THESIS

LIFE CYCLE ENVIRONMENTAL IMPACTS OF UTILIZING HEMP SEED MEAL AS A PROTEIN SOURCE IN SHEEP FEEDLOT RATIONS

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ABSTRACT

LIFE CYCLE ENVIRONMENTAL IMPACTS OF UTILIZING HEMP SEED MEAL AS A PROTEIN SOURCE IN SHEEP FEEDLOT RATIONS

Hemp seed meal is a protein-rich byproduct of the hemp industry, obtained from the cold press extraction process used to produce hemp oil. The objective of this work was to evaluate the environmental impact of using hemp seed meal as a protein supplement in sheep production. A cradle-to-gate life cycle assessment (LCA) was conducted on three sheep production systems which differed in the feedlot phase: one fed a feedlot ration containing soybean meal as the protein source (soybean meal diet), one fed hemp seed meal in the feedlot ration (hemp diet), and one fed organic hemp seed meal in the feedlot ration (organic hemp diet). Animal performance data were collected from a nutrition trial. Hemp production, harvest, and processing data were provided by a hemp product company. Economic and physical allocation were applied to the hemp diet systems, and the ReCiPe Midpoint (H) methodology was used to calculate the global warming (*i.e.*, carbon footprint), water consumption, land use, and fossil resource scarcity impacts on a per kg lamb live weight basis for each system. Carbon footprint ranged from 10.1 to 11.4 kg CO_2eq/kg LW, water consumption ranged from 1.3 to 4.2 m^3/kg LW, fossil resource scarcity ranged from 0.5 to 0.8 kg oil eq/kg LW, and land use ranged from 2.8 to 6 m^2a crop eq/kg LW. Impact assessment results were not sensitive to a 10 or 20% increase in electricity demand at processing. The use of IPCC Tier 2 methods for estimating enteric methane emissions from sheep resulted in a 7.5–8.5% increase in the carbon footprint, relative to a mechanistic equation present in the Ruminant Nutrition System model. Physical allocation resulted in greater impacts of the hemp diet systems than the soybean diet systems for all categories except land use. However, economic allocation resulted in greater impacts for the soybean diet systems than the hemp diet systems for all categories evaluated. This was explained by inherent differences between the allocation method, as physical allocation attributed 80% of the environmental burden to hemp seed meal, while economic allocation attributed 0% of the environmental burden to hemp seed meal due to the current lack of an economic value for hemp seed meal. The production volume of dependent products ("dependent products", or products for which a change in demand does not affect production volume, commonly referred to as co- or byproducts) are driven by monetary value of the determining product (the product for which a change in demand affects the production volume), but relationships between co-products change overtime. Therefore, as the hemp industry continues to develop, an economic value may be placed on hemp seed meal with implications for its relative ability to reduce the environmental impacts of livestock production. As agricultural industries strive to become more environmentally efficient, they must be adaptive to changes in both monetary value and environmental impact, which are intrinsically related. This research demonstrated the importance of allocation choice in assessing the impact of feeding byproducts on the environmental impact of livestock production systems. Economic allocation better reflected the monetary driving factor for hemp production than physical allocation. As such, the inclusion of hemp seed meal in a feedlot ration reduced the environmental impact of sheep production systems.

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INTRODUCTION

Hemp seed meal is a byproduct of the hemp industry generated during cold press extraction of hemp seed to produce hemp oil. Currently, hemp seed meal has little to no uses and is landfilled, composted, or stored for potential future use, despite its nutritional value for livestock—including high protein content. It has been proposed that hemp seed meal could be fed to livestock as a protein source, although hemp seed meal is not currently an approved feedstuff for livestock. However, there is mounting empirical evidence that hemp seed meal may be safe to feed to livestock (Butts et al., 2022; Winders et al., 2023).

Instead of disposing of byproducts as waste, they can be repurposed as livestock feed. Livestock can convert feed resources that are unsuitable or undesirable for human consumption into high quality, human-edible protein (van Hal et al., 2019). The utilization of livestock to convert low-opportunity-cost feedstuffs like byproducts, food waste, and grass resources into human edible protein can be beneficial to solving the challenge of providing food while minimizing environmental impacts (van Hal et al., 2019).

To the author's knowledge, there have only been three life cycle assessments (LCAs) of sheep production in the U.S. and no LCAs evaluating feeding hemp products to livestock (Dougherty et al., 2017, 2019b; Sim and Prabhu, 2018). This project builds upon a hemp seed meal feeding trial conducted at Colorado State University (Butts et al., 2022). The goal of this study was to evaluate the impact of feeding hemp seed meal as a protein supplement in a feedlot ration on the environmental impacts of sheep production.

LITERATURE REVIEW

U.S. Sheep Production

Small ruminants, such as sheep, can be an asset to production systems because they can thrive on land that would be unsuitable for large ruminants (such as cattle), and can provide additional ecosystem services (Dougherty et al., 2019a). The shift from sheep to cattle in the 1960s and 1970s resulted in a decrease in the efficiency of land use, because many rangelands are not well suited for cattle production (Parker & Pope, 1983). The biological potential of sheep to utilize noncompetitive feedstuffs may provide the sheep industry with a more substantial role in animal protein production while agricultural industries work to improve sustainability and reduce their environmental impacts.

Despite their efficiency at converting human inedible feedstuffs to high quality protein, the U.S. sheep population has been declining since 1942 when it reached a high of 56 million head (Field, 2020). Currently, the U.S. sheep population consists of about 5 million head, a 91% decrease from its peak (NASS, 2022a). The West is home to about 80% of U.S. sheep production (Field, 2020). The three states with the largest populations of sheep are Texas with 700,000 head, California with 575,000 head, and Colorado with 430,000 head (NASS, 2022a). The majority of U.S. sheep producers have small flocks of less than 50 head, though about 40% of the west's sheep producers have flocks greater than 50 head (Field, 2020). These larger flocks represent about 93% of the West's sheep population (Field, 2020). Only about one-third of the West's sheep systems are only sheep, while the remainder are diversified operations with other revenue sources (Field, 2020).

Currently, the United States does not produce enough lamb to meet demand for consumption. Imports account for more than half of U.S. supply, and come primarily from Australia and New Zealand (USDA ERS, 2020). Per capita lamb consumption was the highest in 2021 since the early 1990s, at 1.36 pounds per person (ASI, 2022). This increase in consumption is a result of the COVID-19 pandemic, which caused shifts in consumer habits and an improvement in the year-round availability of lamb in stores (ASI, 2022). Due to strong consumer demand in 2021, the industry saw record high prices (ASI, 2022). Feeder and slaughter lamb prices were at a record high, with price gains of more than 40% in 2021 (ASI, 2022). Slaughter lamb prices averaged $217.25 per cwt in 2021, 46% higher than the 2015-2019 average price (ASI, 2022). In 2020, lamb was the only fresh or processed meat that grew pound sales (ASI, 2022). Additionally, lamb had the largest growth in pound sales compared to other meats in 2019 (ASI, 2022).

U.S. lamb production is seasonal, with a majority (about 85%) of the lamb crop being born in the first five months of the year (Field, 2020; USDA APHIS, 2014; Redden et al., 2018). This seasonality is primarily due to sheep being seasonal breeders with highest fertility from September to December (Redden et al., 2018). In the west, range sheep are usually wintered in low elevations with little precipitation and moved to higher elevations during the summer. It is also most common to lamb in a special lambing pasture in the West, but in other regions shed lambing is more common (USDA APHIS, 2014). The gestation length of sheep is about 5 months (147 to 150 days), and the average lambing rate is 1.3 live lambs per birth.

Most range-produced lambs are “feeders” that are first raised by producers and sent to feedlots after weaning, and the majority of feedlot lambs are obtained from range sheep producers (Field, 2020). The majority of lambs are harvested between 6 to 12 months of age (Redden et al., 2018).

A feeding period of 40-60 days is typical to finish healthy lambs (Field, 2020). Target average daily gain for lambs on feed is about 0.2-0.4 kg per head per day, with an average target end weight of 63.5 kg.

Generally, the most limiting nutrient in ewe rations is energy (Morrical, 2017; Pond, 2005). Throughout the stages of production, the ewe's energy requirements fluctuate (Morrical, 2017). As such, in production systems involving flocks on rangelands, the amount and quality of forage is especially important (Pond, 2005). If ewes cannot consume enough forage to meet their energy requirements, they will lose weight. Typical sheep management involves "flushing" ewes from 3-4 weeks prior to breeding until a few weeks into the breeding season. Flushing is the practice of providing improved nutrition by providing the animal with feed supplements (e.g., hay or protein cubes) to increase energy intake by 10% (Morrical, 2017; Pond, 2005). Ewes in late gestation also require increased energy intake, as two-thirds of fetal growth occurs during the last 6 weeks (Morrical, 2017; Pond, 2005). If ewes are bred on dormant range, they may require increased energy and protein supplementation throughout their pregnancy. Sheep rely on the microbial population in their rumens to produce vital amino acids. As such, the quantity of protein is more important than the quality of protein in the diet (Pond, 2005). Additionally, feeds high in protein are usually the most expensive. As ruminants, sheep can utilize agro-industrial byproducts unlike monogastrics so byproduct protein supplements could be beneficial to producers.

Hemp Production

Cannabis sativa L. (both cannabis and hemp) has been utilized by humans for a variety of products for over six millennia (Fike, 2016; Schluttenhofer & Yuan, 2017). The crop has innumerable uses, ranging from fibers and textiles to seed grains, essential oils, health products, or human and animal feeds (Ellison, 2021; Fike, 2016; Schluttenhofer & Yuan, 2017). Hemp was first harvested around 8,500 years ago (Fike, 2016). *Cannabis sativa L.* is originally from Central Asia, but has been grown all over the world (H. Van Der Werf et al., 1996), where it was cultivated for fiber and seeds, and was used for canvas and cordage for naval vessels (Fike, 2016).

Demand for the crop decreased as production of cotton increased and price decreased, and ships began to use steam or fossil fuels (Fike, 2016). This, in addition to concerns about the hallucinogenic properties of the Cannabis plant lead to the Marihuana Tax Act in 1937, leading to the demise of the hemp industry in the United States (Fike, 2016). In the mid-1990s interest in hemp in the United States was rekindled after European and Canadian decisions to allow hemp cultivation (Fike, 2016). Since 2011 there has been an increase in hemp production (both tonnage and acreage) worldwide, and the United States has become the largest importer of hemp products (Schluttenhofer & Yuan, 2017). In 2018, the Agriculture Improvement Act of 2018 (also known as the 2018 Farm Bill) was passed, removing hemp and hemp seeds from the Drug Enforcement Administration's (DEA) controlled substances schedule (NASS, 2022b). Since then the hemp industry in the U.S. has grown rapidly (Schluttenhofer & Yuan, 2017). In 2021, the U.S. had 54.2 thousand acres of open planted industrial hemp, valued at $712 million (NASS, 2022b). The total value of all hemp planted in 2021 was $824 million (NASS, 2022b). In 2021, there were 10,100 planted and 3,100 harvested acres of hemp in Colorado (NASS, 2022b).5

Cannabinoids are a unique class of compounds found in *Cannabis sativa* that have pharmaceutical and psychoactive properties (Laverty et al., 2019). Of particular interest in the United States are tetrahydrocannabinol (THC) and cannabidiol (CBD), the two most abundant natural derivatives (Laverty et al., 2019). THC is known for its psychoactive effects, while CBD is not psychoactive but has other therapeutic properties (Burgel et al., 2020). Cannabis crops containing less than 0.3% THC are considered hemp varieties, and those containing more than 0.3% THC are considered marijuana varieties (Dolgin, 2019; Fike, 2016; Schluttenhofer & Yuan, 2017). Limits differ in other countries, ranging from 0.2 to 1% THC (Dolgin, 2019). The U.S. limit was set by the 2018 U.S. Farm Bill and could be seen as arbitrary and/or misleading, as THC levels can vary depending on plant part, developmental stage, and growing conditions (Dolgin, 2019; Fike, 2016). Studies analyzing genetic and biological differences between hemp and marijuana have shown a less definitive difference between the two (Dolgin, 2019). Recent DNA sequencing of a THC-producing cannabis strain (Purple Kush) and a CBD-producing strain (Finola hemp) found that only the THC-producing strain had a THC-producing version of the THC synthase gene and only the hemp had a CBD-producing version of the CBD synthase gene (Laverty et al., 2019). With additional research, sequencing may be used to improve producers' ability to determine if a seedling would be better for hemp or marijuana production, and to assist with breeding better genetics for one purpose or another (Dolgin, 2019). As crops with THC content above legal limits must be destroyed, the ability to make this distinction could assist hemp producers in avoiding excessive THC content and losing their crop.

