times before disposal, and disposable gloves, hair nets and shoe covers.

Steel racks that held the hanging bags were also covered here, with an assumed lifetime of 30 years. Finally, the “Packaging and delivery” stage included wooden crates and the transport to deliver products to the distribution center, Rungis, 38 kilometers away.

2.2.3.Allocation procedures

SCGs used in the substrate were treated using the simple cut-off method (Ekvall and Tillman, 1997) to allocate their impacts to the system that was directly responsible for them, such as the café that used them to make coffee. As a result, the only burdens the mushroom farm is responsible for come from the transport of the grounds from their place of use to the farm site.

The farm produces a co-product along with oyster mushrooms: SMS. Allocation between co-products of a system is a notoriously debated issue in the LCA community, as several options exist but there is no consensus on which approach is best (Finkbeiner et al., 2014). System expansion with avoided burdens is a common and appropriate method, but it can require assumptions that are highly uncertain. According to this method, the system is expanded to include the alternative product that is displaced (or avoided) by the co-product of the system. It is assumed that the system’s co-product replaces the alternative product, resulting in negative (or avoided) production of the alternative product and negative environmental impacts (Vadenbo et al., 2017). However, this option would be problematic here because SMS provides many functions and does not clearly replace just one product. It is used as a substitute for composts, mineral fertilizer, or potting soil, and the effect of substituting for each of these products is extremely variable. To avoid making assumptions about such sensitive processes, economic allocation was used to distribute impacts based on the annual revenue from SMS and oyster mushrooms. We chose economic allocation because it appropriately represented the relationship and value partition between mushrooms and SMS. For example, mass allocation would not be appropriate here because the SMS produced has almost six times the mass of the mushrooms produced while carrying only a fraction of the market value of mushrooms. Thus, it appears inappropriate to assign SMS six times more impact than mushrooms. Accordingly, mushroom production at the farm was allocated 85% of the environmental impacts.

2.2.4. Carbon sequestration from SMS

The mushroom farm transforms a large amount of SCGs (30.3 tonnes in 2018) into SMS (51.3 tonnes fresh weight, 22.0 tonnes dry weight in 2018), which is used as a soil amendment. The SMS at this farm contains 86% organic matter (dry weight), and a significant portion of this is organic carbon (43%, according to Paredes et al. (2009)) that is immobilized in the soil and sequestered, avoiding the emission of CO_2 to the atmosphere. Part of this carbon sequestration benefit is attributed to the mushroom production, according to mass allocation between the co-products SMS and mushrooms (85% and 15% by mass, respectively), unlike allocation of impacts of inputs which was done economically. According to measurements of SMS characteristics from the farm and values in the literature (Medina et al., 2012; Paredes et al., 2009), the amount of CO_2 eq. per kilogram of mushroom that was sequestered in the soil rather than emitted to the atmosphere was calculated (see details in Appendix 1). The amount of CO_2 emissions avoided was entered as a negative emission of CO_2 to air in the SimaPro modelling software. Climate change results are presented with and without this sequestered carbon term.

2.2.5. Life cycle impact assessment

The impacts discussed in this study are climate change (CC), non-renewable energy demand (ED), water depletion (WD), land use (LU), and freshwater eutrophication (FE). These impact categories were chosen because they are important agricultural-related burdens. Additionally, they capture the food-energy-water nexus, which is an increasingly prevalent conceptual framework that highlights the interdependency of these essential resources that have large consumption and are vulnerable in cities (Garcia and You, 2016). The impacts were modeled as midpoint indicators using SimaPro 9.0 software and several impact assessment methods, as described below.

CC, WD, LU and FE were modeled using the Environmental Footprint 2.0 method (European Commission, 2017). The specific methods are the IPCC 2013 100-year model for CC (IPCC, 2013), the EUTREND model for FE (same as the model used in ReCiPe 2008 (Goedkoop et al., 2009)), the soil quality index based on LANCA for LU (Beck et al., 2010), and the AWARE method for WD (Ansorge and Beránková, 2017). Although these methods were selected as the best available, some of them are more accepted than others. WD and LU, for example, were given the lowest recommendation level of 3, which means they are the recommended methods but should be used with caution. The FE model has a recommendation level of 2, defined as needing some improvements, and the CC model received a recommendation level of 1, which is recommended and satisfactory.

ED was modeled using the single-issue characterization method Cumulative Energy Demand V1.11 (MJ), and the sum of the non-renewable fossil, nuclear, and biomass energy demand are used here. It is important to report ED impacts because, although they are generally related to CC impacts, they are not susceptible to variation in local or regional electricity grids, which can have large effects on CC results.

A common issue in the LCA literature is that different impact categories are reported and various impact assessment models are used, rendering results difficult to compare from one study to another. To address this, the results for all Environmental Footprint impact and Cumulative Energy Demand categories are reported in Tables A2 and A3 in the Appendix, although they are not all discussed in this paper. Additionally, results from other common impact assessment methods, ReCiPe 2016 and 2008 (hierarchical, midpoint) (Goedkoop et al., 2009; Huijbregts et al., 2017) and CML (baseline, v4.7) (Guinée et al., 2002) are reported in Tables A4, A5 and A6 in the Appendix for the purpose of comparison to future studies.

2.3. Sensitivity Analyses

Sensitivity analyses are commonly done to evaluate the significance of decisions made regarding the modeling of the system. We performed two sensitivity analyses: first on the electricity grid, substituting electricity mixes for neighboring countries Germany, Spain and Italy – given the unique characteristics of the French mix, with a predominance of nuclear energy. Next we tested the importance of our decision to use economic allocation for the co-product SMS rather than system expansion with avoided burdens, because allocation is often a sensitive issue in LCA. We compared our results using economic allocation to results from substituting mineral fertilizer for SMS to test how sensitive the results were to this choice. Assumptions and calculations for identifying the quantity of avoided fertilizer from equivalent nutrients in SMS were taken from Robinson et al. (2018).

