A SPATIALLY EXPLICIT GREENHOUSE GAS FOOTPRINT OF BEEF PRODUCTION SUPPLY CHAINS IN THE UNITED STATES

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ABSTRACT

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Across all food products, beef has consistently been reported as having one of the largest greenhouse gas (GHG) footprints. In order to reduce the amount of GHGs emitted as a result of beef production, a better understanding of the GHG emissions linked to the complexities of the beef supply chain is critical. Here we estimate the GHG footprint attributed to domestic beef consumption in major U.S. metropolitan areas and non-metro regions using a spatially and temporally explicit model of the U.S. beef production supply chain network which tracks the flow of feed, cattle, and beef from origin to destination. The beef production network was created for the year 2012 using commodity flow data from the Commodity Flow Survey and Freight Analysis Framework, commodity production data, and leverage network principles. A life-cycle assessment based on the resulting beef production network is conducted using GHG emission factors and energy consumption data obtained through a comprehensive literature review and established GHG accounting protocols. We estimate a U.S. average GHG footprint of 8.7 ± 3 kg CO2e/lb retail beef. Cattle production contributes the vast majority (75%) of GHG emissions related to beef production with enteric-fermentation alone contributing 66%. Across all domestic beef destinations (except Alaska and Hawaii), the proportional contribution of GHG emissions from each step of the supply chain to the total supply chain GHG footprint was relatively consistent. Though transport as a emissions source showed the greatest range in emissions relative to other sources in individual beef supply chains, at the national level

transportation only accounts for 4% of beef supply chain emissions. This underscores the importance of addressing feed and cattle production practices, particularly enteric fermentation as the largest emissions source, as opposed to focusing only on reducing vehicle miles traveled within the supply chain. Unlike previous work that focuses on calculating GHG emissions for either one individual region or generalized across the U.S., this study developed a hybrid life cycle assessment - urban metabolism approach combined with regional-level commodity flow data to track GHG emissions for individual beef supply chains in a manner that is inclusive of and comparable across each metro- and non-metropolitan area.

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LIST OF ABBREVIATIONS

AFOLU - agriculture, forestry, and other land use

CBW - Cattle Buyers Weekly

CFN - commodity flow network

CFS - Commodity Flow Survey

DM - dry matter

EPA - Environmental Protection Agency

ERS - Economic Research Service

FAF4 (or FAF) - Freight Analysis Framework version 4

FB OOS - farm-based out-of-scope

GHG - greenhouse gas

GWP - global warming potential

IOA - input-output analysis

IPCC - Intergovernmental Panel on Climate Change

MA - metropolitan areas

LCA - life cycle assessment

LULUCF - land-use, land-use change, and forestry

LW - live weight

MMT - million metric tons

NASS - National Agricultural Statistics Service

SCTG - Standard Classification of Transported Goods

UM - urban metabolism

USDA - United States Department of Agriculture

PREFACE

This thesis is presented as a self-contained manuscript with extended introductory and discussion chapters. Chapter 2 serves as a self-contained manuscript formatted for future submission to the journal *Environmental Research Letters*. As a result of combining these chapters within the university formatting requirements, some redundancy in information will result throughout.

CHAPTER 1:

INTRODUCTION

1.1 Global Climate Change

Data from paleoclimate research helps us to understand how Earth's climate has changed over the past tens-of-thousands to millions of years (NRC 2020). Paleoclimate records show that global shifts in Earth's climate have happened very slowly over time scales of thousands or millions of years due to variations in Earth's orbit in relation to the sun (Milankovitch cycles), cyclical changes in the intensity of solar radiation, the location of land masses, volcanic eruptions, and levels of CO_2 in the Earth's atmosphere (NRC 2020).Today, changes in global climate are happening at a faster rate than ever before in Earth's history (USGCRP 2018, Mann *et al* 2008). Over the last 100 years, the average global temperature has increased approximately 1°C (1.8°F) (IPCC 2018). The current rate of warming is approximately 10 times faster than the fastest known sustained change in global-scale climate in Earth's history (NRC 2020). Human activity is the main cause of the climate change we are experiencing today (Maibach *et al* 2014). Activities such as burning fossil fuels, clearing forests, and certain farming practices have increased the amount of greenhouse gasses (GHG) emitted into the atmosphere on an annual basis (IPCC 2014a). As the amount of GHGs in the atmosphere increases, more of the heat radiating off the Earth's surface is trapped by GHGs in the atmosphere, leading to an increase in Earth's temperature.

The Intergovernmental Panel on Climate Change (IPCC), an intergovernmental body, routinely publishes thorough, systematic assessments of current scientific understanding relevant to anthropogenic climate change; new reports are released every 6-7 years. Without rapid reductions in GHG emissions, the IPCC projects that average global temperature will continue to rise to at least 1.5°C above pre-industrial levels by around 2040 (IPCC 2018). The effects of global warming will vary over time and across the globe. Across the US, the impacts of climate change will differ regionally ranging from the increased occurrence and severity of droughts, extreme heat events, flooding, and wildfires, as well as decreased snowpack, and sea-level rise. Some of these impacts are already occurring and have the potential to severely damage our social, economic, and environmental systems (USGCRP 2018). Climate change also threatens the stability of our food systems and food security worldwide (FAO *et al* 2017).

The IPCC has advised that an international effort must be made to both (1) reduce GHG emissions through ambitious mitigation measures in order to slow or stop the rate of climate warming; and (2) make adjustments to our social, economic, and environmental systems to adapt to the impacts of climate change (IPCC 2014b). In order to avoid surpassing a 1.5°C global warming, annual emissions of anthropogenically sourced GHGs would need to drop 50% below 2010 levels by 2030 and 100% below 2010 levels by 2050 (IPCC 2018). In 2016, global GHG emissions totaled ~49 billion tonnes CO_2 equivalent (CO_2e;Climate Watch 2021). U.S. emissions in 2016 were almost 6 billion tonnes CO_2e, making up approximately 12% of global emissions (Climate Watch 2021). Global emissions have continued to increase (Global Carbon Budget 2021) and while U.S. emissions have decreased by about 12% since 2007, this small decrease in U.S. emissions is nothing close to the drastic reductions in GHG emissions necessary to mitigate global climate change. In order to generate solutions for climate change mitigation, an extensive amount of ongoing research (e.g., Ceschia *et al* 2010, Chen *et al* 2020, Garnett 2011, Gurney *et al* 2020, Hallström *et al* 2015, Heller *et al* 2018, Poore and Nemecek 2018, Sonesson *et al* 2010, Vergé *et al* 2007, Weber and Matthew 2008, Yue *et al* 2017) seeks to learn more about anthropogenic sources of GHG emissions and ways that those emissions can be reduced.