Hemp is an annual herbaceous plant that can grow under diverse and variable conditions (Rehman et al., 2021). It can grow 1–6 m tall, and produces rigid, woody stalks that are 2.5–5.0 cm in diameter (Fike, 2016). The plant's morphology, expression, and quality vary depending on planting density, seeding rate, environment, photoperiodicity, and management (Fike, 2016; Rehman et al., 2021). Hemp grows well between 13 and 27 °C, in soil with a pH around 6 (Fike, 2016; Rehman et al., 2021). It is capable of growing in a wide range of soil types, but is more successful in well-drained loams high in organic matter and low in acidity (Fike, 2016). Soil moisture is important, and optimum yields of the plant require 50–70 cm of moisture (Fike, 2016). For fiber production, it is typically planted at a depth of about 3 cm, with row spacing of 8–18 cm, and density of 100–200 plants/m^2 (Fike, 2016). At high seeding rates the plants develop thinner stalks, which are more ideal for fiber production, and at low seeding rates the hemp is highly branched, which is more ideal for seed production (Fike, 2016). Hemp grown for fiber is typically harvested 70–90 days after seeding once the male plants have finished flowering, and hemp grown for seed or oil is typically harvested later in the plant's life cycle when the seeds are mature (Fike, 2016). Harvesting hemp at the initiation of flowering improves quality, strength, and yield of fiber (Schluttenhofer & Yuan, 2017).

Hemp has a multitude of uses in numerous industries (Ellison, 2021; Fike, 2016; Schluttenhofer & Yuan, 2017; H. Van Der Werf et al., 1996). The hemp plant's medicinal compounds, fiber, and seeds have been used in over 25,000 products (Fike, 2016; Schluttenhofer & Yuan, 2017), in varying industries like construction, health and personal care, food and beverage, energy, and livestock feeds or bedding (Ellison, 2021; Rehman et al., 2021). The plant is typically grown either for fiber or for seed (which is used to produce oil), and the harvest time is different depending on the intended end product. If the hemp crop is a fiber variety it will be harvested and decorticated (a process where the hemp fibers are removed from the stalk to result in hemp fiber and hemp hurds) (Fike, 2016). After decortication the fiber will go through further processing and can be used to create products such as carpeting, insulation, cordage, or fabric (Fike, 2016). The hemp hurd is the woody core of the crop, and can be used for livestock bedding, compost, or paper and pulp (Fike, 2016). If the hemp crop is a seed variety, the seeds can be used for planting the following year's crop, or can be pressed or crushed to produce hemp seed oil, with hemp seed cake as a byproduct (Fike, 2016). Hemp seed cake, or "hemp seed meal", is high in neutral detergent fiber (NDF), acid detergent fiber (ADF), and crude protein (CP) and can be used as a protein supplement, while seeds themselves can be used as an energy feed (Rehman et al., 2021, Winders et al., 2023). Despite the high nutritional value, hemp products are currently not approved feedstuffs for livestock in the United States. However, hemp's removal from the Controlled Substances Act has increased research efforts to better understand the impacts of utilizing hemp as feedstuffs for livestock.

Life Cycle Assessment

The goal of a LCA is to model the environmental impact of a good or service. Analyses include the inputs, outputs (including products and emissions), and their interrelationships in complex systems. LCAs are governed by ISO standards 14040:2006 (with Amendment 1:2020) and 14044:2006 (with Amendment 1:2017 and Amendment 2:2022) (ISO, 2006; 2017; 2020). There are 4 phases of an LCA: goal & scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation.

In the goal and scope definition phase, researchers explicitly state the purpose of their study (Matthews et al., 2014). When defining the goal of the LCA, researchers must unambiguously state the intended application, the reason for carrying out the study, the intended audience, and whether the results are intended to be used in comparative assertions (ISO, 2006; ISO 2020). When defining the scope of the LCA, researchers should clearly describe the product system, state the functional unit, define the system boundary, outline allocation procedures, state LCIA methodology and the chosen impacts, explain how the data should be interpreted, and state any data requirements, value choices, assumptions, or limitations (ISO, 2006; ISO, 2020). The functional unit must fit the goal and scope of the study, and must be measurable (ISO, 2006; ISO, 2020). The functional unit should bridge the gap between the function and the inputs/outputs of a system (Matthews et al., 2014). Examples of functional units include one kilogram of live weight (LW) for a study examining emissions from the production of sheep for meat, one kilogram of greasy wool for a study examining sheep wool emissions, or one unit of carpet (0.09 m^2) for a study comparing emissions for types of carpet (Wiedemann et al. 2015, Sim and Prabhu 2018). The system boundary determines which processes are included in the study, and at what level of detail (ISO, 2006; ISO, 2020). The rationale for including or excluding processes should be clearly stated (ISO, 2006; ISO, 2020).

The next phase is the development of the LCI, where input and output data are collected for all the processes included within the study. Methodology for data collection should be clearly stated (ISO, 2006; ISO, 2020). Once data have been collected, they are aggregated into impact categories in the LCIA phase. This phase has three mandatory elements: selection of impact categories, category indicators, and characterization models, assignment of LCI results to impact categories, and calculation of category indicator results (ISO, 2006; ISO, 2020). This is the phase where a researcher would calculate the carbon footprint, or other impact categories, associated with a product. Finally, these results must be interpreted. The interpretation phase involves identification of "hotspots" based on the results, an evaluation considering completeness, sensitivity, and consistency checks, and a discussion of the conclusions, limitations, and recommendations (ISO, 2006).

Allocation

Systems, especially agricultural systems, can be multifunctional in that they have more than one product output (i.e., "co-product", "byproduct", or "waste product"). This requires practitioners to allocate inventory data and impact results between the products. Allocation is defined by ISO 14044 as "partitioning the input or output flows of a process or product system between the product system under study and one or more other product systems" (ISO, 2006; ISO, 2020). The sum of all product shares must equal the total input and output flows for the process. For example, an LCA of a wool production system would have to allocate the environmental footprint of the entire sheep production system between wool and meat. There are multiple methods for performing allocation, and the method chosen can have a significant effect on the results of an LCA (Ekvall & Finnveden, 2000). As such, selecting an allocation approach can be consequential and is the subject of much debate (Cederburg & Stadig, 2003; Finkbeiner, 2021; Mackenzie et al., 2017).

The International Organization for Standardization (ISO) provides a standard for performing LCAs. This framework contains a step-wise procedure for practitioners to utilize when allocating emissions in multifunctional production systems.

ISO 14044:2006 states:

> Step 1: Allocation should be avoided, wherever possible, by either dividing the process to be allocated into sub-processes or by expanding the product system to include additional functions related to the co-products, also known as system expansion.
>
> Step 2: If allocation cannot be avoided, the environmental impacts should be partitioned to reflect the physical relationship between the products (e.g., mass).
>
> Step 3: If a physical relationship cannot be established, other methods that reflect a relationship between the products should be considered (e.g., economic value).

The ISO standard is criticized for lacking definitions for key technical terms and leaving space for inconsistency across LCA studies (Heijungs et al., 2021b; Pelletier et al., 2015; Schaubroeck et al., 2022). These inconsistencies can lead to differences in the methods used and results of LCAs, which decreases the ability for comparison across studies. As such, allocation decisions should be selected in accordance with the study's goal and scope, and should be clearly stated (Schaubroeck et al., 2022). Additionally, applying this standard—which was developed to evaluate industrial processes—to agricultural systems may not be appropriate due to the intrinsic differences between them (Mackenzie et al., 2017). Agricultural systems are incredibly complex, multi-output, socio-ecological systems whose inputs and outputs are inextricably linked. As such, avoiding allocation through system expansion may not be appropriate or feasible for agricultural systems. System expansion requires large amounts of extraneous data and would require large, complex models that can be less transparent and require more assumptions (Mackenzie et al., 2017). As such, the utility of system expansion is questionable and could lead to less accuracy and less valuable results for agricultural systems (Pelletier et al., 2015; Mackenzie et al., 2017). Recently there was an amendment made to the ISO 14044 standard that added verbiage about using substitution as a method of system expansion to solve multifunctionality issues (ISO, 2020). This amendment has, however, been criticized for failing to clarify whether the ISO 14044 standard prefers system expansion, substitution, or neither (Finkbeiner, 2021; Heijungs et al., 2021b, 2021a).

As using system expansion may be impractical or undesirable, practitioners may look next to physical or other relationships, such as economic value, to make allocation decisions (Pelletier et al., 2015). Economic allocation is the last of the steps described in the ISO 14044 standard and is sometimes interpreted as the least desirable (Pelletier et al., 2015; Schaubroeck et al., 2022). A study comparing three biophysical allocation methods, one hybrid protein mass allocation and economic allocation method, and two system expansion methods for sheep production systems found that the total greenhouse gas (GHG) emissions per kg of total products (meat + wool) were similar across their case study farms, but their results by product were highly sensitive to the method of allocation (Wiedemann et al., 2015). The system expansion via substitution methods resulted in a lower carbon footprint for wool than the other allocation methods they applied because of the substitution system's high livestock emissions. Using the economic allocation method, differences in the economic value of products resulted in large variation (4 to 52%) in the proportion of impacts allocated to wool in the different case studies (Wiedemann et al., 2015). The results using economic allocation were also inconsistent and unrepresentative of the underlying biophysical characteristics for wool (Wiedemann et al., 2015). Overall, the study recommended attributional LCA studies use the biophysical method because it apportions maintenance protein requirements between wool and meat (Wiedemann et al., 2015). However, the argument has been made that "biological systems do not function with the goal of producing the items which humans deem to be economically valuable", therefore, it is important that inputs and outputs to a system are partitioned in a way that reflects the underlying (or causal) relationships driving the environmental footprint (Mackenzie et al., 2017). Additionally, what is deemed a weakness of economic allocation can also be seen as a strength. Economic values change over time, which means that the drive to produce different products due to their economic value will also change over time. Therefore, the fact that prices change over time could be seen as a strength of economic allocation (Wiedemann et al., 2015).

Overall, it can be argued that allocation choice is essentially arbitrary, especially if systems are too complex to model their causal relationships (Mackenzie et al., 2017; Pelletier et al., 2015; Schaubroeck et al., 2022). Consistent with later studies, Cederburg and Stadig (2003) found that the choice of allocation for co-products of meat and surplus calves impacted the results of milk production LCAs, as each allocation method led to different results. Best practice is for researchers and practitioners to clearly explain their rationale behind their allocation decisions, why they chose the method utilized, and how their decision supports the goal and scope of the LCA (Kyttä et al., 2022; Mackenzie et al., 2017; Pelletier et al., 2015).