2.4. Alternative Scenarios

We modeled alternative scenarios to assess how impacts would change if the mushroom production system changed. The first involved a 50% reduction in the frequency of delivery for SCGs, mycelium, and mushrooms, with twice the volume transported each trip. This was to illuminate the potential efficiency issues of transportation in this short food supply chain. It is generally accepted that short food supply chains can suffer from increased environmental and economic impacts from inefficiencies when shipping low volumes of food on the road, which in this case is also coupled with frequent deliveries (Brunori et al., 2016).

The second alternative scenario tested a more typical oyster mushroom substrate: wheat straw. Mushrooms can grow successfully on a wide variety of substrates, and are typically cultivated on agricultural waste or byproducts such as cotton seed hulls, corn cobs, sorghum stalks, or coconut shells. A common and successful material is straw (Sánchez, 2010). From this perspective, the valorization of SCGs as the bulk substrate material at this case study farm is unique to a commercial farm of this size, and is done because of the farmers' commitment to circular economy and the opportunity of being situated nearby a large city with a high concentration of coffee consumption. A comparison was made to production with a more typical substrate composed largely of straw (43% wheat straw, 53% water, 3% mycelium and 1% $CaCO_3$). The life cycle inventory for wheat straw was taken from the Ecoinvent database, where an economic-based allocation was done to distribute 7-10% of the impacts from wheat grain production (Nemecek and Kägi, 2007). It was assumed that all other on-farm practices and the final yield remained the same. The straw was transported twice the distance as the SCGs (65 km away) because it is not an urban product. It was delivered every 3 weeks, rather than every week for the SCGs, because there is less risk of stocks of straw becoming contaminated.

The third alternative scenario investigated the effect of the overall farm yield by using the maximum monthly value that the farm achieved in 2018. In agricultural LCA studies, where the functional unit is related to food production, results are usually quite sensitive to the yield (Notarnicola et al., 2015). Mushroom farming can have highly variable yields over time due to losses from pests and infection of substrate (Stamets, 2000), and indeed the case study farm incurred losses between 5 and 66% in 2018 (measured in percent of prepared bags of substrate that did not go on to yield mushrooms). According to farmers, the minimum loss rate has been achieved simply through rigorously following the sanitation protocol, including washing hands, wearing lab coats and shoe covers, and keeping doors of the cultivation rooms closed. Average loss rates were used in this LCA study, but since minimum loss rates are achievable with no other changes in production, a scenario with optimal production was modeled using the minimum loss rate recorded in 2018 (5%).

3. Results

The impacts of production of 1 kilogram of oyster mushrooms are presented in Table 2. The percent contribution of each life cycle stage to the overall life-cycle impacts is shown in Figure 2**Erreur ! Source du renvoi introuvable.**. No single life cycle stage dominated all impact categories, but the substrate transformation and cultivation stages were both dominating contributors to several impact categories. The packaging and delivery stage was extremely important in land occupation, and the substrate materials stage generally had modest contributions of 8-27% but was not the major factor in any impact category.

Substrate transformation was the major contributor to CC impacts throughout the life cycle, accounting for 44% of the greenhouse gas (GHG) emissions. In fact, a single process within this stage, gas consumption for pasteurization in the autoclave, accounted for 43% of the CC impacts for the entire life cycle. Substrate materials contributed 24% of the CC impacts over the life cycle, mostly from the frequent delivery of materials. The cultivation stage, which was comprised nearly exclusively of electricity inputs, accounted for 13% of the CC impacts, largely from air temperature regulation. Packaging and delivery of the final product had a modest contribution of 13% to CC impacts, with transport contributing about twice as much as the packaging materials. Finally, carbon sequestration of SMS accounted for 6% of CC impacts.

Contributions to CC were broken down by process type in addition to life cycle stage. The process categories considered were gas, electricity, transport, and materials. Transport included weekly delivery of SCGs and mycelium, infrequent delivery of wood chips and $CaCO_3$, and daily delivery of mushrooms to the market. Material included impacts from producing the materials themselves. Electricity and gas included their use on the farm, and the background processes embedded in the database. The categories of gas, electricity, transport, and material contributed 43%, 14%, 31%, and 12%, respectively (Figure 3). Transport from short supply chains, which here were the SCGs and mushroom delivery, contribute 16% of the CC impacts (7 and 9% respectively).

Carbon sequestration from SMS amounted to 0.19 kg CO_2 eq/kg mushroom stored in the soil. This amount was subtracted from the CC impact to give a net CC impact of 2.99 kg CO_2/kg mushroom, which was a 6% abatement. This reduction was rather small because most of the benefits from carbon sequestration were actually allocated to the SMS co-product instead of the mushrooms.

The cultivation stage, with its many electricity inputs, drove the ED with a 60% share. Specifically, air temperature regulation and LED lighting were the largest contributors, with 38% and 13% of the ED over the entire life cycle, respectively. Although gas powered pasteurization drove the CC impacts, which are often closely linked with ED, it only contributed 15% of the ED impacts. This is because the electricity grid in France is largely composed of nuclear energy rather than fossil fuels, so the processes using electricity rather than gas benefitted from low CC impacts (International Energy Agency, 2017).

The direct land occupation of the farm site was small compared to the demands on land in the background system, contributing 12% and 88%, respectively. LU impacts were mostly from wood for wooden crates, used as packaging, which contributed 58% of impacts. The remaining LU impacts came mostly from agricultural production of rye, which contributed 22% of impacts and was used in the production of mycelium for substrate materials.