1.2 Greenhouse Gas Emissions

Composition of Anthropogenic Greenhouse Gas Emissions

GHG emissions produced by human activities are predominantly carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), plus trace gasses like fluorinated gasses (F-gasses). In 2016, the proportion of global emissions by GHG were: CO_2 (74%), CH_4 (17%), N_2O (6%), and F-gasses (2%) (Climate Watch 2021). Within the US, the breakdown of GHG emissions by gas type for 2016 was very similar: CO_2 (80%), CH_4 (10%), N_2O (7%), and F-gasses (3%) (U.S. EPA 2021). GHG emissions at the global and U.S. level according to gas type are summarized below in Table 1.1.

Table 1.1 2016 GHG emissions at global and U.S. national level by proportion of gas type. Sources: Climate Watch 2021, EPA 2021.

	Carbon dioxide (CO_2)	Methane (CH_4)	Nitrous oxide (N_2O)	Fluorinated gasses (F-gasses)
Global[1]	74 %	17 %	6 %	2 %
US[2]	80 %	10 %	7 %	3 %

Each of these GHGs can contribute to global warming when accumulated in Earth's atmosphere. However, each gas contributes to that warming to a different degree depending on three factors: its current concentration in the atmosphere, its atmospheric lifetime (i.e., how long it typically stays in the atmosphere), and the wavelengths of longwave energy emitted from Earth's surface that it absorbs. All of these factors determine a GHG's global warming potential (GWP) - the ability of a given mass of a GHG to trap heat and contribute to warming relative to CO_2. GWPs are a relative metric used to determine the global warming impact of different types of GHGs and to convert non-CO_2 GHGs into CO_2e - amounts of GHG emissions and are a unit commonly used in GHGgreenhouse gas accounting. As the reference gas, the GWP for CO_2 is 1 and all other GHGs have a higher GWP in relation. For example, the global warming potential of methane (CH_4) emitted from the combustion of fossil fuels is 29.8 over a 100-year time horizon; meaning that the emission of one tonne of methane is equivalent to the emission of 29.8 tonnes of carbon dioxide (29.8 tonne CO_2e) (IPCC 2022). The CO_2e or CO_2 equivalent metric represents the amount (often in metric tons or tonnes) of CO_2 emissions that would cause the same amount of radiative forcing over a given time horizon as a mixture of CO_2 and non-CO_2 GHGs (IPCC 2018).

Anthropogenic Sources of Greenhouse Gas Emissions

Globally, 2019 anthropogenic sources of GHG emissions can be broken down by economic sector into the following: energy supply (34%), agriculture, forestry, and other land use (22%), industry (24%), transportation (15%), and buildings (6%) (IPCC 2022). By comparison, within the US, 2019 anthropogenic GHG emissions came from the following sources: transportation (29%), electricity (25%), industry (23%), commercial and residential buildings and waste (13%), and agriculture (10%) (U.S. EPA 2021). In order to achieve net zero GHG emissions by 2050 as recommended by the IPCC, emissions from all anthropogenic sources must either be reduced to zero or reduced low enough that they can be offset by an equivalent amount of additional GHG sequestration in order to reach a net balance of zero emissions (IPCC 2014a). Each anthropogenic source of GHG emissions and contributing economic sector must be explored for climate change mitigation potential.

Agriculture as a Source of Greenhouse Gas Emissions

As noted above, in 2019 the agriculture, forestry, and other land use (AFOLU) economic sector contributed 22% of global GHG emissions (IPCC 2022). In addition to agricultural GHG emissions, the AFOLU sector also includes non-agricultural GHG fluxes from activities such as deforestation for development or commercial logging, afforestation, and forest or peat fires (IPCC 2014a). Emissions related to the operation of machinery used for relevant agricultural and non-agricultural activities are typically accounted for in the energy sector and excluded from AFOLU (IPCC 2014a). However, fossil fuel emissions generated from the use of agricultural machinery such as tractors, irrigation pumps, and other machinery on croplands alone contributes approximately 0.4–0.6 $GtCO_2e$ per year (Ceschia *et al* 2010; FAOSTAT 2013); if incorporated into the AFOLU sector, emissions from farm machinery would make up ~3% of all AFOLU emissions (IPCC 2022).

Within the US, emissions from agriculture make up a smaller but sizable percentage of total GHG emissions. According to the U.S. Environmental Protection Agency (EPA), agriculture was responsible for 9.6% of U.S. GHG emissions in 2019 - a 13.3% net increase since 1990 (U.S. EPA 2021). It is important to note that the EPA's estimate for the agriculture sector excludes emissions from land-use, land-use change, and forestry (LULUCF) and agriculture-related energy use. Like the IPCC, the EPA includes emissions from electricity and use of agricultural machinery in the energy sector. Unlike the IPCC, the EPA includes emissions from cropland, rangeland, and pasture related land-use in a LULUCF category separate from the agriculture sector (U.S. EPA 2021). Emissions from changing terrestrial carbon stocks due to land-use practices and land-use changes on pasture, rangeland, and croplands made up 1.1% of total U.S. GHG emissions in 2019 and should not be overlooked as an impact of the U.S. agriculture sector.

According to the EPA, almost all of the GHGs emitted by the U.S. agricultural sector in 2019 were either methane, CH_4 (40.8%) or nitrous oxide, N_2O (58%) with CO_2 from urea fertilization and liming making up less than 2% of emissions (U.S. EPA 2021). When including agriculture-related LULUCF, the GHG breakdown becomes CH_4 (37%), N_2O (52%), and CO_2 (11%) for the agriculture sector. Though non-CO_2 GHG emissions from agriculture made up only 10-15% of all global anthropogenic emissions (FAOSTAT 2013; Tubiello *et al* 2013), they make up just over half (56%) of global anthropogenic non-CO_2 emissions (U.S. EPA 2012).

EPA analysis suggests that, within the US, agricultural soil management was responsible for over half (55%) of GHG emissions from agriculture in 2019. Agricultural soil management emits N_2O via activities such as the growth of nitrogen-fixing plants, application of fertilizers, and deposition of manure from livestock (U.S. EPA 2021). Because the EPA accounts for the GHG emissions related to land-use, land-use change, and forestry in a category separate from agriculture, EPA statistics for agricultural soil management do not account for the soil carbon loss that occurs due to land conversion, tillage, and poor soil management practices (U.S. EPA 2021). Combined, enteric fermentation (a digestive process that occurs in cattle, sheep, goats, and other ruminants) and manure management are also responsible for a significant portion (41%) of U.S. agricultural emissions. The remaining 4% of agricultural GHG emissions, as reported by the EPA, come from rice cultivation, urea fertilization, liming, and field burning of agricultural residues (U.S. EPA 2021, see figure 1.1).