Environmental Footprint of U.S. Sheep Production

To the author's knowledge, there are only three published, peer-reviewed LCAs of sheep production in the United States: two LCAs evaluating sheep production in California (Dougherty et al., 2017; 2019b), and one comparative LCA of wool and nylon carpets in the United States (Sim and Prabhu, 2018). The first study was completed a partial LCA of a sheep production system in California (Dougherty et al., 2017). The system boundary included sheep-lamb, stocker, and finishing stages of lamb production, which they reported as responsible for 86.1%, 4.2%, and 9.7% of emissions, respectively (2017). With all emissions allocated to lamb production, the carbon footprint was 28.6 kg carbon dioxide equivalents (CO_2eq)/kg live weight (LW). A later analysis of five case studies representative of different California sheep production systems reported carbon footprints ranging from 13.9 to 30.6 kg CO_2eq/kg market lamb production on a mass basis, 10.4 to 18.1 kg CO_2eq/kg market lamb production on an economic allocation basis, and 6.6 to 10.1 kg CO_2eq/kg market lamb production on a protein-mass allocation basis (Dougherty et al., 2019b). The 2019 study found that enteric fermentation was the largest source of emissions (68—79% of footprint), while the 2017 study found enteric fermentation to only be 34% of total emissions (Dougherty et al., 2017; 2019b). An LCA comparing energy and carbon emissions of wool and nylon carpets reported that production of a 0.09 m^2 wool carpet required 20.4 MJ of energy, and produced 6.4 kg CO_2eq (Sim & Prabhu, 2018). The authors conclude that in order to reduce carbon emissions the raw material production stage (43.61% of total carbon emissions) needed to improve (2018). The LCI data used in that study were derived from an LCA of the Australia merino wool industry (energy footprint = 12.5 MJ/kg, carbon footprint = 19.5 kg CO2eq/kg) (Wiedemann et al., 2016). Overall, considering expected carpet demand and the entire wool life cycle, wool carpet required less energy and produced fewer carbon emissions per 0.09 m^2 than the nylon carpet (Sim & Prabhu, 2018).

Outside of the U.S. there have been a considerably larger number of LCAs of sheep production. A review of environmental performance of sheep production found 29 LCAs completed between 2005 and 2020, and only two of the LCAs were U.S. studies (Bhatt & Abbassi, 2021). The majority of sheep production LCAs have been based in Europe or Australia, and most have focused on sheep meat (Bhatt & Abbassi, 2021). Carbon footprints ranged from 3.5–25 kg CO_2eq/kg LW, 2–5 kg CO_2eq/kg fat and protein corrected milk (FPCM), and 20–60 kg CO_2eq/kg greasy wool (Bhatt & Abbassi, 2021). Direct methane emissions from livestock were found to be the single largest contributor to GHG emissions, typically contributing 50—70% of the overall carbon footprint (Bhatt & Abbassi, 2021).

Environmental Footprint of Hemp Production

To the author’s knowledge, there have been no published, peer-reviewed LCAs of hemp completed in the United States, and no published, peer-reviewed LCAs of the environmental footprints of hemp seed meal irrespective of location. However, several LCA studies of hemp production and hemp products have been published in other countries (Table 1).

Table 1. Summary of carbon footprints for various hemp products.

Paper	Product	Carbon Footprint	Location
Campiglia et al., 2020	Hemp Seed Production	0.161 kg CO_2eq – 18.720 kg CO_2eq per 1 kg of seeds produced	Italy
Bernas et al., 2021	Hemp Food Oil	No carbon footprint value	Czech Republic
Saarinen et al., 2017	Hemp Seed (as a food)	0.163 kg CO_2eq per 100 g	Finland
Van der Werf, 2004	Hemp Fibre	2330 kg CO_2eq per 1 ha	France
González-García et al., 2010	Hemp Fibre	1600 kg CO_2eq per ton	Spain
Lecompte et al., 2017	Hemp Straw for Hemp Concrete	168.3 – 255.0 kg CO_2eq per ton of hemp straw	France
Wötzel et al., 1999	Hemp Fibre for Automotive Parts	4.778 CO_2eq per 1 basic hemp component	Germany
Pretot et al., 2014	Hemp Concrete Wall	-0.016 kg CO_2eq per square meter of wall	France
Van der Werf & Turunen, 2007	Hemp Textile Yarn	1350-1810 kg CO_2eq per 100 kg of yarn	Central-European, Hungary, France, Belgium, Netherlands
González-García et al., 2011	Hemp Hurds for Ethanol Production	No carbon footprint	Spain

One study evaluated the environmental impacts of agronomic practices for hemp seed crop grown in Italy from cradle to factory gate (Campiglia et al., 2020). Seven industrial hemp varieties, three plant densities, and two levels of nitrogen fertilization were evaluated. Eighteen of the 24 final scenarios resulted in carbon footprints below 0.68 kg CO_2eq, which is comparable with other crops (Campiglia et al., 2020). The varieties with the highest impact were E68/F75/S27 genotypes at 18.7 kg CO_2eq with 50 kg ha^{-1} of N fertilizer and a 40 plant m^{-2}

density (Campiglia et al., 2020). The variety with the lowest impact at 0.161 kg CO_2eq was Ferimon with 50 kg ha^{-1} of N fertilizer and a 120 plant m^{-2} density (Campiglia et al., 2020).

Bernas et al. completed a comparative LCA of winter rapeseed, sunflower, and hemp as food oils (2021). They utilized mass allocation and evaluated nine different environmental impact categories: fossil depletion, water depletion, freshwater ecotoxicity, terrestrial ecotoxicity, human toxicity, marine eutrophication, freshwater eutrophication, terrestrial eutrophication, and climate change. Per unit of production (1 m^3 of food oil) hemp oil had the lowest climate change impact out of the three food oils (45% less than environmental impact of rapeseed oil) (Bernas et al., 2021). However, per hectare, hemp biomass had the highest climate change impact out of the three crops (Bernas et al., 2021).

MATERIALS & METHODS

This LCA was conducted in accordance with the ISO 14040-series guidelines (ISO, 2006; ISO, 2020). The software utilized for this LCA was openLCA 1.11.0, an open-source software developed by GreenDelta.

Goal and Scope Definition

The primary goal of this research was to evaluate the effect of utilizing hemp seed meal as a protein source in lamb feedlot diets on the environmental impacts of sheep production. This work expands upon a nutrition study that evaluated the impact of feeding hemp seed meal to finishing wethers (Butts et al., 2022). These studies will provide information to both the hemp and sheep industries and inform efforts to legalize hemp-derived animal feed products. The scope of this work was a cradle-to-gate assessment of a sheep production system wherein lambs were fed either soybean meal or hemp seed meal as a protein source during the finishing phase. The functional unit for this study was 1 kg of lamb live weight. This functional unit allowed comparison of the environmental impacts of sheep production when lambs were fed a conventional feedlot diet including soybean meal as the protein source, with environmental impacts when lambs were fed hemp seed meal.

Product System Description

The feeding trial associated with this LCA evaluated the impact of feeding hemp seed meal to finishing wethers on animal performance and DMI. Five isonitrogenous and isocaloric diets, each with differing hemp seed meal inclusion rates, were fed to 40 western white-faced wethers (eight per treatment). Wethers were fed for 90 days, followed by a five-day balance trial with total collection of urine and feces. The study found no difference in DMI or ADG between treatments, and no difference in Ca, Mg, K, or Na digestibility (Butts et al., 2022). The authors concluded that hemp seed meal has no harmful effects and is comparable to other protein supplements (Butts et al., 2022). As such, for the purpose of this LCA, only two of the five the diets were modeled: the diet with 0% hemp seed meal inclusion (only soybean meal) and the diet with 0% soybean meal inclusion (only hemp seed meal).

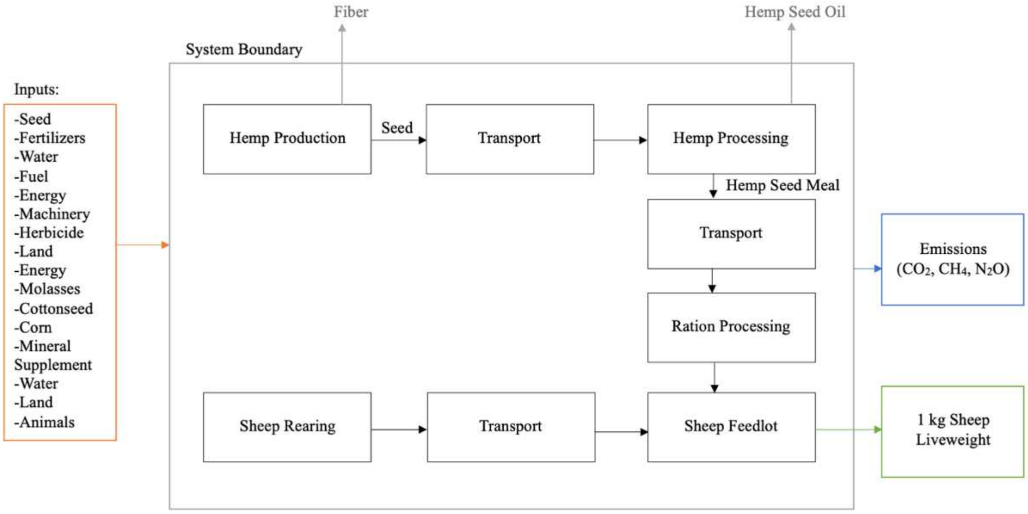

Figure 1. System boundary diagram for the hemp diet system.

Three sheep production systems were modeled: two where the feedlot ration protein source was hemp seed meal (hereafter referred to as the “hemp diet system” (Fig. 1) and the “organic hemp diet system” (Fig. 2)) and one where the ration protein source was soybean meal (hereafter referred to as the “soybean diet system” (Fig. 3)). The system boundary for this analysis included production of each of the crops in all rations, sheep rearing, and the feedlot phase. Post-feedlot impacts from slaughter and processing are excluded from this analysis.

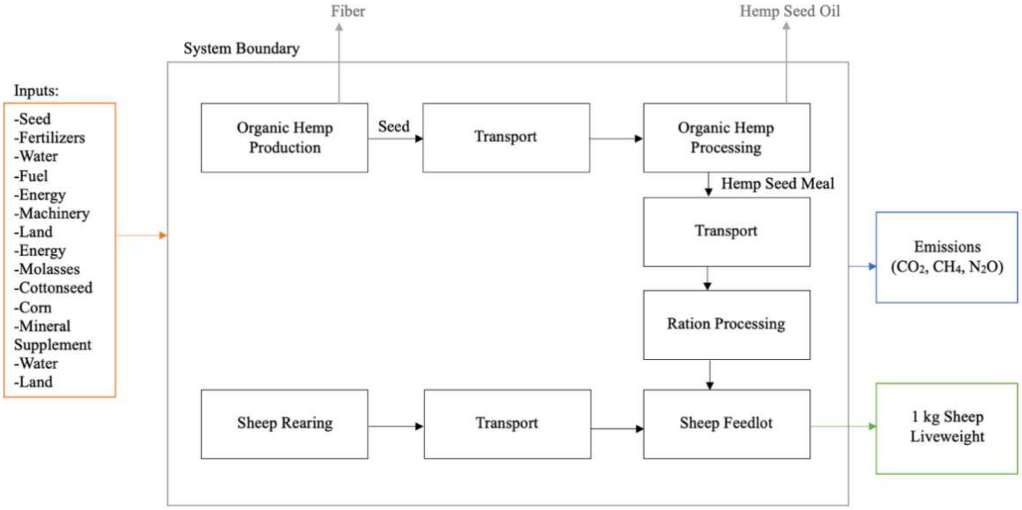

Figure 2. System boundary diagram for the organic hemp diet system.

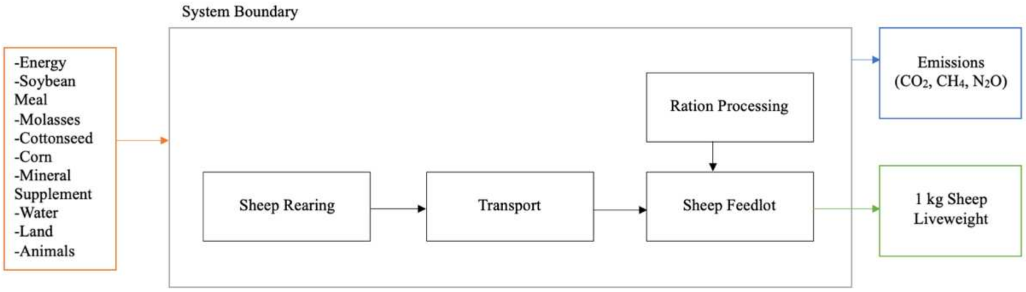

Figure 3. System boundary diagram for the soybean diet system.