WD was driven by a variety of different processes with water use occurring in the both foreground and background systems. Most of the contributions came from the cultivation stage (69%), due to water demands from cleaning rooms (where the production rooms are periodically washed down with a hose), humidification of cultivation rooms, and air temperature regulation. The water used for the room cleaning and humidification was tap water used on-site at the farm, while for air temperature regulation the water used was from electricity production in the background system. Most of the water use can be placed in one of 3 categories: electricity, on-site tap water, or embodied water in the wooden crates (Table 3).

Impacts to FE were driven by the cultivation stage, mostly from electricity production, with 41% of the total impacts. Other sources of FE came from the transport in the substrate materials and packaging and delivery stages, accounting for 17% and 14% of total FE impacts, respectively.

3.1. Sensitivity analyses

If the same production system were located in and used the electricity mixes of neighboring countries Germany, Italy, or Spain, the CC impacts (with carbon sequestration) would increase to 7.65, 6.00, and 5.29 kg CO_2 eq/ kg mushroom, respectively. However, the ED would decrease by 16-31%, likely due to differing efficiencies of electricity production.

In the second sensitivity analysis, results showed differences of 5-22% in impacts between the two allocation methods, showing mixed responses across impact categories (Figure 4). WD was the most sensitive with a 22% difference between allocation methods, whereas CC was the least affected. One method did not have consistently higher or lower impacts than the other, and the choice of allocation system had mixed effects overall.

3.2. Alternative scenarios

In the first alternative scenario we modeled a more efficient transport scheme where deliveries were done less frequently but a larger volume was shipped each time. Despite the farm's focus on local material sourcing and delivery of mushrooms, there was a substantial impact from short supply chain transport to the total CC impacts (16%). If the weekly deliveries of SCGs and mycelium were cut in half to delivery every 2 weeks, the CC impact (with carbon sequestration) would decrease by 10% to 2.70 kg CO_2 eq. Further reductions of 5% could be made by harvesting and delivering mushrooms every two days, resulting in 2.55 kg CO_2 eq. emitted per kg of mushrooms. These adjustments to the supply chain would result in a net reduction of GHG emissions of 15%.

Next we modeled a scenario where straw was used instead of SCGs, because it is a more typical substrate material for oyster mushroom production. Production with the straw-based substrate had much larger impacts than a SCG-based substrate for FE (33% larger) and LU (784% larger), and slightly larger impacts for WD (6%). The cultivation of straw accounted for a large majority of these impacts, which was expected because they are all closely tied to agricultural production, and straw is a by-product of grain production. CC and ED impacts were lower for the straw-based substrate by 5% and 3%, respectively. CC and ED impacts are not largely changed by this substitution of straw because, like SCGs, straw is a byproduct of another system with little value. Therefore, straw was allocated a minor share of these impacts (7-10%). In both scenarios the CC and ED impacts of materials themselves are small. The delivery logistics of those materials emerge as the more important factor driving impacts, where the straw-based substrate scenario has less frequent deliveries than the baseline SCG scenario.

Finally we evaluated the impacts of a scenario with realistically increased mushroom yields, using the minimum loss rate recorded on the farm. This linearly reduced all environmental impacts by 43-46%, except for LU, which decreased by 19%. LU responded differently because it is largely affected by wooden crate use for packaging, and the amount of packaging was one of the few inputs that increased with increased in production. For example, the resulting CC impacts with and without carbon sequestration dropped to 1.71 and 1.81 kg CO_2 eq. respectively.

4. Discussion

4.1. Effects of circular economy and short supply chains

The mushroom farm had low CC impacts from the materials used, accounting for only 12% of the total impact. This suggests that the circular economy model, which was prioritized in the farm design by focusing on upcycling opportunities, was effective at minimizing its impacts. Furthermore, we hypothesized that upcycling of SCGs represented a “more circular” production system than more commonly-used agricultural byproducts such as straw. A comparison to oyster mushroom cultivation with straw showed this was true for some impacts (WD, LU and FE), but other impacts (ED and CC) were not largely affected, because reusing straw (a byproduct) is also a circular system itself. However, the farm-level scope of this LCA did not allow us to model other benefits of using SCGs that would likely be reflected in the CC and ED categories. In particular, the diversion of SCGs away from incineration can generally be considered a net benefit despite a possible energy-generation from incineration (Beylot and Villeneuve, 2013), whereas straw would not be incinerated because it has many applications and its own market. Specifically, municipal waste collection and treatment of the SCGs used per kilogram of mushroom at the farm, using the average French waste treatment mix, would incur an emission of 1.98 kg CO_2 eq /kg mushroom, which is substantial compared to the impacts of using the same amount of SCGs for mushroom production (2.99 kg CO_2 eq /kg mushroom).

Additionally, the use of urban-generated waste (SCGs) within urban and peri-urban agriculture can create new links between local businesses and promote innovation. Using this scope of study, it is difficult to evaluate the full advantages of upcycling SCGs.

The circular approach of using SMS as a soil amendment is reflected in the results, in that there were no burdens from waste management and there were some benefits from carbon sequestration. However the actual impact of avoided waste management of SMS, and the corresponding credits to the farm, are not explicitly shown in our results, according to our modeling decisions. Furthermore, the farm's intentional placement in a peri-urban area nearby the farms that use SMS allows for reduced transport distances, which were not attributed to the mushroom farm given the system boundaries we set.

Regarding the short supply chain aspect of the farm, it appears that the environmental benefits of a reduced distance for transport is offset by frequent trips with small volumes. Average food supply chains have transport processes contributing moderately to CC impacts, with 6-11% through the entire life cycle and specifically 4% from delivery to the final distribution point (Robinson et al., 2018; Weber and Matthews, 2008). Transport at the mushroom farm incurred significant CC impacts, with a 31% share overall, in which 10% came from the final delivery of the product. Although an emphasis is often placed on the delivery of the final product, impacts from transportation of input materials outweighed product deliveries, as has been found in other studies (Martin and Molin, 2019). These contribution calculations only consider the transport in the foreground system, and not transport processes embedded in the database representing the background system, so the actual contribution of transport could be even larger. Our findings support claims that proximity alone is not a sufficient indicator of environmental sustainability, and individual attributes and practices of the system can play a more important role (Edwards-Jones et al., 2008; Kiss et al., 2019; Mundler and Rumpus, 2012).