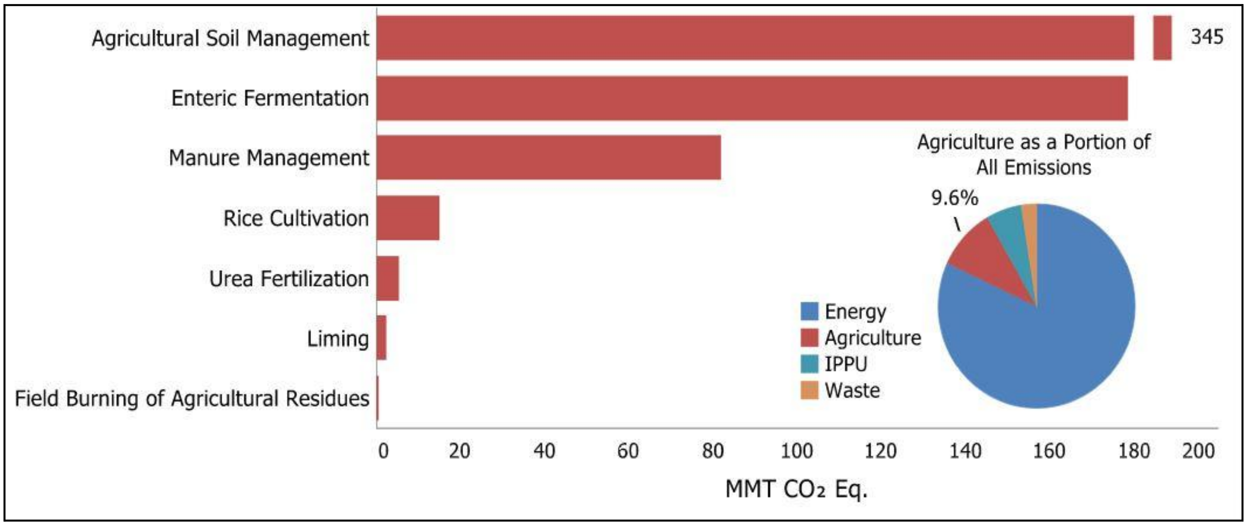

Figure 1.1 Sources of GHG emissions (in million metric tons or MMT CO_2e) within the U.S. agricultural sector in 2019. Source: EPA 2021.

Impact of Livestock

Not all agricultural products are responsible for an equal proportion of the GHGs emitted by the agricultural sector. Animal-related agriculture and the production of livestock are responsible for a significant portion of anthropogenic GHG emissions at both a global and national level. Approximately 14.5% of global GHG emissions can be attributed to livestock production (Gerber *et al* 2013). Within the US, the majority (66%) of agricultural GHG emissions came from livestock production in 2018 (USDA 2022). This 66% includes emissions of CH_4 from enteric fermentation in livestock, N_2O & CH_4 from managed livestock waste, and N_2O & CH_4 from grazed land. Enteric fermentation alone is the largest anthropogenic source of CH_4 in the U.S. (U.S. EPA 2019). Not included in the 66% are any emissions related to the production of animal feed for livestock. In the US, use of nitrogen fertilizer in soil management is a significant source of emissions within the agricultural sector and approximately 50% of fertilizer use supports the production of animal feed and pasture (Steinfeld *et al* 2006).

Of all global GHG emissions from livestock production, cattle are responsible for the majority (65%) (Gerber *et al* 2013, USDA 2016). Beef and dairy cattle alone are responsible for 6% of total global GHG emissions, more than any other livestock species (Gerber *et al* 2013, USDA 2016). Compared to other livestock populations (including sheep, chickens, pigs, etc.), the U.S. cattle population releases an extremely high amount of CH_4 through enteric fermentation. Additionally, emissions of CH_4 and N_2O from waste management (especially for dairy cattle) and N_2O, CH_4, and CO_2 from grazed lands are higher for cattle than for any other livestock species (see figure 1.2). Beef cattle are the single largest contributors to U.S. GHG emissions from livestock - in 2013, emissions from beef cattle made up 63% of all livestock emissions in the U.S (USDA 2016).

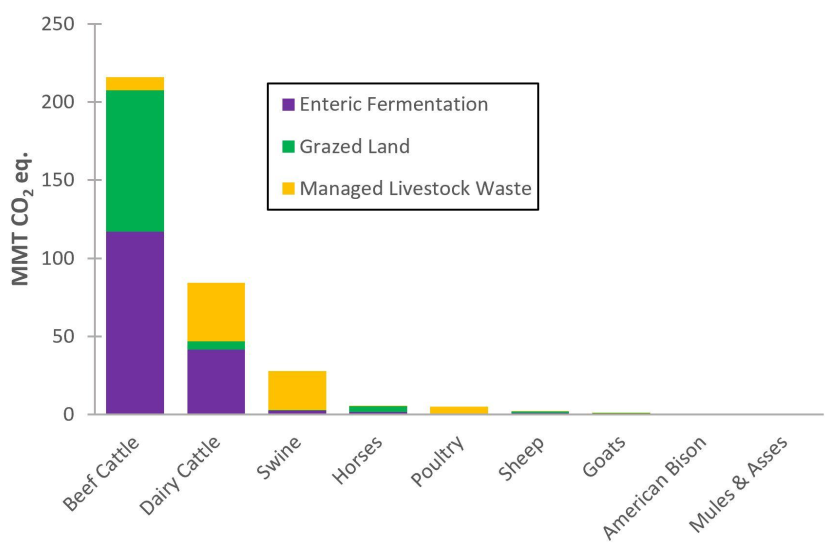

Figure 1.2 U.S. GHG emissions in million metric tons (MMT) CO_2e by livestock category and source in 2013. Note: Methane emissions from manure deposited on grasslands is not partitioned by animal type. MMT CO_2 eq. is million metric tons carbon dioxide equivalent. Emissions for each source include: enteric fermentation - CH_4 , grazed land - N_2O, CH_4 , CO_2 , and livestock waste - CH_4 , N_2O. Data source: USDA 2016

1.3 Food Production Systems

Some of the climate change mitigation solutions being explored involve changes in how society produces, provides, and consumes goods and services (Girod *et al* 2014). Knowledge that the agricultural sector contributes significantly to global and national GHG emissions (IPCC 2014a, IPCC 2022, EPA 2012 2019 2021, USDA 2016 2022) has motivated deeper interdisciplinary research into both the climate change impacts and mitigation opportunities of food production (Sonesson *et al* 2010, Vergé *et al* 2007). GHG emissions-related information is often grouped or aggregated by economic sector. However, to gain a comprehensive understanding of the GHG emissions impact of specific goods and services, it is necessary to look at the full lifecycle emissions of specific goods and services which involve multiple economic sectors. Food production includes not only the agricultural sector, but also the industrial, transportation, and electricity sectors (Heller and Keoleian 2000, Crosson *et al* 2011). For example, large-scale poultry farms use a substantial amount of electricity for lighting, heating and cooling systems, ventilation, as well as feeding and watering systems; this electricity consumption generates GHG emissions which contribute to the overall environmental impact of poultry production (Kilic 2016). Chickens are often transported on trucks from hatchery to production farm and from farm to processing plant, an activity that also generates GHG emissions (Harris 2015). As previously mentioned, land-use and land-use change related to agricultural activities are a significant source of GHG emissions but are not always accounted for when assessing the climate impact of agricultural production. In order to fully understand the impact food production has on climate change, recent studies (Chen *et al* 2020, Clune *et al* 2017, Crippa *et al* 2021, Garnett 2011, Poore and Nemecek 2018) aim to quantify and analyze the GHG emissions generated by entire supply chains for different foods.