Sheep rearing systems in Colorado, generally, are extensive and low input. The sheep rearing phase was modeled as representative of sheep production systems on the Western Slope of Colorado, wherein lambing occurs on native grassland and sheep are managed with minimal inputs. As such, the rearing phase was modeled with only land inputs, with lambs and ewe emissions as outputs. The lambs were raised on rangeland without supplemental feed, weaned, and transported to a feedlot in northeastern Colorado. Lambs were assumed to be weaned at 120 days of age and 35.7 kg. At the feedlot they were fed either a hemp or soybean meal-based ration for 90 days. The sheep rearing phase was modeled the same for all systems.

Hemp production included growing hemp from planting through harvest. After harvest, the hemp seed was transported from the field to a processing plant by semi-truck. At the processing plant the seed was cleaned, and cold press extraction was used to separate oil from cake. From there the hemp seed cake was transported to the feedlot where it was mixed into a diet and fed to the wethers.

Allocation

The ecoinvent 3.8 regionalized cutoff unit process database was used. Both physical (mass) allocation and economic allocation were utilized for each hemp system (both conventional and organic). Allocation was applied to hemp seed and hemp fiber at the hemp farm gate, as well as hemp oil and hemp seed meal at the hemp seed processing gate for the hemp systems (Table 2). Economic allocation factors were derived from monetary values for the products (HempBenchmarks, 2021). Physical allocation factors were derived from yield data from a hemp product company. The pre-existing unit process data for soybean meal in ecoinvent were disaggregated, avoiding the need for allocation.

Table 2. Allocation factors used at the production- and processing-gate for hemp diet systems.

	Allocation Method	
	Economic	Physical
Production		
Hemp Seed	0.92	0.20
Hemp Fiber	0.08	0.80
Processing		
Hemp Oil	1.00	0.19
Hemp Seed Meal	0.00	0.81

Table 3. Hemp production and processing inputs and outputs, for conventional and organic hemp production systems.

	Hemp Production System	
	Conventional	Organic

Field Inputs		
Urea (N Fertilizer), kg	65,635	0.0
Glyphosate, kg	490	0.0
Irrigation, m^3	2,600,000	2,360,000
Cattle Manure, tons	2,894	2,620
Poultry Manure, tons	1,116	1,010
Seed, kg	23,426	21,208
Sowing, hectares	585.5 (1 pass)	530.1 (1 pass)
Land Occupation, hectares	585.5	530.1
Combine Harvesting, hectares	585.5 (1 pass)	530.1 (1 pass)
Baling, bales	3,263	2,955
Fertilizing, hectares	1,171.1 (2 passes)	1,060.2 (2 passes)
Field Outputs		
Hemp Fiber, kg	1,175,000	1,060,000
Hemp Seed, kg	300,600	270,000
Hemp Seed Transport		
Hemp Seed, kg	18,140	18,140
Transport (Semi-Truck), tons*km	18*120	18*120
Hemp Processing Inputs		
Electricity (Medium Voltage), kWh	0.045	0.045
Heat (Central or Small Scale), MJ	0.015	0.015
Heat (Natural Gas), MJ	0.637	0.637
Heat (Other than Natural Gas), MJ	0.328	0.328
Transported Hemp Seed, kg	1.82	1.82
Hexane, kg	0.00046	0.00046
Oil Mill, item	$1.4e^{-10}$	$1.4e^{-10}$
Tap Water, kg	0.4	0.4
Hemp Processing Outputs		
Hemp Oil, kg	0.24	0.24
Hemp Seed Meal, kg	1.0	1.0

Life Cycle Inventory

Data Sources and Collection

Agronomic data for hemp production and hemp processing data were sourced from hemp producers through a hemp product company (Table 3). Three years of production data were available. Tillage data for year two and yield data for year three were unavailable. Production for year one differed greatly from years two and three, and as such was not considered. Land planted, fertilizer, herbicide, amount of seed, and irrigation data from year two and year three were averaged together, and used in the analysis. Only tillage data from year three and yield data from year two were used. In addition, data were provided for grain and fiber strains. As fiber strains are not used to produce hemp oil and therefore hemp seed meal, only grain strains were considered in this study. Sheep production data were sourced from the literature with input from local extension faculty and are summarized in Table 4. Lamb performance data, rations, and nutrient composition of each diet were obtained from the aforementioned CSU nutrition trial (Table 5 and Table 6). Where primary data were unavailable, LCI data from the ecoinvent 3.8 regionalized cutoff unit process database were used.

Table 4. Sheep production inputs for hemp and soybean diet systems.

	System	
	Hemp Diet	Soybean Diet
Sheep Rearing		
Land Occupation, ha/sheep	1.62	1.62
Sheep Transport		
Lambs	160	160
Transport (Semi-Truck), km	531	531
Sheep Feedlot (90 days)		
Dry Matter Intake, kg/sheep	330	360
Water Intake, L/sheep	361	374

Table 5. Hemp and soybean diet composition, on a percent as-fed basis.

	Diet, % AF	
	Hemp	Soybean
Ingredient		
Cottonseed Hulls	14.8	14.7
Corn, ground	57.2	62.3
Hemp Meal	19.5	0.0
Soybean Meal	0.0	14.4
Molasses, cane, dry	6.7	6.7
Limestone	1.8	1.5
Dicalcium Phosphate	0.0	0.5
Ranch-O-Min vitamin mineral mix	0.01	0.01

Table *6*. Hemp and soybean diet composition.

	Diet, 100 kg	
	Hemp	Soybean
Nutrient		
CP, %	13.94	13.94
ME, Mcal/kg	2.62	2.84
NEm, Mcal/kg	1.72	1.90
Neg, Mcal/kg	1.09	1.26
Ca, g/kg	8.16	8.18
P, g/kg	4.32	4.31
Zn, mg/kg	27.56	25.26
Mn, mg/kg	32.13	32.01
Cu, mg/kg	14.52	13.45
I, mg/kg	0.17	0.17
S, mg/kg	1.99	1.91
Vit A, IU/kg	2746.15	2926.13
Vit D, IU/kg	88	88
Vit E, ppm	2.12	1.74
Ca:P Ratio	1.89	1.90

Enteric methane emissions for sheep rearing were calculated using IPCC Tier 1 emissions factors (8 kg CH_4 head^{-1} year^{-1} for a sheep weighing 65 kg). Enteric methane emissions for lambs in the feedlot were calculated using the Ruminant Nutrition System (RNS) version 0.8.8466.28492 (Tedeschi & Fox, 2016). Manure N_2O emissions for both the sheep rearing and feedlot phases were calculated using IPCC Tier 1 emissions factors (0.01 kg N_2O-N kg N^{-1}) (IPCC, 2006).

Cut-off Criteria

A cut-off threshold of 1e-14 was set for each product system. This threshold was chosen because it shortened calculation time without changing the results.

Assumptions & Limitations

Agricultural systems are complex, drynamic, and require a vast amount of data to model. Acquiring the quantity and quality of primary data necessary to complete an LCA is challenging, and often requires assumptions be made when modeling them. As such, several critical assumptions and their potential limitations are described below. To account for the variability, an uncertainty analysis was completed and is described in more detail in subsequent sections.

Crop management data (e.g., variety of seed and acres planted, fertilizer use, irrigation, tillage) for hemp production were quite variable due to the recent proliferation of the industry and associated variability in production practices. This resulted in difficulty characterizing what may be "representative" of the hemp industry. Only three incomplete years of data were readily available, with great variation from year one to year two and three. In addition, though nitrogen fertilization rate was available, fertilizer type was not. Fertilizer type was assumed to be urea based upon the recommendation of a Montana State University extension agent familiar with hemp production systems (Peggy Lamb, personal communication). Additionally, no hemp seed processing data were available, requiring the use of a soybean cold press extraction process from ecoinvent 3.8 as a proxy. Due to this assumption, a sensitivity analysis was completed on electricity usage at hemp processing to determine the impact an increase in electricity use would have on the environmental impacts of sheep production.

It is also important to note this LCA is based upon a research feeding trial. Therefore, the feedlot modeled is a research feedlot, not a commercial feedlot. At the research feedlot, sheep handling, feed mixing, animal feeding, and orts collection were managed using manual labor from faculty and students. As such, fuel used during the feedlot phase was excluded. This likely resulted in lower global warming and fossil resource depletion results when compared to other LCAs of sheep production.

Lastly, no comparison between conventional and organic hemp seed meal was made in the aforementioned research trial. While this likely would have negligible impacts on animal performance, conventional and organic crops are managed differently and may have differing impacts on the environment. As such, due to the availability of both conventional and organic hemp agronomic data, both were modeled, and animal performance was assumed to be the same between both.

Life Cycle Impact Assessment

The LCIA method utilized for this research was ReCiPe 2016 Midpoint (H). ReCiPe includes eighteen midpoint indicators and three endpoint indicators. Midpoint (H) represents the hierarchist perspective and is based upon scientific consensus for time frame and impact mechanisms. It is the "middle ground" perspective for impact indicators compared to individualistic (short-term interest, technological optimism) and egalitarian (precautionary, longest time frame) (Table 7). While Midpoint (H) is considered the default model, it is important to note that midpoint choice impacts the characterization factors used to calculate environmental impacts and therefore impacts results. Four of the eighteen midpoint indicators were considered: global warming (kg CO_2eq), water consumption (m^3), land use (m^2*a crop eq), and fossil resource scarcity (kg oil eq). Global warming (carbon footprint) was calculated according to the IPCC AR5 guidelines. Global warming potentials of 1, 34, 36 and 265 were used for CO_2, biogenic CH_4, fossil CH_4, and N_2O, respectively.

Table 7. ReCiPe value/perspective choices influence on climate change and water use indicators.

	Perspective		
	Individualistic	Hierarchist	Egalitarian
Climate Change			
Time horizon, years	20	100	1,000
Climate-carbon feedbacks non-CO_2	No	Yes	No
Future socio-economic developments	Optimistic	Baseline	Pessimistic
Adaptation potential	Adaptive	Controlling	Comprehensive
Water Use			
Regulation of stream flow	High	Standard	Standard
Water requirement for food production, m^3/yr/capita	1000	1350	1350
Impacts on terrestrial ecosystems considered	No	Yes	Yes

Sensitivity Analysis: Electricity Use at Hemp Processing

Sensitivity analyses were conducted for a 10 and 20% increase in electricity demand for hemp seed processing due to the use of soybean meal cold press extraction process as a proxy for hemp seed meal processing. It is likely that soybean processing is more efficient than hemp seed processing due to hemp seed being newer and likely not having the same level of process optimization. Testing the sensitivity of the results to an increase in electricity use provides insight into the magnitude of the impact of processing electricity use on one kg LW.