Overall, processes related to materials from circular economy and transport from short supply chains are not the major sources of impacts across the life cycle. Rather, on-site energy consumption from gas and electricity are extremely impactful. Efforts to improve energy efficiency, or reduce energy use altogether, would likely have more significant benefits to environmental sustainability than making changes to the substrate recipe and changing materials, as the farm currently is focusing on. The most impactful and easiest to implement measures for reducing impacts actually do not require changes in material, transportation or implementing circular economy principles, but adjustments to farmers' behavior to avoid pests and diseases so as to increase the mushroom yield.

4.2. Energy source and climate change

ED at the mushroom farm was relatively high, and was comparable with the ED of greens and herbs in an indoor high-tech hydroponic system (Pennisi et al., 2019). They calculated ED per kilogram in 20 different production systems, and found a range of 53-227 MJ/kg, with an average of 145 MJ/kg, compared to 143 MJ/kg of mushroom found here. Despite this intense ED here, the CC impacts were not proportionally large, compared to other mushroom LCA studies. This is due to the particular electricity grid of France that was used in this study, which is composed of 78% nuclear energy (Ecoinvent, 2018; International Energy Agency, 2017). This allowed for relatively low GHG emissions at the expense of ionizing radiation and other impacts, which were not discussed but are presented in Table A1 in the Appendix. In the case of indoor farming, where large amounts of energy are used, the electricity grid can have a large influence on the resulting CC impacts. In another mushroom farming LCA, Robinson et al. (2018) found important variations in the CC impacts when looking at regions of the USA with different energy grids using more or less coal or renewable energy. Considering LCAs of indoor hydroponic vegetable farming, which similarly use large amounts of energy, Martin and Molin (2019) found approximately 33% increases in CC impacts when using a Nordic electricity mix rather than a Swedish mix in a farm growing basil. In an indoor hydroponic farm growing leafy greens, Romeo et al. (2018) found a decrease in CC impacts of 60% when modeling the difference between the French electricity grid and a wind powered electricity source. This variability highlights the importance of reporting ED in LCAs because this metric is not sensitive to geographic variation in electricity grids.

4.3. Comparison to other mushroom LCAs

It is difficult to directly compare our results to other mushroom LCA studies because most have focused on the common button mushroom (*Agaricus bisporus*), which has different cultivation practices and substrate materials from the oyster mushroom studied here. Additionally, differences in regional and farm-specific practices, background systems, and modelling choices can always lead to differences in results, with unknown importance. Nonetheless, it is useful to cautiously present other mushroom LCA results to position our work.

The only other published oyster mushroom LCA comes from production in Thailand at farms of multiple sizes (Ueawiwatsakul et al., 2014). Our case study is comparable to the small farm size they defined (<20,000 kilograms mushrooms produced per year), and major differences include the substrate, which was composed largely of sawdust in Thailand, and the generation of steam from firewood combustion. Despite these differences, similar CC impacts were calculated, amounting to 3.01 kg CO_2 eq. /kg mushroom (Figure 5). However, medium sized farms had larger impacts, of 5.0 kg CO_2 eq. /kg mushroom. They also found large burdens from sterilization of substrate and transport of substrate materials, although due to unique local/regional constraints.

More studies are available for the production of the button mushroom (*Agaricus bisporus*) because it is a more common mushroom. Gunady et al. (2012) assessed button mushroom cultivation in Western Australia and calculated GHG emissions close to ours (at 2.75 kg CO_2 eq./kg mushroom), and found that the largest contribution was from transportation of raw materials, especially the regular transportation of compost from 46 km away. To reduce this impact, they suggested using energy efficient and low GHG fuels, increasing the load factor of trucks to 100%, and avoiding an empty return. They did not mention reducing the frequency of material delivery. In Leiva et al.'s (2015a) LCA of button mushroom production in Spain, CC impacts amounted to 4.42 kg CO_2 eq./kg mushroom, largely due to energy consumption during the growing process and distribution. An LCA of button mushroom production in the USA by Robinson et al. (2018) showed smaller CC impacts between 2.13-2.95 kg CO_2 eq./kg mushroom. Electricity use, fuel consumption and methane from compost emissions made up the majority of the impacts. Total transport emissions only contributed 6-9% of CC impacts, which further contrasts with the high contribution of transport in our study (31%) despite the peri-urban farm using mostly locally sourced materials.

Oyster and button mushrooms have different nutritional and energy contents, with 33 and 22 kcal/kilogram, respectively (U.S. Department of Agriculture and Agricultural Research Service, 2019). Comparing CC results based on energy content, rather than mass, shows oyster mushrooms performing slightly better than button mushrooms (Figure 5). This concurrence evidences the robustness of our comparison, and supports the conclusion that CC impacts were within the range of other mushroom farms.

4.4. Considerations for LCA modeling

The boundary of the system excluded delivery to the final consumer, which was a limitation because this can be an impactful stage (Mundler and Rumpus, 2012). Additionally, we used data from the farm for a 2 month period of production, which risks being unrepresentative of the annual production. However we verified that, although this was one of the most productive periods for the farm during 2018, a proportionally large amount of materials and energy were used as well. Finally, any study on sustainability is limited when it only considers one aspect, where here we focused on environmental sustainability. An inclusion of economic and social aspects would be holistic and ideal, but was outside the scope of this study.