Food Supply Chains

Almost all of the food consumed in the U.S. is part of a food supply chain. A food supply chain consists of everything involved in the production of food, often beginning with the land where crops are cultivated and ending at either the grocery store, restaurant, at-home point of consumption, or as food waste (Garnett 2011). The boundaries of what is considered the "beginning" or "ending" of a food supply chain may differ depending on the focus of the study (IOM and NRC 2015). For example, some studies might set their supply chain boundaries to include the energy-intensive production of nitrogen fertilizers as inputs to crop production (Sutton *et al* 2013), where other studies might exclude anything that happens before crops are planted (Countryman *et al* 2016).

When analyzed from a supply chain perspective, the global food production system contributes between a quarter (Poore and Nemecek 2018) to one third (Crippa *et al* 2021) of the world's anthropogenic GHG emissions. A 2018 study by Poore and Nemecek evaluated the food production system according to four main categories of GHG emissions sources: (1) land use; (2) crop production; (3) livestock & fisheries; and (4) processing, transport, packaging, and retail (see figure 1.3). It should be noted that Poore and Nemecek used the term "supply chain" to refer only to the activities listed above in category (4), whereas other studies may define "supply chain" to include all four categories as they apply to a specific food product. The majority of emissions from food production are generated by agriculture and land-use activities, particularly livestock production. Land-use for livestock, production of animal feed, and on-farm raising of livestock and aquaculture make up over half (53%) of all emissions from the food production system (Poore and Nemecek 2018). Less than 25% of emissions from food production originate from food processing, transport, packaging, and retail activities (Poore and Nemecek 2018, Crippa *et al* 2021, Weber *et al* 2008).

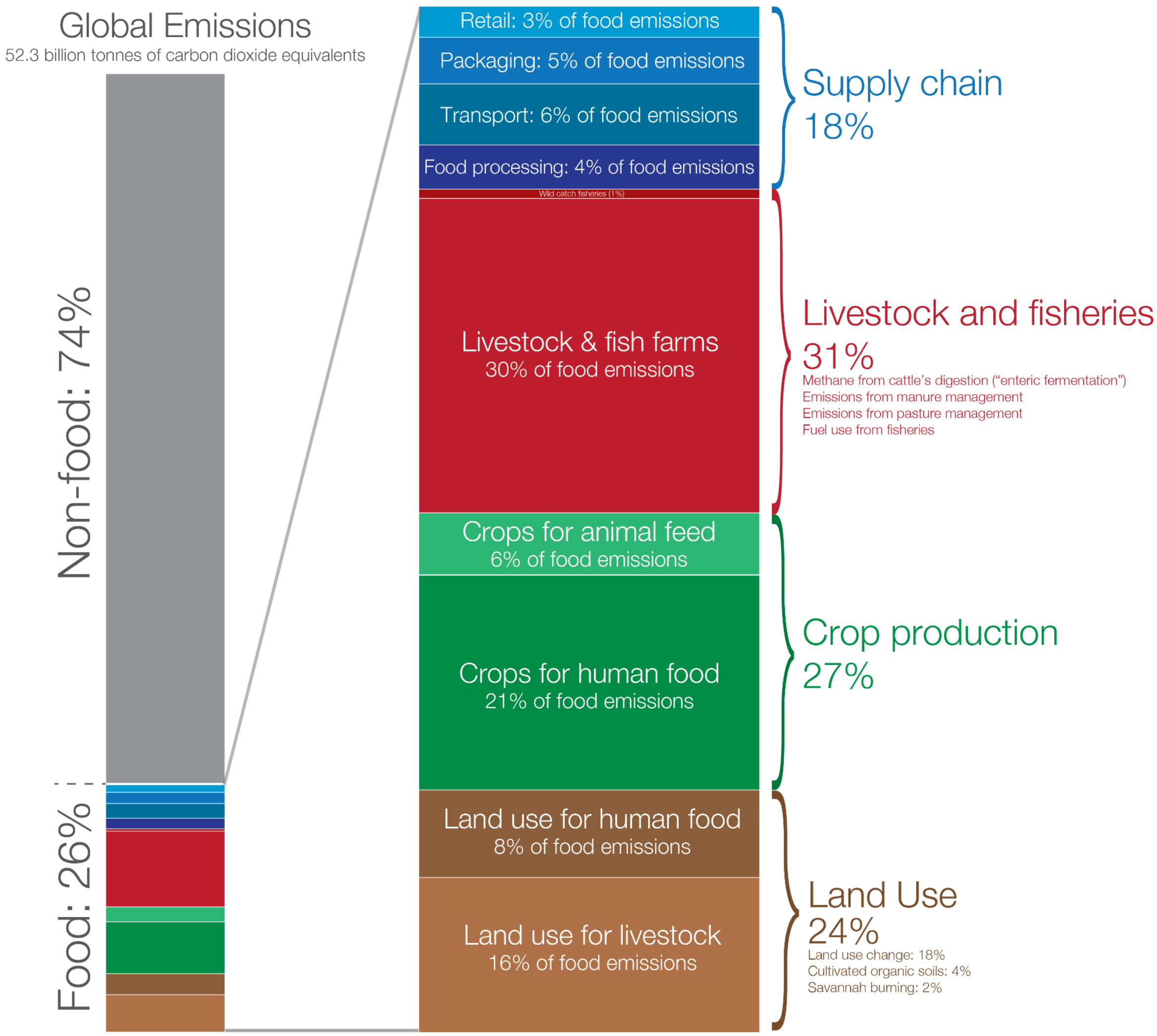

Figure 1.3 Global greenhouse gas emissions from food production by source type. Source: Ritchie 2019, Poore and Nemecek 2018

1.4 Animal vs. Plant-Based Foods

Exploring food production from the perspective of multisectoral supply chains rather than isolated economic sectors is a more holistic approach for understanding the GHG emissions associated with a particular good, product, or service. When evaluating emissions from the food production system at the level of individual food products, studies have found that certain foods have larger GHG footprints and are responsible for a larger portion of emissions than other foods (Clune *et al* 2017, Poore and Nemecek 2018, Virtanen *et al* 2011, Yue *et al* 2017). Numerous studies (e.g., Xu and Lan 2016, Virtanen *et al* 2011, Yue *et al* 2017) and meta-analyses (e.g., Poore and Nemecek 2018, Clune *et al* 2017) have shown that animal-based food products are responsible for significantly more GHG emissions than plant-based foods. A 2018 study by Poore and Nemecek, one of the largest meta-analyses concerning the environmental impact of food products, analyzed data from 570 studies covering ~38,700 commercially viable farms in 119 countries and 40 food products. Of all food products, beef was found to have the largest GHG footprint (~60 kg CO_2e/kg of beef; Poore and Nemecek 2018). Beef's GHG footprint was more than twice as large as the second largest food GHG footprint: mutton and lamb at 24 kg CO_2e per kg (see figure 1.4). Of those food products rich in protein - nuts, peas, beans, and tofu had the lowest GHG footprint per gram of protein (see figure 1.4).