Sensitivity Analysis: Methane at Sheep Feedlot

A sensitivity analysis was completed to compare feedlot methane emissions estimated using RNS (Tedeschi & Fox, 2016) and emissions estimated using the IPCC Tier 2 methane equation (IPCC, 2019). The RNS estimates methane emissions as a function of propionate production,

$$Methane = C3\ x\ CH_4Y \qquad (1)$$

where methane is equal to propionate (C3) multiplied by methane yield (CH_4Y, g/g) (Tedeschi & Fox, 2018). RNS calculates methane yield as

$$CH_4Y = (\frac{1}{2 \cdot MfC3} - \frac{3}{4}) \times (\frac{16}{74}) \qquad (2)$$

where M*f*C3 is molar fraction of propionate (Tedeschi & Fox, 2018). Finally, the molar fraction of propionate is calculated by RNS using acetate (C2), propionate (C3), and butyrate (C4) with equation 3 (Tedeschi & Fox, 2018).

$$MfC3 = \frac{C3/74}{C2/(60+C3)/(74+C4)/88} \qquad (3)$$

Methane emissions were averaged across diet, resulting in an emission of 1.44 kg CH_4 head^{-1} for 90 days. This result was compared with methane emissions calculated using the IPCC Tier 2 emissions equation (IPCC, 2019). The IPCC Tier 2 equation (Equation 4) is used to calculate an emission factor (EF, kg CH_4 head^{-1} yr^{-1}) based on gross energy intake (GE, MJ head^{-1} day^{-1}), a methane conversion factor (Y_m, 6.5% for mature sheep), and the energy content of methane (55.65 MJ/kg CH_4) (IPCC, 2019).

$$EF = \frac{GE \cdot \left(\frac{Ym}{100}\right) \cdot 365}{55.65} \qquad (4)$$

The IPCC Tier 2 emissions method resulted in methane emissions of 11.64 kg CH_4 head^{-1} yr^{-1}, or 2.87 kg CH_4 head^{-1} for 90 days.

Uncertainty Analysis

There are several sources of uncertainty in a study, including data quality, incomplete sampling, random error, model appropriateness, and impact assessment methodology (Weidema et al., 2013). As such, uncertainty can compromise the reliability of a study's results and conclusions. Monte Carlo simulations (MCS), were utilized to evaluate the uncertainty associated with the study results. A total of 1,000 runs were simulated for each diet system. The MCS provided a distribution of the results, as well as the mean, median, standard deviation, minimum and maximum values, and 90% confidence intervals.

A pedigree matrix is utilized to evaluate each flow, and the corresponding indicator scores are categorized into five data quality categories: reliability, completeness, temporal correlation, geographic correlation, and technological correlation. Each category is given a rank from 1 to 5, with 1 indicating the highest quality/lowest uncertainty and 5 indicating the lowest quality/highest uncertainty. Once ranking is finalized, the uncertainty distribution, geometric mean, and geometric standard deviation are calculated and applied for each flow. Base uncertainty was set at ± 0.15 ($\sigma g = 1.15$) for inputs and outputs, except for soil nitrous oxide emissions and enteric and manure methane emissions. The uncertainty value for nitrous oxide emissions was set at ± 0.50 ($\sigma g = 1.50$) due to the lack of measured nitrous oxide emissions from the hemp production fields. Based on recommendations from IPCC, the uncertainty value for enteric and manure methane emissions was set at ± 0.20 ($\sigma g = 1.20$) (IPCC, 2006).

RESULTS & DISCUSSION

Global Warming

Carbon footprints ranged from 10.1 kg CO_2eq/kg LW to 11.4 kg CO_2eq/kg LW (Fig. 4). These footprints are within the range (3.5 to 25.0 kg CO_2eq/kg LW) reported in a review of LCAs of sheep production systems (Bhatt & Abbassi, 2021), and an assessment of sheep production in England and Wales (5.4 to 33.3 kg CO_2eq/kg LW; Jones et al., 2014). The carbon footprints in this study are similar or slightly lower than the range reported in an assessment of California sheep production systems (11.2 to 17.8 kg CO_2eq/kg LW; Dougherty et al., 2019b), most likely due to differences in the study systems. This study was based on a research facility in Colorado with more extensive sheep rearing systems and fewer feedlot inputs than the California sheep systems modeled in Dougherty et al. (2019b).

Sheep rearing contributed the majority (59 to 66%) of the carbon footprint for each system. The next largest contributor was corn production (14 to 17%). The carbon footprint for hemp seed production was 1.2 kg CO_2eq/kg LW for the conventional system and 0.8 kg CO_2eq/kg LW for the organic system, while soybean production had a footprint of 0.4 kg CO_2eq/kg LW. When physically allocated, hemp seed production contributed a greater proportion of the carbon footprint in the hemp diet systems (8 and 10% for organic and conventional hemp, respectively) than soybean production to the carbon footprint of the soybean diet system (4%).

In the economically allocated systems, due to its treatment as a waste product and the current lack of an economic value for hemp seed meal (Table 2), the environmental burden of hemp production and processing was allocated to the hemp oil instead of the meal. Therefore, the production and processing stages did not contribute to the carbon footprint of lamb live weight produced in the economically allocated systems. As a result, the carbon footprint of the economically allocated hemp diets were 9 and 11% lower than the physically allocated hemp diets for the organic and conventional hemp diets, respectively.

On the other hand, physical (mass) allocation resulted in 80% of the environmental burden of hemp production being allocated to fiber, and 19% of the environmental burden of hemp seed processing being allocated to hemp seed meal (Table 2), due to the relative weights of each output at the farm and processing gates. At the hemp production stage, 80% of the mass output is hemp fiber and 20% is hemp seed. As such, 80% of the footprint is allocated to the fiber and 20% to the seed. At the hemp processing stage, 81% of the mass is hemp seed meal and 19% of the mass is hemp oil, therefore, more of the footprint is allocated to the hemp seed meal. Due to the inherent differences in the allocation methods, the footprints of lamb produced by the hemp diet systems are 6% lower than the soybean diet system when economically allocated but 3-6% greater when physically allocated. Therefore, allocation choice is the factor that impacts which diet is the “most sustainable” based solely on carbon footprint. If the economic or mass allocation factors of the hemp products change over time, so will the footprints.

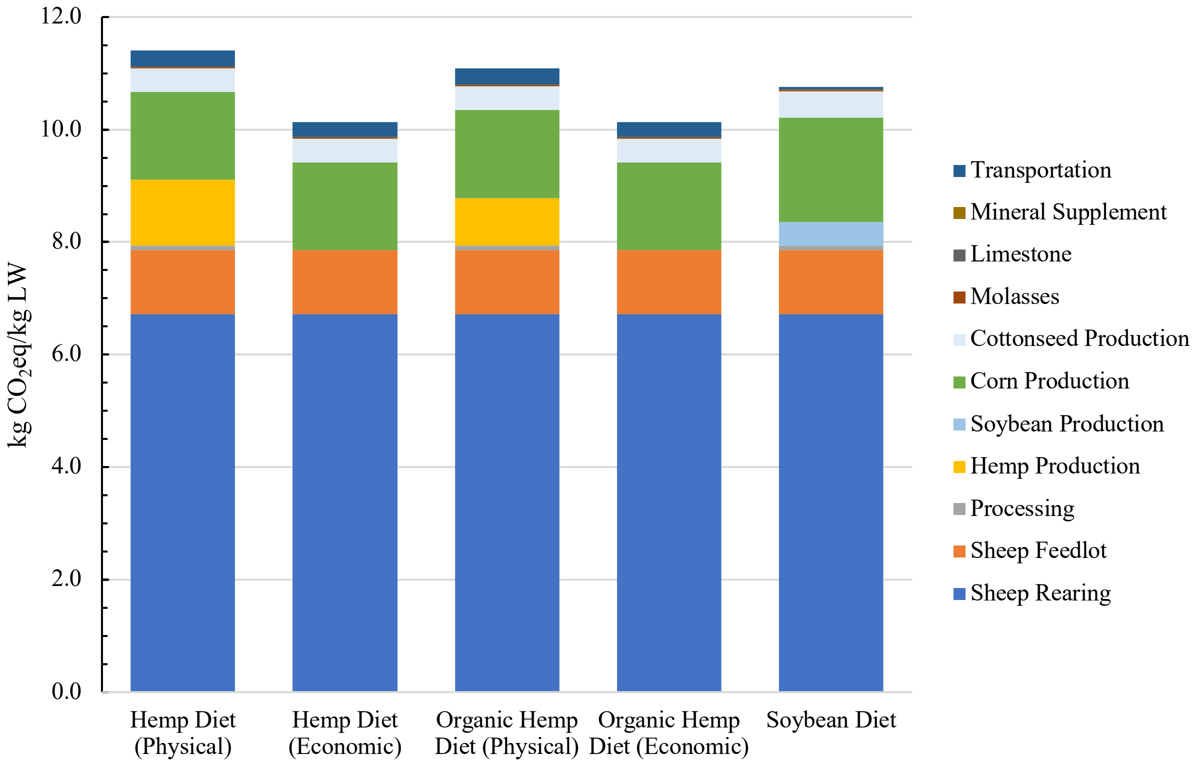

Figure 4. Carbon footprint results by system and allocation choice.

In each system, methane was the primary greenhouse gas emitted, ranging from 68—76% of the carbon footprint (Fig. 5), which is typical for ruminant systems and is driven by enteric methane emissions (Bhatt & Abbassi, 2021). Carbon dioxide contributed about 15—21% of the footprint, and nitrous oxide contributed the remaining 9—11%.

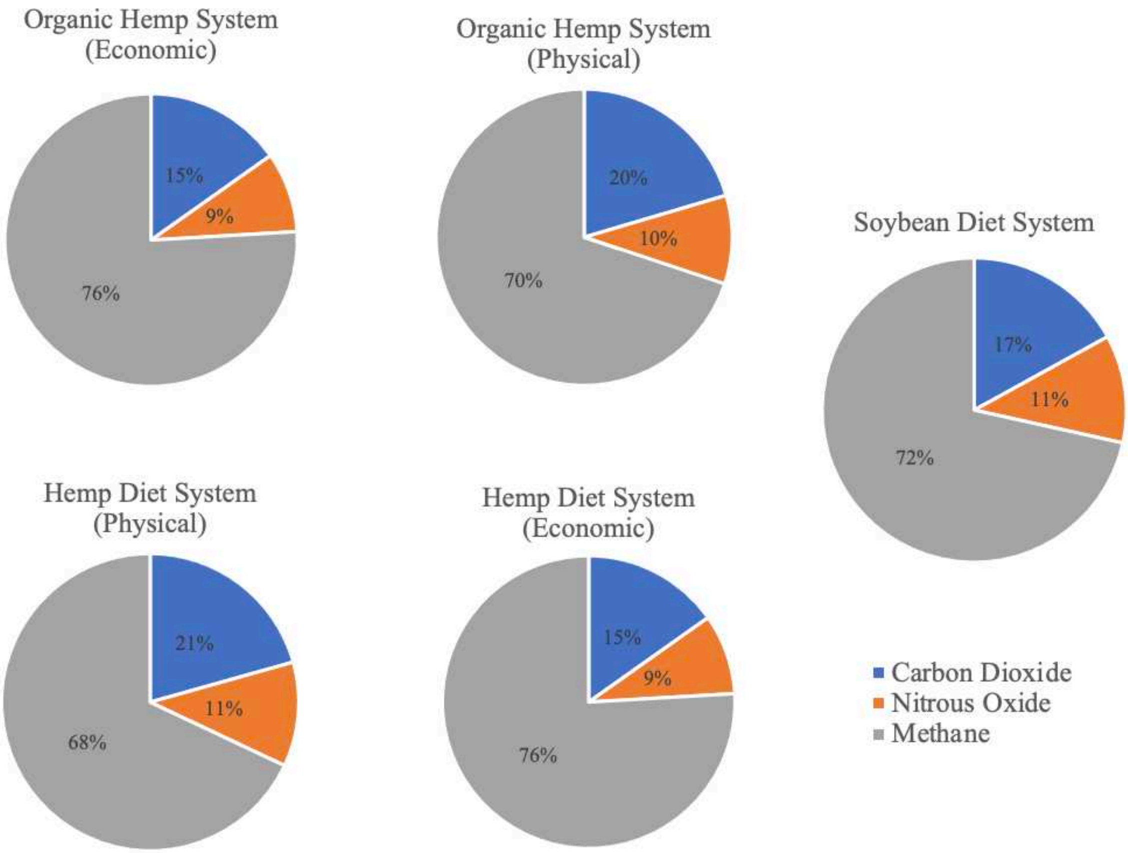

Figure 5. Distribution of each system's carbon footprint by gas emission.