It should be noted that a system modeling choice likely has a large impact here: the decision to treat SCGs, a recycled input, using Ekvall and Tillman's (1997) simple cut off method instead of system expansion and avoided burdens. This choice is necessary because SCGs are a recycled product from the system that created both a beverage in the product's first life cycle, and a mushroom cultivation substrate in its second life cycle. The ISO recommendations for allocation are difficult to apply here (with the following hierarchy: subdivision, system expansion, physical/causal relationships, economic) because the relationship between this primary product and the recycled product is unclear (ISO, 2006). In this example, if we were to use the system expansion method to include the avoided burden of waste treatment of SCGs, then the impacts of the SCG life cycle must also be attributed. In other words, in order to assign positive impacts (avoided burdens) to SCGs, they must also be assigned their fair share of negative impacts as well. To assign those impacts, an allocation must be done between the coffee grounds for making coffee (product of first life cycle) and the recycled SCGs (product second life cycle). There is no satisfactory way to allocate between these two product life cycles and assign negative impacts, so positive impacts from avoided burdens cannot fairly be assigned, and the cut-off method emerges as the most reasonable solution.

4.5. LCA for circular economy

Several benefits of a circular approach could not be explicitly quantified and highlighted in this study due to our consideration of just the mushroom farm, as opposed to, for example, the cafés producing SCGs and the mushroom farm and the farms applying SMS. One such benefit was the avoided waste treatment of SCGs, which was not included. Additionally, in order to reduce environmental impacts, the farm was established in a peri-urban area to balance distance between urban consumers of fresh mushrooms and peri-urban farmers using SMS. Because the SMS exits the system boundary once the farmers pick it up, this reduced distance was not reflected in the results, although it is a consequence of a choice by the farm. In another LCA of a circular food production system, Strazza et al. (2015) assessed the production of fish feed from food waste on a cruise ship. Taking a similar limited, sub-system only approach, they also did not assign credits for the avoided burden of food waste management when it was upcycled, but acknowledge that the disposal of this organic waste in a landfill would be a significant driver of environmental impacts. Our results suggest that the application of LCA in agricultural circular economy systems is restrictive when applied to an isolated subsystem, such as one farm. Indeed, circular economies are composed of a complex network of actors, and studying only one actor does not capture the beneficial exchanges that may be placed outside of their system boundary and inside the system of another (Zhang et al., 2013). An approach that includes the activities of several actors in a circular economy could be better suited to capture the total advantages of circularity in complex systems (Fan et al., 2018; Oldfield et al., 2017). Therefore, we recommend that when aiming to study circular economy aspects with LCA, a network-level scope should be taken.

4.6. Responses from the mushroom farm

We partnered with a functioning commercial farm and used data from real cultivation practices, rather than a research farm, pilot project, or relying heavily on data from the literature. In addition to the scientific value of this work, we hoped to provide meaningful insight and decision support for the farmers, who were concerned about the environmental sustainability of their practices and looking for feasible paths to improve. An academic-oriented LCA may not naturally generate results that are most interesting to the farmers. For example, because we were interested in the short supply chain aspect of the farm, we modeled an alternative scenario with reduced delivery frequency that reduces CC impacts by 15%. The farmers quickly rejected this strategy because their oyster mushrooms must be delivered daily, as they are the only provider of this specialty product to the market and are constrained by customer demand. SCGs and mycelium could not be delivered in larger quantities because they would not have the space to store them, and because the risk of pathogen contamination would increase. The most feasible improvement, according to the farmers, is the increased yield scenario, where simple sanitary actions by the workers could reduce contamination, attain their highest production rates from 2018, and reduce all impacts by 43-46%. Although they were already aware that they should address the issue of contamination, they said that these results have strongly motivated them and their workers to make it a top priority. One unexpected result was the importance of gas pasteurization to CC, and in response the farmers are exploring ways to mitigate it by contacting the manufacturer of the pasteurization machine to adjust settings, insulating the machine, and installing an electricity-powered machine in a new farm under development. Our experience highlights the importance of partnering with functioning, commercial enterprises and maintaining open dialogues with farmers to consider not only the academic but also the practical outcomes of this type of research.

5. Conclusion

We conducted an LCA of the production of 1 kg of oyster mushrooms at a circular, urban farm next to Paris. Our goal of quantifying the environmental impacts and identifying the most impactful parts of production yielded valuable results and insight. On-farm energy use emerged as the most important activity for most impact categories, followed by transportation throughout the life cycle. The use of materials had low impacts in most impact categories due to the emphasis put on upcycling in the farm’s production design. However, our second goal of investigating the circular economy advantages and disadvantages of the system was met with limited success. This was because our decision to study only the farm as an isolated component of a network of actors excluded several processes that may have large environmental impacts, positive or negative. The tradeoff here was that we were able to study activities at the urban mushroom farm in greater detail, which was valuable because, to the best of our knowledge, an LCA has not been done before on this novel type of food production.

Mushroom farming is indeed a relevant application of circular economy and provides many opportunities for closing material and energy loops. The largest improvements in environmental performance could come from an increased commitment to sanitation practices, which would minimize mushroom losses and maximize yield. The circular approaches adopted at the mushroom farm contributed to environmental sustainability, but on-farm energy use was more important in many impact categories. Compared to more typical mushroom farms studied in other LCAs, this farm had similar CC impacts. However, there is potential for considerably reduced impacts if high mushroom yields can be maintained. Comparing different input materials showed large environmental advantages of using SCGs instead of straw. In some cases of circular food production systems, the most significant enhancements to environmental sustainability may come from efficiency improvements within the system rather than further integrating circular principles.