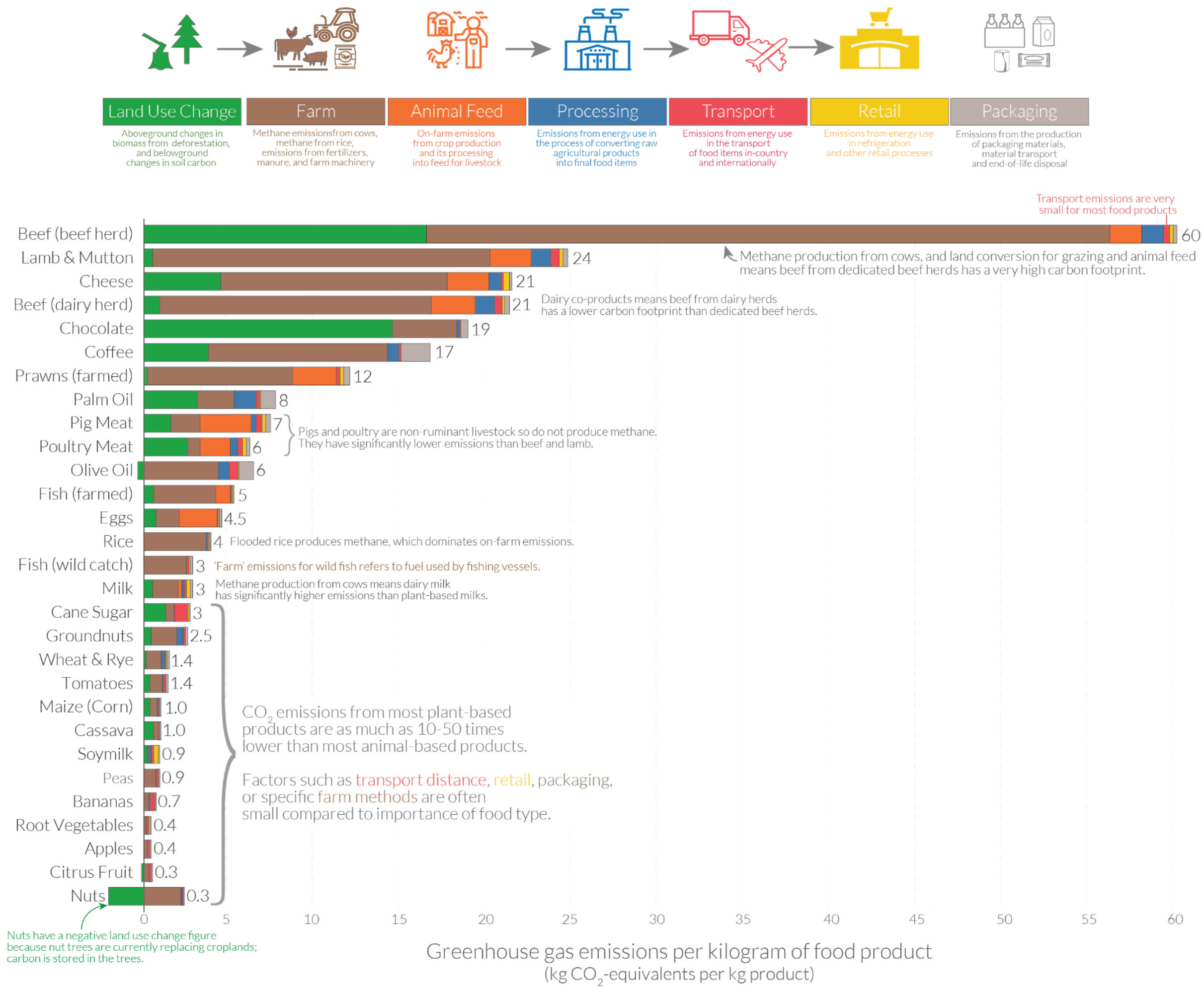

Figure 1.4 Greenhouse gas emissions for food products broken down by sources in the supply chain. Note: Greenhouse gas emissions are given as global average values based on data across 38,700 farms in 119 countries. Source: Ritchie 2020, Poore and Nemecek 2018

While many studies use the kg of CO_2e / kg of food product metric to analyze the GHG footprint of food products (e.g., Xu and Lan 2016, Yue *et al* 2017, Poore and Nemecek 2018), other studies have analyzed the GHG footprint of entire meals (e.g., Virtanen *et al* 2011) and diets (e.g., Heller *et al* 2018, Hallström *et al* 2015). A 2011 study of 30 different types of lunch meals found that beef and milk-based meals were responsible for the greatest amount of GHG emissions (Virtanen *et al* 2011). Similarly, diets high in meat and dairy products (but particularly beef) were found to have a higher GHG footprint compared to low or no-meat diets (Heller *et al* 2018, Hallström *et al* 2015).

Beef Production Supply Chain

Understanding why beef has one of the largest GHG footprints of all food products requires a deeper look into emissions sources within the beef production supply chain (see figure 1.5). Within the US, approximately 97% of beef cattle are raised in conventional, grain-fed systems (USDA ERS 2013, Cheung *et al* 2017, Rotz *et al* 2019). Beef calves are born at cow-calf operations where they are fed a combination of milk and pasture; after a few months, calves may also begin consuming supplemental feed consisting of grains and/or harvested roughage (Capper 2012, Roop *et al* 2014). After calves are weaned, they are transported to stocker or backgrounding operations where their diets shift to mostly grazed roughage (either pasture or rangeland) with supplemental grain and harvested roughage (Broocks *et al* 2017, Fairbairn *et al* 2020, Rotz *et al* 2019). Once cattle have matured to the appropriate weight, they are transported to a feedyard where they are fed a mixture of primarily grain (usually corn but sometimes wheat, barley, oats, sorghum, or soybean meal), harvested roughage (such as hay, corn silage, sorghum silage, etc.), and a very small amount of supplements (necessary minerals, vitamins, and feed additives) (Wagner *et al* 2014, Comerford *et al* 2014, Saha *et al* 2017, Cappellozza 2019, TNC 2016, Cheung *et al* 2017). Feed crops are often grown on farms off-site of the animal feeding operation then trucked to the feed yard where they are processed and prepared in a feed mill (Wagner *et al* 2014, Coffey *et al* 2016). After cattle are "finished" on a grain-heavy diet and reach market weight, they are transported to a slaughter facility. Many slaughter facilities also process the harvested meat further into packaged products that are ready for distribution (Lowe and Gereffi 2009). Some slaughter facilities engage in only a limited amount of processing in which case larger cuts of beef or entire dressed carcasses are transported to a separate facility for additional processing followed by packaging (FAO 1996). After the beef has been processed, packaged products are shipped to wholesalers (who then distribute the products further) or shipped directly to grocery stores, restaurants, and other retail or food service establishments. Once beef products are distributed to retail they are purchased and consumed (either immediately or later on) by consumers; alternately, beef products may also end up as waste (Lowe and Gereffi 2009).