Water Consumption

The water consumption impact category quantifies the amount of water the watershed is losing due to water being consumed by the product system under evaluation (Huijbregts et al., 2016). As such, it is more than simply a metric of water required to produce the product. Water consumption potential ranged from 1.3 to 4.2 m^3/kg LW (Fig. 6). As with the carbon footprint, allocation decisions impacted water consumption results. Water consumption potential for the soybean diet system was 1.5 m^3/kg LW. When economically allocated, water consumption for the hemp diet systems (both conventional and organic) were 16% lower than the soybean diet system, at 1.3 m^3/kg LW. However, when physically allocated, the hemp diet systems (both conventional and organic) had 1.8 times the water consumption potential of the soybean diet system.

Water consumption results were dominated by crop production, a reflection of irrigation. Irrigation practices differed between soybeans, corn, and hemp. Both corn and hemp were irrigated, with corn modeled as receiving 66.8 cm of water per season and hemp modeled as receiving 44.5 cm of water per season. Although corn required 50% more water per season than hemp, its yield was 285 times greater (1.59 kg/m^2 and 0.05 kg/m^2 for corn and hemp, respectively), therefore requiring significantly less water to produce 1 kg of grain.

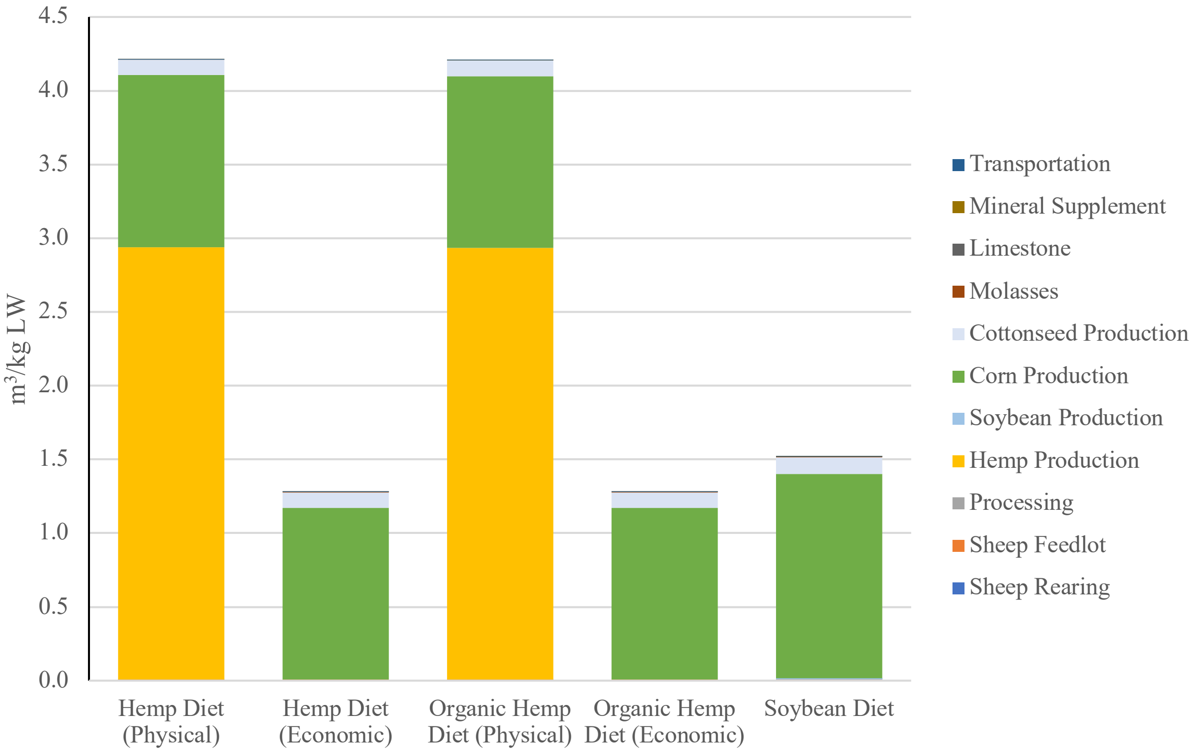

Figure 6. Water consumption results by system and allocation choice.

Land Use

Land use refers to biodiversity and species loss caused by specific types of land use like annual crops or pasture, in annual crop equivalents (Heijbregts et al., 2017). Land use results ranged from 2.8 m^2a crop eq/kg LW to 6 m^2a crop eq/kg LW (Fig. 7). The economically allocated hemp diet systems had the lowest land use (2.8 m^2a crop eq/kg LW), while the soybean diet system had the highest land use, at 6.0 m^2a/kg LW. Soybean production constituted a much larger proportion of the land use impact of the soybean diet system than did hemp production of the hemp diet systems (2.7 m^2a crop eq/kg LW or 45.0%, and 0.2 m^2a crop eq/kg LW or 7.5%, respectively). Corn production is the largest contributor to the land use result in the hemp systems (72%), and the second largest contributor in the soybean system (44%). Sheep rearing had no contribution to the land use impact because the metric does not include marginal land, and aims to measure loss to biodiversity.

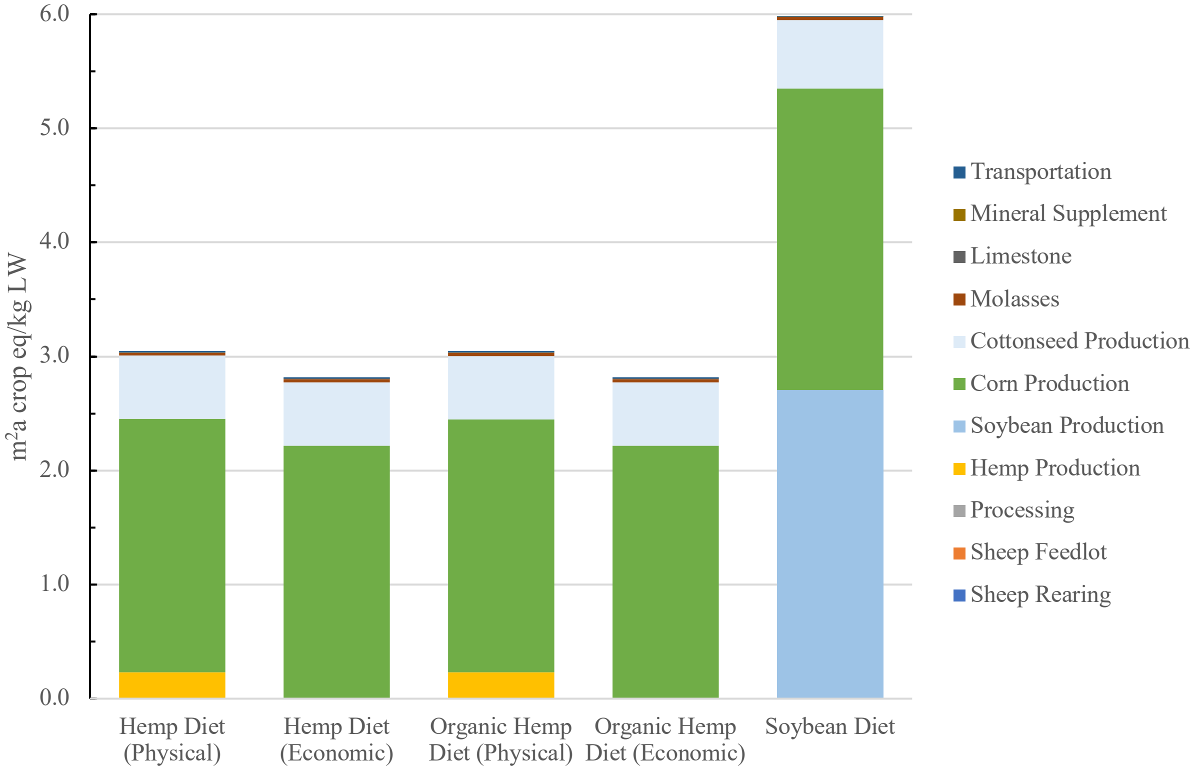

Figure 7. Land use results by system and allocation choice.

Fossil Resource Scarcity

Fossil resource scarcity refers to the ratio of the heating value of a fossil resource and the energy content of crude oil (Huijbregts et al., 2016). Fossil resource scarcity considers all energy utilized throughout a system, considers the fossil fuels depleted, and adjusts based on future scarcity of fossil energy. Fossil resource scarcity results ranged from 0.5 to 0.8 kg oil eq/kg LW (Fig. 8). In all the systems, the largest contributor to fossil resource scarcity was corn production. The post-harvest grain drying process required electricity. It is likely that if the corn was dried naturally, its contribution to the fossil depletion impact would be reduced.

When economically allocated, the hemp diet systems (both conventional and organic) had an 18% lower fossil resource scarcity result than the soybean diet system. However, when physically allocated, the hemp diet systems (both conventional and organic) had a 37 and 27% greater fossil resource scarcity impact, respectively.

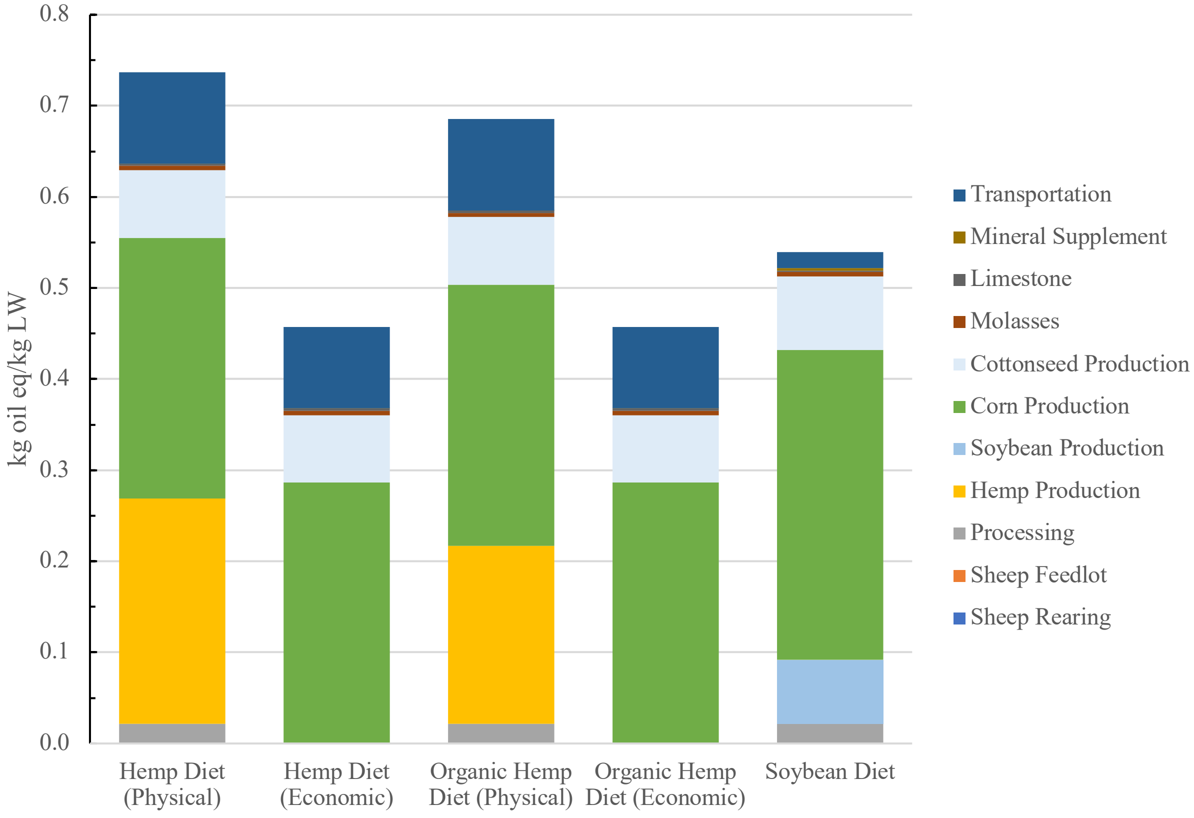

Figure 8. Fossil depletion results by system and allocation choice.