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Figures and Tables

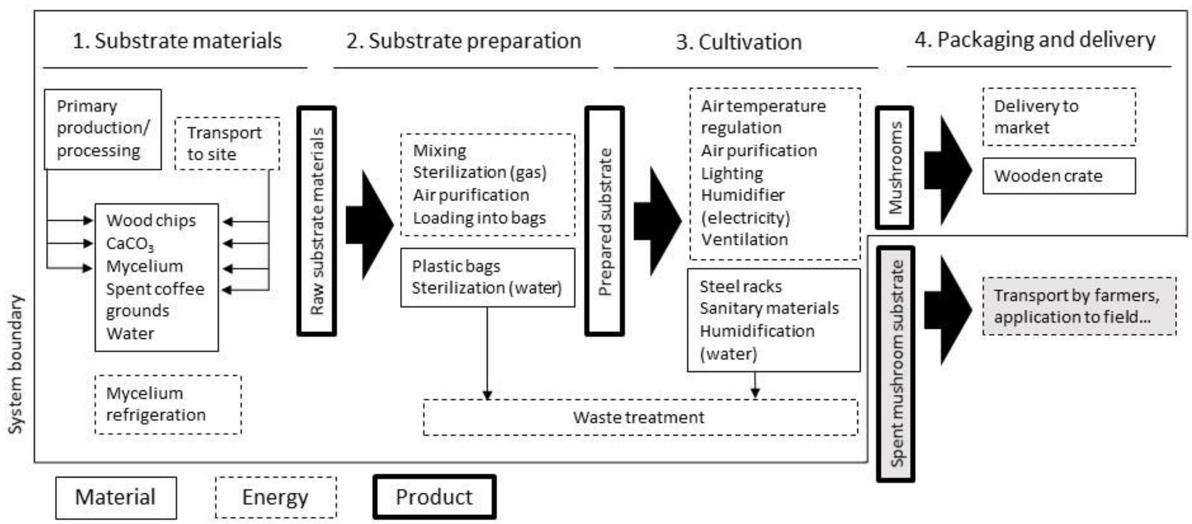

Figure 1: The process diagram of production at the mushroom farm shows what was included in the system boundary, and how life cycle stages were delineated.

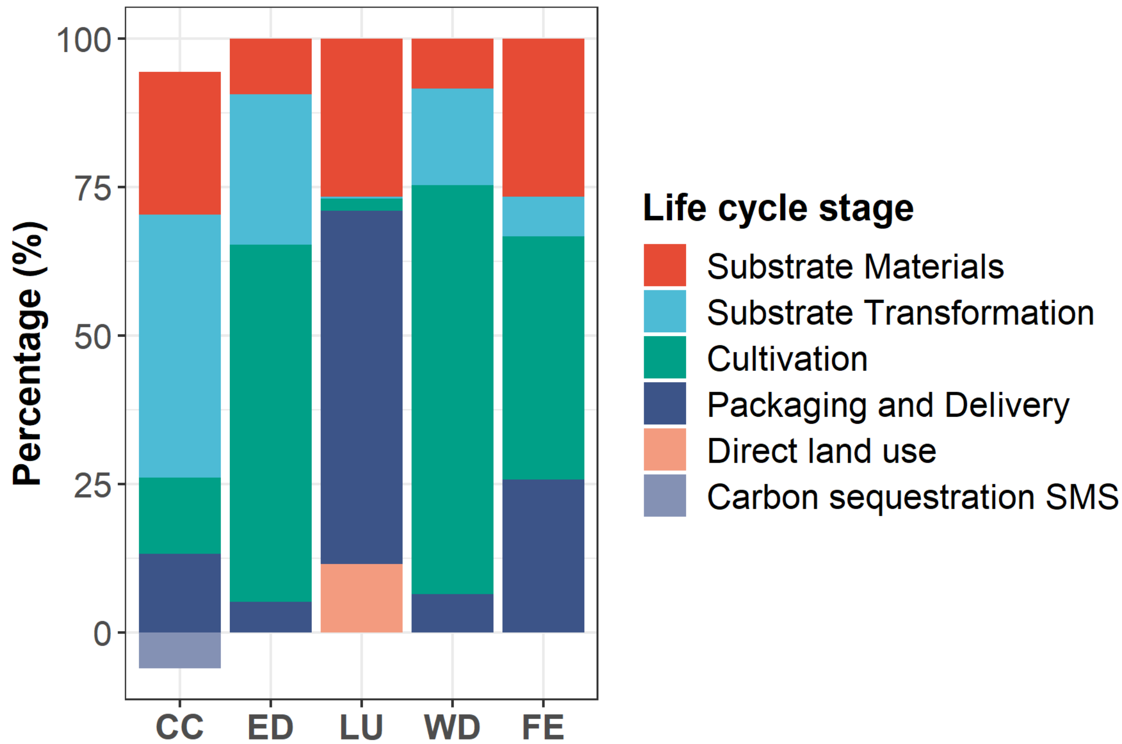

Figure 2 The contribution of each life cycle stage to each impact category is shown. The impact categories are climate change (CC), non-renewable energy demand (ED), land use (LU), water depletion (WD), and freshwater eutrophication (FE).