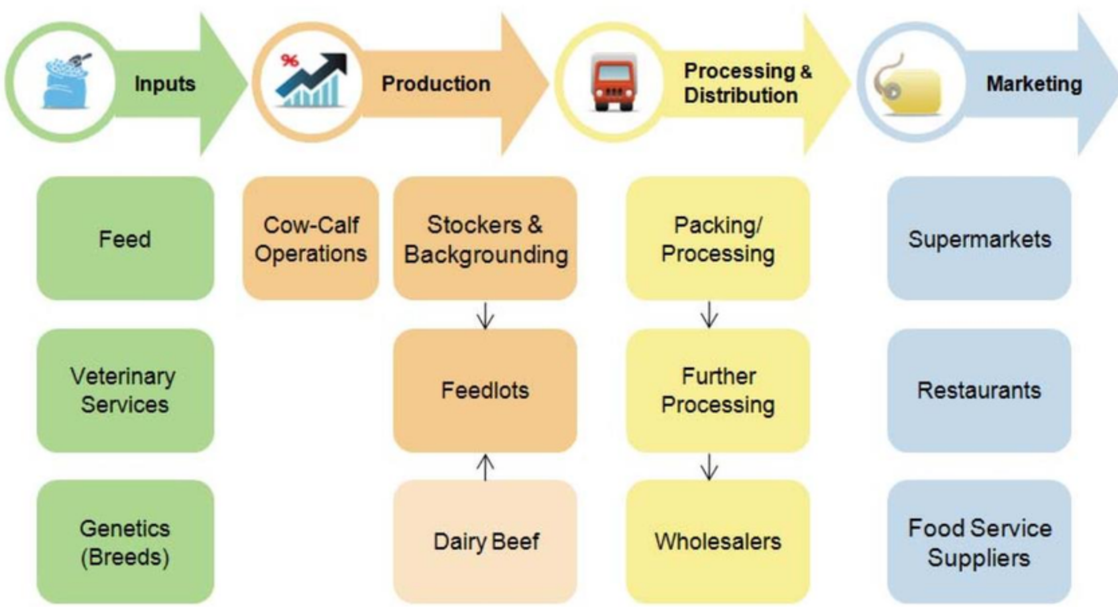

Figure 1.5 A value chain analysis of the U.S. beef and dairy industries. Source: Lowe and Gereffi 2009

One way of summarizing the beef supply chain is by breaking it down into seven main categories for GHG emission sources: (1) land use change for growing feed crops or grazing cattle, (2) cattle feed production and processing, (3) cattle raising, (4) cattle slaughter and processing, (5) transportation, (6) beef product packaging, and (7) retail processes. At a global and local scale, previous research (Chen *et al* 2020, Poore and Nemecek 2018, Gerber *et al*

2013) suggests that the cattle raising category of the beef supply chain generates the greatest amount of GHG emissions in the beef supply chain; the main emission sources being enteric fermentation followed by manure management. Changes in land use as a result of expanding or shifting needs for pasture and arable land for feed crops is the second biggest source of GHG emissions in the beef supply chain (again at a global scale). All parts of the supply chain after cattle leave the farm make up a small minority (<5%) of total GHG emissions generated by beef production (Poore and Nemecek 2018, Gerber *et al* 2013).

1.5 Impact Assessment Methods

Multiple methodology approaches have been applied to quantify the environmental impacts of products or services (e.g., beef), entire systems (e.g., food system), or specific groups of consumers (e.g., cities). Two assessment methods, life cycle assessment (LCA) and input-output analysis (IOA), and one methodology framework, urban metabolism (UM), will be reviewed here. Each approach has its strengths and limitations, with some studies using a hybrid approach that combines multiple assessment types or frameworks to compensate for the drawbacks of using any one method on its own. Use of a hybrid approach can also produce a more comprehensive, spatial explicit representation of the system or entity being studied (Suh *et al* 2004, Wenz *et al* 2015, Goldstein *et al* 2013, Zhang *et al* 2015).

Life Cycle Assessment

Many studies that aim to quantify the full environmental impact of a particular product or service (as opposed to a whole system) use a LCA approach (Reap *et al* 2008). The LCA method analyzes the impact a product has over its entire lifespan typically starting with the extraction of raw materials and ending with product disposal, including all processing and transportation steps in between (Chryssolouris 2008). LCA studies can have slightly different beginning and ending boundaries for what is included in the "lifespan" of a product depending on the study focus. A LCA that evaluates product lifespan from initial raw material extraction, to material processing and/or manufacturing, and transportation, to distribution and disposal is known as a cradle-to-grave study. Other LCA variants include cradle-to-gate (e.g., Roop *et al 2014)*, cradle-to-retail (e.g., Nijdam *et al* 2012), and gate-to-gate (e.g., Finnegan *et al* 2017). Each of these LCA variants have different boundaries depending on what portion of the product life cycle is being studied (Muthu 2020, Jiménez-González 2000). For example, for a LCA focused on beef production, "gate" could mean feed crop farm, feedlot, or packaging plant (Roop *et al* 2014, Finnegan *et al* 2017). A gate-to-gate study might even mean the study boundaries begin at the farm "gate" when calves are born and end at the packaging plant "gate" before the product is shipped to retail; this type of study would not include the production of cattle feed. In addition to clearly established boundaries regarding which processes are included in analysis, a key part of a LCA is the use of a functional unit to report final impact assessment results. GHG emissions attributed to a certain product are commonly expressed as the mass (in kg, lb, tonne, etc.) of GHG or CO_2e emitted per unit mass of product (e.g., kg, lb, or tonne; Roop *et al* 2014, Nijdam *et al* 2012).

LCAs are critiqued for being labor- and time-intensive and for excluding contributions to a good or service's overall impact by setting too narrow of a system boundary (Suh *et al* 2004). Data availability and quality are also critical issues for LCAs and often force studies to exclude certain system processes from analysis due to lack of available information. LCA's also often struggle to incorporate spatial variation and local environmental uniqueness into impact assessments (Reap *et al* 2008).

LCA studies that focus specifically on quantifying the GHG emissions attributed to a particular good or service are studying that product's (or service's) GHG "footprint" (Muthu 2020). The GHG footprint is a useful metric for understanding how a particular good, service, individual, or organization contributes to climate change by quantifying its/their GHG emissions (Muthu 2020, Pandey et al 2011). Depending on the scope of the analysis, it may focus solely on CO_2 emissions in order to generate a carbon footprint. GHG footprints are becoming more widely used and reported by individuals, universities, large companies, and even entire cities as the public response to addressing climate change increases (Franchetti and Apul 2013, Goering 2021, Carbon Disclosure Project 2021).