Impact of Allocation Choice on Results & Interpretation

The choice of physical or economic allocation method impacts the outcomes and interpretation of study results. The physically allocated hemp diet systems had greater global warming, water consumption, and fossil resource scarcity than the soybean diet systems. On the contrary, the use of economic allocation reduced the per-unit impact of lamb production such that it resulted in the soybean diet system having the largest impacts for all four categories.

In this study, allocation method was the determining factor for the interpretation of which diet system is “better” (*e.g.*, had lower environmental impacts per unit of product) due to the lack of an economic value for hemp seed meal at the time of this study. Though allocation choice may seem arbitrary, the decision of which approach to use in this study and how to interpret the results is critical to the development of sustainable livestock systems and continued environmental benefit of feeding byproducts to livestock. When considering the relationship between hemp oil and hemp seed meal, hemp oil is the determining product (the product for which a change in demand affects the production volume) and hemp seed meal is the dependent product (Matthews et al., 2014). As such, currently, without hemp oil, hemp seed meal would not be produced. This renders it a “true” byproduct, wherein the meal is a waste product that has been repurposed into livestock feed. Therefore, it can be argued that physical allocation does not align with the relationship between these co-products as it assigns the majority of the environmental impacts to hemp seed meal. Economic allocation better represents the current relationship between these products, and results in the hemp diet systems having lower environmental impacts than the soybean diet system.

There is no one “right” allocation methodology for all products and studies. LCA practitioners should make, and thoroughly document, allocation decisions based on the stated goal and scope of their work (Kyttä et al., 2022; Mackenzie et al., 2017; Pelletier et al., 2015). In the case of this study, economic allocation demonstrates that hemp seed meal is a byproduct, produced without economic value or use, due to demand for hemp oil. There are efforts to find use for hemp seed meal, which will likely lead to changes in monetary value and demand for the product. However, if the demand or monetary value changes and therefore the reason for producing the crop shifts, then so should the burden of environmental impacts (Ekvall & Finnveden, 2000; Mackenzie et al., 2017).

As economic allocation better reflects the relationship between the co-products and the function of the product system, this study concludes that feeding hemp seed meal as a replacement for soybean meal to sheep in the feedlot stage of production results in lower environmental impacts of lamb than feeding a conventional soybean meal diet.

Sensitivity Analysis: Electricity Use at Hemp Processing

Environmental impact results were not sensitive to an increase in electricity demand for hemp processing (Table 8). Neither a 10 nor a 20% increase in electricity demand impacted water consumption or land use results for any of the systems. Only miniscule increases were observed for carbon footprint and fossil depletion (0.02—0.16%). As such, if electricity use for processing is greater than that used in the model, it is likely that it would not lead to a large enough change to cause a difference in interpretation of results.

Table 8. Sensitivity of climate change, water depletion, agricultural land occupation, and fossil depletion results to an increase in hemp processing electricity.

	Sensitivity Index[1]	
	+10% Electricity	+20% Electricity
Hemp diet system (physical allocation)		
Global Warming	0.02	0.04
Water Consumption	0.00	0.00
Land Use	0.00	0.00
Fossil Resource Scarcity	0.08	0.15
Organic hemp diet system (physical allocation)		
Global Warming	0.02	0.04
Water Consumption	0.00	0.00
Land Use	0.00	0.00
Fossil Resource Scarcity	0.08	0.16

[1] Sensitivity index was calculated as the ratio of the difference between the new environmental impact result and the original, divided by the original value.

Sensitivity Analysis: Methane at Sheep Feedlot

The use of IPCC Tier 2 methods for calculating enteric methane emissions increased carbon footprint increases by 7.5—8.5% compared to when enteric methane emissions were modeled using RNS (Table 9).

Table 9. Impact of enteric methane emission equations on climate change results.

	Enteric Methane Equation		
	RNS[1]	IPCC Tier 2[2]	% Change
Hemp Diet (physical allocation)	11.4	12.3	7.5
Hemp Diet (economic allocation)	10.1	11.0	8.5
Organic Hemp Diet (physical allocation)	11.1	12.0	7.8
Organic Hemp Diet (economic allocation)	10.1	11.0	8.5
Soybean Diet	10.8	11.6	8.1

[1] RNS = Ruminant Nutrition System (Tedeschi & Fox, 2018)

[2] IPCC Tier 2 (IPCC, 2019)

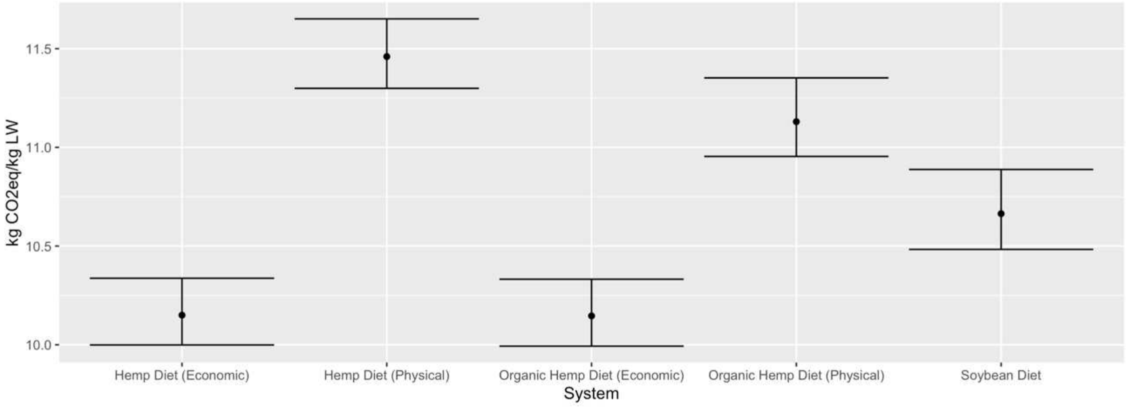

Figure 9. Uncertainty analysis for global warming results, by system and allocation type.

However, there is a significant difference between the land use of the soybean diet system and all of the hemp diet systems.

Uncertainty Analysis

Mean and 90% confidence intervals from the MCS for each environmental impact category are reported in the following section. Lack of overlap between confidence intervals of different systems suggests high confidence that the environmental impact results for those systems are significantly different.

Overall, for global warming potential, land use, and fossil resource scarcity, uncertainty results support the previous conclusions (Fig. 9, Fig. 10, Fig. 11).

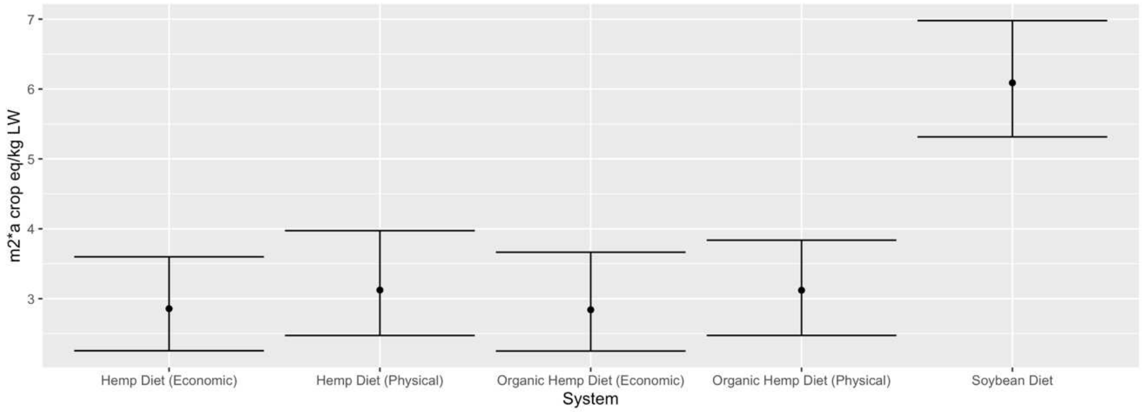

Figure 10. Uncertainty analysis for land use results, by system and allocation type.

Lack of overlap between the soybean diet system land use confidence interval and the hemp diet systems supports that the soybean diet system consistently has a larger land use impact than the hemp diet systems (Fig. 10).

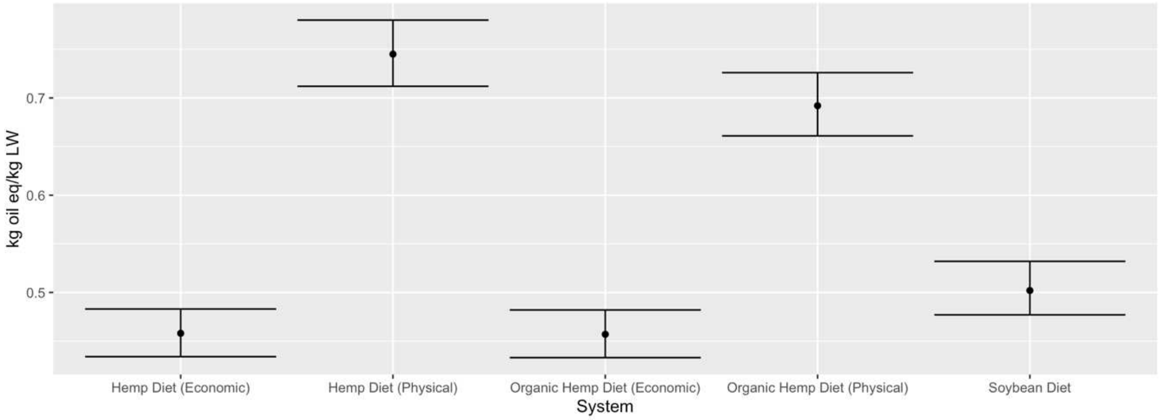

Figure 11. Uncertainty analysis for fossil resource scarcity results, by system and allocation type.

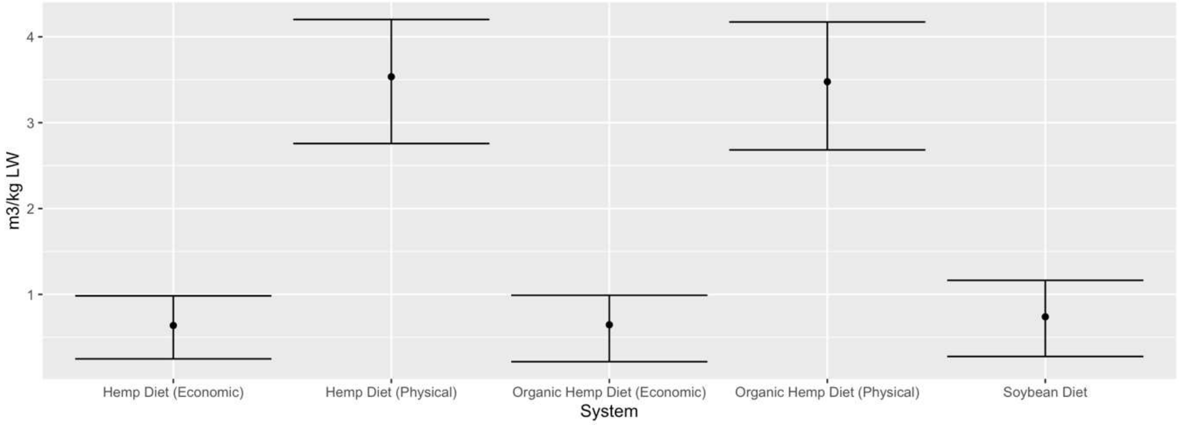

Figure 12. Uncertainty analysis for water consumption results, by system and allocation type.