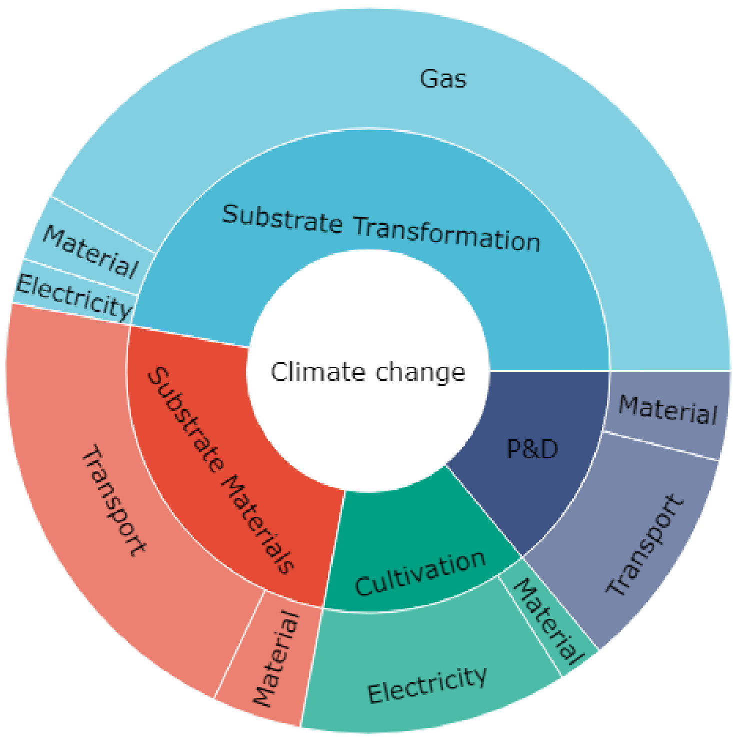

Figure 3 The proportion of climate change impacts are broken down by life cycle stage in the inner circle, and by process type in the outer circle. The abbreviation P&D stands for "Packaging and Delivery".

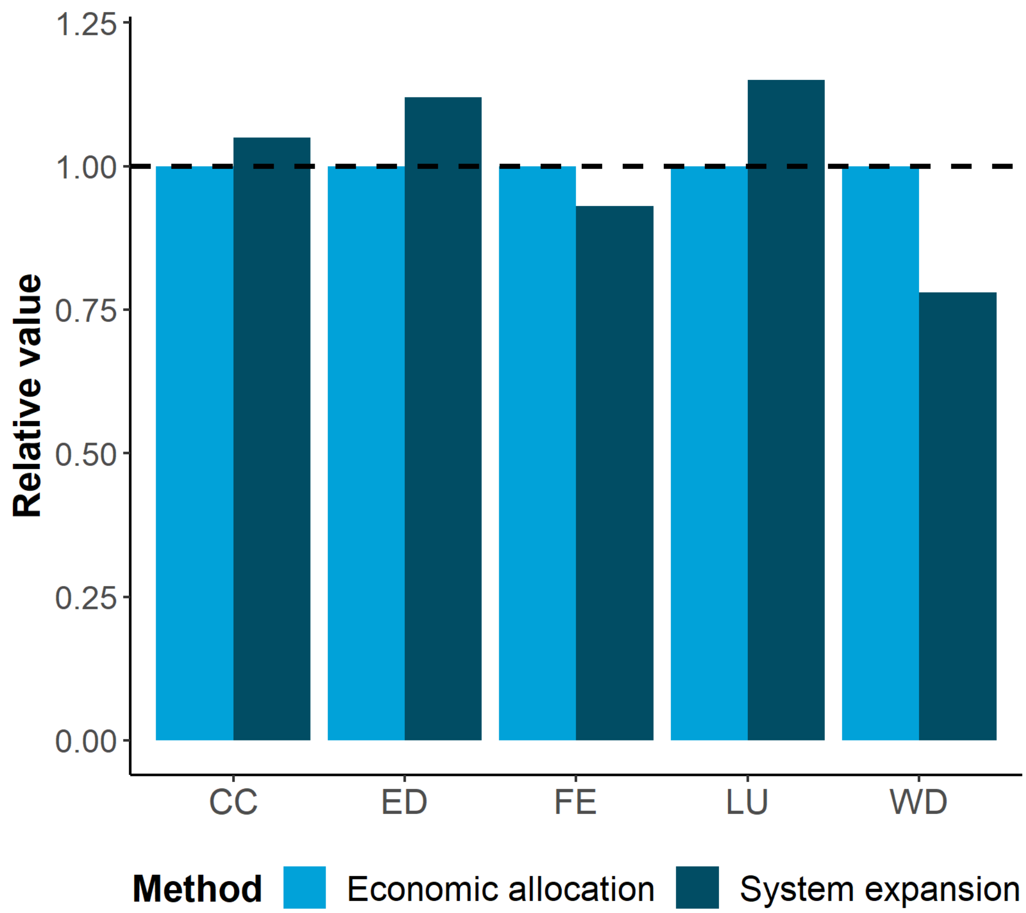

Figure 4 Impacts are compared between use of economic allocation (the main method used in this study) and an alternative method, system expansion, to treat the co-product spent mushroom substrate. The impact categories are cliamte change (CC), non-renewable energy demand (ED), land use (LU), water depletion (WD), and freshwater eutrophication (FE). For some impact categories, there is a large difference between allocation methods, and for some there is hardly any difference.