Input-Output Analysis

Input-output analysis (IOA) is another useful tool for assessing the environmental impact or GHG footprint of a product (Kanemoto *et al* 2016, Fry *et al* 2018, Reap *et al* 2008, Bullard *et al* 1978). Input-output tables are produced by the U.S. Bureau of Economic Analysis (BEA) and updated annually for 71 industries; more detailed statistics are conducted every 5 years with data being subdivided into 405 industries (U.S. BEA 2021). While LCA is a bottom-up approach starting at the beginning boundary of the supply chain and following the production process up through the supply chain to the sale, use, and/or disposal of the product, an IOA is a top-down approach (Wenz *et al* 2014, Lenzen 2001). IOAs analyze the monetary transactions between economic sectors to understand industry interdependencies. Analysis of input-output data can reveal the types and relative contribution of processes that contribute to the production of a particular good or service (Grant 2009, Suh *et al* 2004). IOAs are able to provide a more comprehensive, complete picture of production systems and unlike LCAs, do not suffer from the issue of truncation errors due to scope boundary limitations (Fry *et al* 2018, Reap *et al* 2008, Suh *et al* 2004).

One of the major drawbacks to IOA, however, is that data, though comprehensive and updated annually for national statistics purposes, is highly aggregated within economic sectors or industries making it difficult to isolate specific commodities of interest for analysis (Bullard *et al* 1978, Lenzen 2001, Suh *et al 2004*). Input-output data is also aggregated at the national-level; in order to understand production networks at a more spatially explicit level, further, often more complex data processing must be done (Wenz *et al* 2015, Kanemoto et al 2016, Lenzen *et a*l 2012). Some IOA studies have disaggregated national-level, sectoral data to the level of counties or cities by using proxy data such as population, income, and GDP (Wenz *et al* 2015, Moran et al 2018). The use of such proxy data, while defensible, is unlikely to capture the local uniqueness of production systems. Additionally, input-output tables are most commonly based on monetary transactions between industries, and the use of monetary values to model commodity flow relations based on physical weight can lead to flow distortions (Suh *et al* 2004).

Urban Metabolism

The concept of urban metabolism (UM) has been used as a framework to study the total environmental impact of groups of consumers, primarily cities. UM originated from the theory of cities functioning analogous to living organisms - consuming resources, converting them to energy for growth, and producing waste (Kennedy *et al* 2007, Zhang *et al* 2015). Many UM studies aim to quantify annual fluxes (inputs, outputs, and storage) of energy and materials (water, fuel, electricity, nutrients, waste, etc) across all economic sectors for a defined urban area (Wolman 1965, Kennedy *et al* 2007, Goldstein *et al* 2013, Walker *et al* 2014). Other studies have focused on tracking fluxes of specific resources in the urban system such as water (e.g., Lv *et al*

2020), food (e.g., Bohle 1994), energy (e.g., Barragán-Escandón 2017), or the nexus of all three (e.g., Walker *et al* 2014). A Material flows analysis (MFA) is a similar technique that reports resource fluxes specifically as a unit of mass much like mainstream urban metabolism studies (with the exclusion of energy flows) (Kennedy *et al* 2011). Traditionally, studies have used a top-down approach (e.g., use of the macro level input-output data) to urban metabolism analysis (Wolman 1965); however, bottom-up approaches (e.g., LCA) have also been applied (Goldstein *et al* 2013, Ramaswami *et al* 2008). The UM assessment approach is particularly useful for quantifying the GHG emissions emitted from an urban system in order to quantify a city's GHG footprint (Kennedy *et al* 2011, Goldstein *et al* 2013).

A common critique of urban metabolism, specifically when being used for quantifying a city's GHG footprint, is that a significant amount of the emissions a city is responsible for are produced outside of the specific urban system being studied. Additional information must be incorporated into the analysis in order to account for the emissions embedded in upstream and downstream flows (Kennedy et al 2011, Goldstein et al 2013, Zhang *et al* 2015). The UM methodology is also in need of standardization so that studies can be more appropriately compared both for the same urban system and across different cities (Goldstein et al 2013, Zhang *et al* 2015).

1.6 Research Gaps and Role of this Study

The GHG footprint attributed to the beef production supply chain has been quantified at a global and U.S. national level (Gerber et al 2013, USDA 2016, Eshel *et al* 2014, Poore and Nemecek 2018). Multiple studies have aimed to identify the largest sources of GHG emissions from beef production in the U.S. according to activity (Crosson *et al* 2011), cattle life cycle stages (Phetteplace *et al* 2001), or supply chain stages (Steinfeld *et al* 2006, Li *et al* 2020). A bottom-up LCA approach has been the most common method for analyzing GHG emissions associated with beef (Roop *et al* 2014, Nijdam *et al* 2012, Pelletier *et al* 2010); however, hybrid IO-LCA assessment forms have also been used (Li *et al* 2020).

While a few studies have focused on creating a model of the beef supply chain that tracks commodity flows at a more detailed, spatially explicit level, these studies have only covered small regions of the U.S. (Ge *et al* 2022, Pelletier *et al* 2010). To date, no published studies have modeled the full U.S. domestic beef production supply chain network with sub-state level origins and destinations tracking the flow of each major commodity: cattle feed, cattle, and beef.

Urban metabolism studies have estimated the GHG footprint of food systems (foodprint) for entire cities; however, very few of these studies have disaggregated urban food consumption to the level of individual commodities such as beef (Goldstein *et al* 2015, Chapman *et al* 2017). At the time of this writing, no published studies exist that have estimated the full supply chain GHG footprint attributed to demand for domestic beef at the city-level across the U.S.

This study uses a hybrid approach - a bottom-up LCA approach within an urban metabolism framework - to quantify spatially explicit GHG emissions associated with U.S. beef supply chains that support urban demand for domestic beef in 70 U.S. metropolitan areas. A main goal of this study is to develop a consistent methodology that allows for the comparison of GHG footprints attributed to beef supply chains across several of the largest metropolitan areas in the U.S. We then use the developed methodology and model to explore the following research questions:

1. What is the U.S. domestic beef production supply chain that supports urban beef demand in 70 U.S. metropolitan areas?
2. What is the GHG footprint of each metropolitan area's domestic beef supply chain?

3. What portion of the national-level beef supply chain contributes most to the GHG footprint nationally and across metropolitan areas?
4. How do domestic beef supply chains and their attributed GHG emissions compare between metropolitan areas?
5. What specific changes in the domestic beef supply chain for certain metropolitan areas might help reduce their GHG footprint attributed to beef demand?

Study Methodology Overview

By using LCA methodology to analyze regional-level commodity flow data within the framework of urban metabolism, this study aims to create a comprehensive and tractable model of the U.S. beef supply chain and it's attributed emissions that includes the granular spatial variation lacking from many GHG focused LCA studies (Reap *et al* 2008). Bilateral data from the U.S. Census Bureau Commodity Flow Survey (CFS) and the Freight Analysis Framework version 4 (FAF4) provided by Oak Ridge National Laboratory are used to create a domestic commodity flow network (CFN) that tracks the movement and mass of relevant commodities (feed, cattle, beef) from their origin to consumption destination. CFS and/or FAF4 data have been used in previous studies to generate a CFN for water (Richter *et al* 2020), food systems (Lin *et al* 2016), and specific food products (Vora *et al* 2021); this study builds off these previous efforts.