However, the MCS results indicated that when accounting for uncertainty there was no significant difference between the hemp diet systems and the soybean diet system, negating the appearance of water consumption superiority of the hemp diet systems.

CONCLUSION

The results of this cradle to farm-gate LCA showed that one kg of lamb LW fed a feedlot ration containing either soybean meal or hemp seed meal produced 10.1 to 11.4 kg CO_2eq, required 1.3 to 4.2 m^3 of water consumption, resulted in fossil resource scarcity of 0.5 to 0.8 kg oil eq, and required 2.8 to 6.0 m^2a crop eq of land use. The physically allocated hemp diet systems had the greatest global warming, water consumption, and fossil resource scarcity impacts, while the economically allocated hemp diet systems had the least. The soybean diet system had the largest land use requirement, no matter allocation method of the hemp diet systems, and had greater impacts than the hemp diet systems for all categories when economic allocation was used.

This study highlighted the significance of allocation method in evaluating the impacts of feeding byproducts on the environmental impacts of livestock production systems. It contributes to the broader discussion about the significance of allocation choices on results and consequent interpretation. In this study, economic allocation was argued to be the more appropriate approach for evaluating the impact of feeding a novel byproduct to sheep on the environmental impacts of sheep production, as it more accurately reflects the relationship between hemp oil and hemp seed meal production. Additionally, the use of economic allocation can account for future changes in demand and monetary value of emerging commodities. Therefore, this research concludes that replacing soybean meal in a feedlot diet with hemp seed meal reduced the environmental impacts of sheep production.

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APPENDIX

Table 10. Life cycle inventory for soybean diet system.

Output to Market	Amount	Unit	Represents
Sheep Liveweight	56.2	kg	
Sheep Wool	2.72155	kg	
Ration Production	Amount	Unit	
Market for Cottonseed | Cottonseed | Cutoff, U - RoW	267.249587	kg	Cottonseed Hulls
Lime Production, milled, loose | lime | Cutoff, U- RoW	26.7516837	kg	Limestone
Maize grain production | maize grain | Cutoff, U - US	1131.05087	kg	Corn, ground
Mineral Supplement, for beef cattle | mineral supplement, for beef cattle | Cutoff, U- GLO	8.26870223	kg	Mineral Supplement
Market for Molasses, from sugar beet | Molasses, from sugar beet | Cutoff, U- GLO	120.736161	kg	Molasses, cane, dry
Soybean Meal and Crude oil production | Soybean Meal | Cutoff, U- US	260.310996	kg	Soybean Meal
Sheep Rearing	Amount	Unit	
Occupation, grassland, natural, for livestock grazing	1.62	ha*a	Rangeland
Transportation-Sheep	Amount		
Sheep	160	Unit	
transport, freight, lorry >32 metric ton, EURO6 | transport,	10*482	t*km	Semi-truck

freight, lorry >32 metric ton, EURO6 | Cutoff, U - RER			
Sheep Feedlot	Amount	Unit	
Sheep Ration	360	kg	Total ration fed, produced by ration production
Sheep	1	Unit	1 Sheep, produced by sheep rearing
Water, well, NA	374688.04	ml	Water
Emissions to Air	Amount		
Methane, biogenic	1.44	kg	Manure and enteric methane emission at feedlot
Dinitrogen Monoxide	0.049878	kg	Manure nitrogen emission at feedlot
Methane, biogenic	10.8	kg	Manure and enteric methane emission at rearing
Dinitrogen Monoxide	0.035	kg	Manure nitrogen emission at rearing

Table 11. Life cycle inventory for hemp diet system.

Output to Market	Amount	Unit	Represents
Sheep Liveweight	56.2	kg	
Sheep Wool	2.72155	kg	
Ration Production	Amount	Unit	
market for cottonseed | cottonseed | Cutoff, U - RoW	268.87328	kg	Cottonseed Hulls
Hemp Seed Cake	353.410154	kg	Hemp seed cake
lime production, milled, loose | lime | Cutoff, U - RoW	71.9221048	kg	Limestone
maize grain production | maize grain | Cutoff, U - US	1037.82846	kg	Corn
mineral supplement production, for beef cattle | mineral supplement, for beef cattle | Cutoff, U - GLO	0.35961052	kg	Mineral Supplement

market for molasses, from sugar beet | molasses, from sugar beet | Cutoff, U - GLO	121.469702	kg	Molasses
Sheep Rearing	Amount	Unit	
Occupation, grassland, natural, for livestock grazing	1.62	ha*a	Range land
Transport- Sheep			
Sheep	160	Unit	
transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | Cutoff, U - RER	10*482	t*km	Semi-truck
Sheep Feedlot	Amount	Unit	
Sheep Ration	330	kg	Total ration fed, produced by ration production
Sheep	1	Unit	1 Sheep, produced by sheep rearing
Water, well, NA	361745.119	ml	Water
Transport- Hemp seed cake	Amount		
Hemp Seed Cake	23586	kg	
market for transport, freight, lorry 16-32 metric ton, EURO6 | transport, freight, lorry 16-32 metric ton, EURO6 | Cutoff, U - RER	23.5*1126	t*km	Semi-truck
Hemp Processing- Cold Press Extraction	Amount		
market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - US	0.04486432	kWh	Electricity
market for heat, central or small-scale, other than natural gas	0.01470274	MJ	

| heat, central or small-scale, other than natural gas | Cutoff, U - RoW			
market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Cutoff, U - RoW	0.6371187	MJ	
market for heat, district or industrial, other than natural gas | heat, district or industrial, other than natural gas | Cutoff, U - RoW	0.32836118	MJ	
Hemp seed, transported	1.82	kg	Hemp seed
market for hexane | hexane | Cutoff, U - GLO	4.60E-04	kg	
market for oil mill | oil mill | Cutoff, U - GLO	1.41E-10	Item(s)	Cold press oil machine
market for tap water | tap water | Cutoff, U - RoW	0.39539596	kg	
Transport- Hemp seed			
Hemp seed	18140	kg	
transport, freight, lorry 16-32 metric ton, EURO6 | transport, freight, lorry 16-32 metric ton, EURO6 | Cutoff, U - RER	18*120	t*km	Semi-truck
Hemp Production			
market for baling | baling | Cutoff, U - GLO	3263.506	Items	Fiber baled and taken off of the field
market for combine harvesting | combine harvesting | Cutoff, U - GLO	1447	ac	Harvesting seeds

market for fertilising, by broadcaster | fertilising, by broadcaster | Cutoff, U - GLO	2894	ac	Fertilizing
market for glyphosate | glyphosate | Cutoff, U - GLO	492.260718	kg	Herbicide, roundup
irrigation, sprinkler | irrigation | Cutoff, U - US	2603053.04	m3	Irrigation
market for manure, liquid, cattle | manure, liquid, cattle | Cutoff, U - GLO	2894	t	Cow manure fertilizer
Occupation, annual crop, irrigated	585.5801	ha*a	Crop land
market for poultry manure, fresh | poultry manure, fresh | Cutoff, U - GLO	1115.7817	t	Poultry manure fertilizer
market for sowing | sowing | Cutoff, U - GLO	1447	ac	Sowing seeds
market for sunflower seed | sunflower seed | Cutoff, U - GLO	23425.6823	kg	Hemp Seed for sowing
urea production | urea | Cutoff, U - RNA	65634.7624	kg	Nitrogen fertilizer
Emissions to Air			
Dinitrogen monoxide	1132.72014	kg	Nitrogen emissions from hemp field
Dinitrogen monoxide	0.049878	kg	Manure nitrogen emission at feedlot
Methane, biogenic	1.44	kg	Manure and enteric methane emission at feedlot
Methane, biogenic	10.8	kg	Manure and enteric methane emission at rearing
Dinitrogen Monoxide	0.035	kg	Manure nitrogen emission at rearing

Output to Market	Amount	Unit	Represents
Sheep Liveweight	56.2	kg	

Sheep Wool	2.72155	kg	
Ration Production	Amount	Unit	
Market for Cottonseed | Cottonseed | Cutoff, U - RoW	268.87328	kg	Cottonseed Hulls
Lime Production, milled, loose | lime | Cutoff, U- RoW	71.9221048	kg	Limestone
Market for Maize Grain, feed | Maize grain, feed | Cutoff, U- RoW	1037.82846	kg	Corn, ground
Mineral Supplement, for beef cattle | mineral supplement, for beef cattle | Cutoff, U- GLO	0.35961052	kg	Mineral Supplement + Dicalcium Phosphate
Market for Molasses, from sugar beet | Molasses, from sugar beet | Cutoff, U- GLO	121.469702	kg	Molasses, cane, dry
Hemp Seed Cake	353.410154	kg	Hemp Seed Meal, produced by Hemp Processing
Sheep Rearing	Amount	Unit	
Occupation, grassland, natural, for livestock grazing	1.62	ha*a	Range land
Transport- Sheep			
Sheep	160	Unit	
transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | Cutoff, U - RER	10*482	t*km	Semi-truck
Sheep Feedlot	Amount	Unit	
Sheep Ration	330	kg	Total ration fed, produced by ration production
Sheep	1	Unit	1 Sheep, produced by sheep rearing
Water, well, NA	361745.119	ml	Water

Transport- Hemp seed cake	Amount		
Hemp Seed Cake	23586	kg	
market for transport, freight, lorry 16-32 metric ton, EURO6 | transport, freight, lorry 16-32 metric ton, EURO6 | Cutoff, U - RER	23.5*1126	t*km	Semi-truck
Hemp Processing- Cold Press Extraction			
market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - US	0.04486432	kWh	Electricity
market for heat, central or small-scale, other than natural gas | heat, central or small-scale, other than natural gas | Cutoff, U - RoW	0.01470274	MJ	
market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Cutoff, U - RoW	0.6371187	MJ	
market for heat, district or industrial, other than natural gas | heat, district or industrial, other than natural gas | Cutoff, U - RoW	0.32836118	MJ	
Hemp seed, transported	1.82	kg	Hemp seed
market for hexane | hexane | Cutoff, U - GLO	4.60E-04	kg	
market for oil mill | oil mill | Cutoff, U - GLO	1.41E-10	Item(s)	Cold press oil machine

market for tap water | tap water | Cutoff, U - RoW	0.39539596	kg	
Transport- Hemp seed			
Hemp seed	18140	kg	
transport, freight, lorry 16-32 metric ton, EURO6 | transport, freight, lorry 16-32 metric ton, EURO6 | Cutoff, U - RER	18*120	t*km	Semi-truck
Hemp Production			
market for baling | baling | Cutoff, U - GLO	2954.52189	Items	Fiber taken off of the field
market for combine harvesting | combine harvesting | Cutoff, U - GLO	1310	ac	Harvesting seeds
market for fertilising, by broadcaster | fertilising, by broadcaster | Cutoff, U - GLO	2620	ac	Fertilizing
irrigation, sprinkler | irrigation | Cutoff, U - US	2356599.5	m3	Irrigation
market for manure, liquid, cattle | manure, liquid, cattle | Cutoff, U - GLO	2620	t	Cow manure fertilizer
Occupation, annual crop, irrigated	530.1382	ha*a	Crop land
market for poultry manure, fresh | poultry manure, fresh | Cutoff, U - GLO	1010.141	t	Poultry manure fertilzer
market for sowing | sowing | Cutoff, U - GLO	1310	ac	Sowing
market for sunflower seed | sunflower seed | Cutoff, U - GLO	21207.7705	kg	Hemp Seed for sowing

Emissions to Air	Amount		
Dinitrogen monoxide	431.270207	kg	
Dinitrogen monoxide	0.049878	kg	Manure nitrogen emission at feedlot
Methane, biogenic	1.44	kg	Manure and enteric methane emission at feedlot
Methane, biogenic	10.8	kg	Manure and enteric methane emission at rearing
Dinitrogen Monoxide	0.035	kg	Manure nitrogen emission at rearing