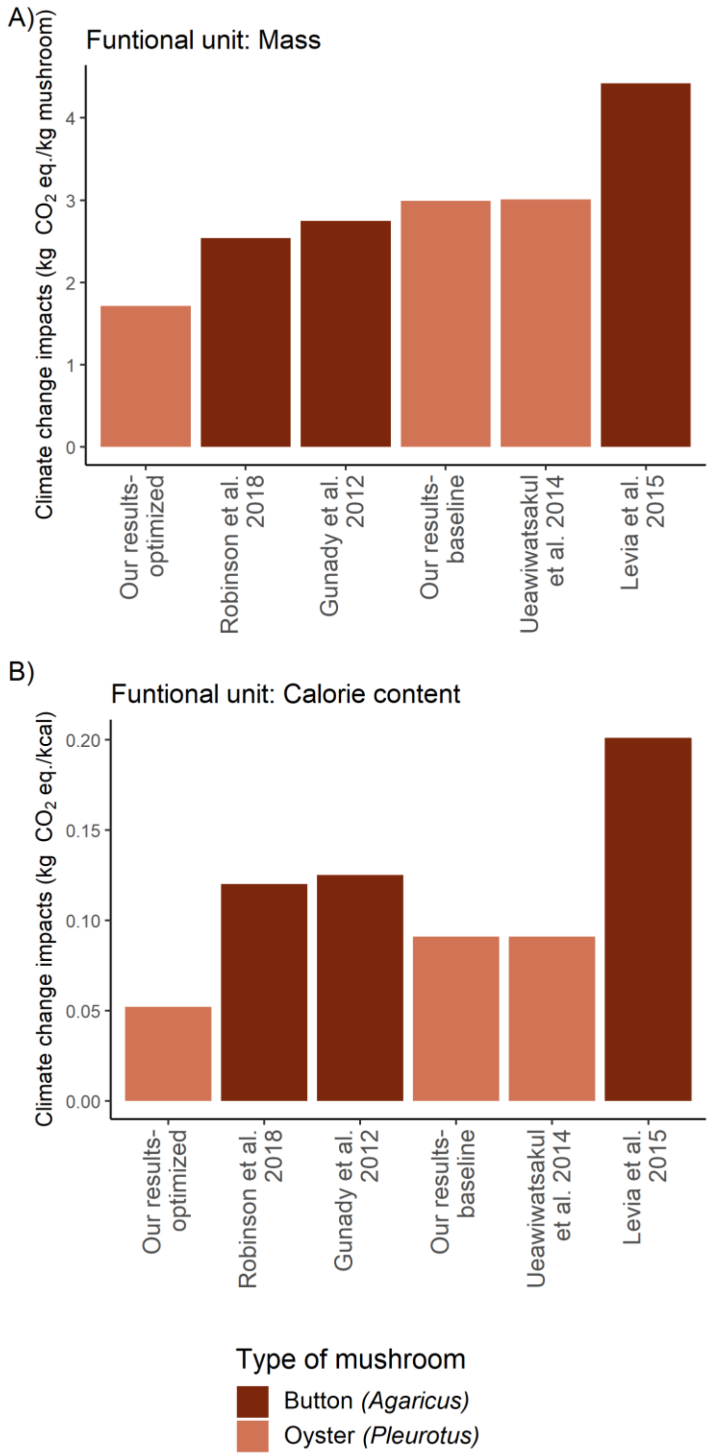

Figure 5 Comparing the climate change impacts calculated in this study to the results from other mushroom LCAs showed that the baseline scenario for the circular, urban farm performed similarly to other mushroom farms. However, under the optimized yield scenario, impacts were much smaller at the circular urban farm. When using calorie content as a functional unit instead of mass, oyster mushrooms perform slightly better than button mushrooms.

Life cycle stage	Input	Material	Value per FU	Unit
Substrate materials	Coffee grounds	Transport, 3.7-7.5 ton lorry (EURO 5)	435.2	kgkm
	Wooden chips	Wood chips, as a byproduct	1.500	kg
		Transport, 3.7-7.5 ton lorry (EURO 5)	145.2	kgkm
	$CaCO_3$	Lime	0.063	kg
		Transport, 3.7-7.5 ton lorry (EURO 5)	0.535	kgkm
	Mycelium	Mycelium inoculated rye seeds	0.358	kg
		Transport, 3.7-7.5 ton lorry (EURO 5)	708.8	kgkm
		Electricity (for refrigeration), French grid	0.012	kWh
	Water	Tap water	1.137	kg
Substrate transformation	Air purification	Electricity, French grid	0.132	kWh
	Conveyor belt	Electricity, French grid	0.079	kWh
	Substrate mixing	Electricity, French grid	0.552	kWh
	Substrate cooling	Electricity, French grid	0.110	kWh
	Sterilization: Gas	Sour gas, global average	5.534	kWh
	Sterilization: Water	Tap water	5.765	kg
	Plastic bags	Polyethylene, low density	0.032	kg
	Air purification	Electricity, French grid	0.188	kWh
Cultivation	Air temperature regulation	Electricity, French grid	4.403	kWh
	Humidifier	Electricity, French grid	0.117	kWh
	LED lighting	Electricity, French grid	1.539	kWh
	Ventilation	Electricity, French grid	0.478	kWh
	Water	Tap water	19.461	kg
	Steel racks	Steel, low-alloyed	0.0082	kg
		Polypropylene	0.0007	kg

	Sanitary materials	Polyethylene, low density	0.0012	kg
		Polyethylene, high density	0.0016	kg
		Synthetic rubber	0.0019	kg
Packaging and delivery	Wood crates	Plywood, for indoor use	0.186	kg
		Transport, 3.7-7.5 ton lorry (EURO 5)	61.801	kgkm
	Delivery	Transport, passenger car, large size, diesel (EURO 5)	0.772	km

Table 1 The full life cycle inventory for the production of 1 kg of mushrooms is shown, separated by life cycle stages. The economic allocation between the farm's two products- mushrooms and spent mushroom substrate- has already been applied, giving the mushroom system 84.8% of all material and energy inputs.

Impact category	**Value**	**Unit**
Climate change (with C seq.)	2.99	kg CO_2 eq.
Climate change (without C seq.)	3.18	kg CO_2 eq.
Non-renewable energy demand	143	MJ
Land use	169	Pt.
Water scarcity	2.42	m^3 depriv.
Freshwater eutrophication	4.65E-04	kg P eq.

Table 2 Life cycle impact assessment results are shown at the level of characterization. Climate change impacts are presented with and without the carbon sequestration contribution from spent mushroom substrate.

	Substrate Materials	Substrate Transformation	Cultivation	Packaging and delivery	Sum
Industrial water (electricity)	1%	5%	34%	0%	40%
Tap water (on site)	3%	10%	35%	0%	48%
Wooden crates	0%	0%	0%	5%	5%
Other	4%	1%	0%	2%	7%
Sum	8%	16%	69%	7%	100%

Table 3 There was important water scarcity impacts in the foreground system from tap water use on the farm, and in the background system from electricity generation. Wooden crates, used for packaging, had particularly high embodied water scarcity impacts.

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