GHG intensity coefficients (e.g., mass of CO_2e emitted per unit of activity) for activities and sources within the feed production (upstream), cattle production, and slaughter, processing, and distribution (downstream) segments of the supply chain were obtained from the literature and/or established GHG inventory protocols. These coefficients were then applied to each segment of the CFNs and steps in the supply chain to generate geographically specific GHG footprints. Supply chain GHG emissions were summed up to the level of their final downstream metropolitan destination in order to quantify the total GHG emissions associated with urban beef demand.

Chapter 2 explores in greater detail the GHG accounting concepts and study methodology introduced in this chapter, and serves as a self-contained manuscript. Chapter 3 examines the social and political dimensions and implications of this research in addition to offering suggestions to advance this field of study.

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CHAPTER 2:

A SPATIALLY EXPLICIT GREENHOUSE GAS FOOTPRINT OF BEEF PRODUCTION SUPPLY CHAINS IN THE UNITED STATES

Abstract

Across all food products, beef has consistently been reported as having one of the largest greenhouse gas (GHG) footprints. In order to reduce the amount of GHGs emitted as a result of beef production, a better understanding of the GHG emissions linked to the complexities of the beef supply chain is critical. Here we estimate the GHG footprint attributed to domestic beef consumption in major U.S. metropolitan areas and non-metro regions using a spatially and temporally explicit model of the U.S. beef production supply chain network which tracks the flow of feed, cattle, and beef from origin to destination. The beef production network was created for the year 2012 using commodity flow data from the Commodity Flow Survey and Freight Analysis Framework, commodity production data, and leverage network principles. A life-cycle assessment based on the resulting beef production network is conducted using GHG emission factors and energy consumption data obtained through a comprehensive literature review and established GHG accounting protocols. We estimate a U.S. average GHG footprint of 8.7 ± 3 kg CO_2e/lb retail beef. Cattle production contributes the vast majority (75%) of GHG emissions related to beef production with enteric-fermentation alone contributing 66%. Across all domestic beef destinations (except Alaska and Hawaii), the proportional contribution of GHG emissions from each step of the supply chain to the total supply chain GHG footprint was relatively consistent. Though transport as a emissions source showed the greatest range in emissions relative to other sources in individual beef supply chains, at the national level transportation only accounts for 4% of beef supply chain emissions. This underscores the

importance of addressing feed and cattle production practices, particularly enteric fermentation as the largest emissions source, as opposed to focusing only on reducing vehicle miles traveled within the supply chain. Unlike previous work that focuses on calculating GHG emissions for either one individual region or generalized across the U.S., this study developed a hybrid life cycle assessment - urban metabolism approach combined with regional-level commodity flow data to track GHG emissions for individual beef supply chains in a manner that is inclusive of and comparable across each metro- and non-metropolitan area.

1. Introduction

As the negative impacts of anthropogenic-induced climate change become increasingly recognized as a serious threat to the stability of both human and environmental systems, it has become critical to better quantify sources of greenhouse gas (GHG) emissions and the activities that produce them. Within the U.S., agriculture is responsible for approximately 9% of total U.S. emissions. The majority of emissions from the agriculture sector are CH_4 (41%) and N_2O (58%) (U.S. EPA 2021). Agricultural soil management is the highest emitting agricultural activity contributing over half (55%) of agriculture related emissions in 2019 (U.S. EPA 2021). Enteric fermentation (a digestive process in ruminant animals such as cattle and sheep) and manure management inherent in animal agriculture, contribute another large chunk (41%) of total U.S. agricultural emissions. Almost all of enteric fermentation emissions are produced by the U.S. cattle population with beef cattle being the largest contributor. In fact, in 2013 beef cattle were responsible for 63% of all emissions from livestock (including poultry) related agriculture in the U.S. (USDA 2016).

The significant contribution of agriculture and specific agricultural products to GHG emissions at both a global and national level (IPCC 2014a, IPCC 2022, EPA 2012 2019 2021, USDA 2016 2022) has prompted more research into the climate change impacts and mitigation opportunities of food production (Sonesson *et al* 2010, Vergé *et al* 2007). However, food supply systems (and the corresponding GHGs emitted) involve activities that span several economic sectors outside of the agricultural sector including the industrial, transportation, and electricity sectors (Heller and Keoleian 2000, Crosson *et al* 2011). In order to fully understand the impact food production has on climate change, recent studies (Chen *et al* 2020, Clune *et al* 2017, Crippa *et al* 2021, Garnett 2011, Poore and Nemecek 2018) aim to quantify and analyze the GHG emissions generated by entire supply chains for different foods.

Food supply chains range in complexity depending on the specific food product, but often begin with the land where crops are produced (either for animal feed or direct human consumption) and ending at the consumer (either at a retail/food services location or at-home) or as food waste (Garnett 2011). However, depending on the focus of the study, the supply chain "beginning" and "ending" boundaries can vary (IOM and NRC 2015). A 2018 study by Poore and Nemecek evaluated food production supply chains according to four main categories of GHG emissions sources: (1) land use; (2) crop production; (3) livestock & fisheries production; and (4) processing, transport, packaging, and retail. They found that land-use for livestock, production of animal feed, and on-farm raising of livestock and aquaculture make up over half (53%) of all emissions from the global food production system, with processing, transport, packaging, and retail activities contributing to less than 25% of production-related emissions, a finding similar to that from other studies (Poore and Nemecek 2018, Crippa *et al* 2021, Weber *et al* 2008). They also found that beef production generated the greatest amount of GHG emissions per kg of product and twice as much GHG as the second largest emitter, mutton and lamb (Poore and Nemecek 2018); these findings have been heavily supported by results from numerous other studies (e.g., Xu and Lan 2016, Virtanen et al 2011, Yue et al 2017) and meta-analyses (e.g., Clune et al 2017).

Understanding why beef has one of the largest GHG footprints of all food products requires a deeper investigation into emissions sources within the beef production supply chain. The beef production supply chain can be broken into three major components: (1) cattle feed production, (2) cattle production, and (3) beef slaughter/processing. Within the US, approximately 97% of beef cattle are raised in conventional, grain-fed systems (USDA ERS 2013, Cheung et al 2017, Rotz et al 2019). Conventional systems of cattle production involve multiple stages beginning with birth and rearing at a cow-calf operation until weaning before being moved to a stocker, backgrounding, or similar operation. During this middle life-cycle stage, cattle will consume some combination of grazed roughage (pasture or rangeland), harvested roughage (e.g., hay or silage), and/or grain (e.g., corn or barley) until they weigh enough to be moved to a feedlot (Broocks et al 2017, Fairbairn et al 2020, Rotz et al 2019). At the feedlot, cattle are fed a mixture of primarily grain, harvested roughage, and a very small amount of supplements (minerals, vitamins, and feed additives; Wagner et al 2014, Comerford et al 2014, Saha et al 2017, Cappellozza 2019, TNC 2016, Cheung et al 2017). After being "finished" on this grain-heavy diet and reaching market weight, cattle are shipped off for slaughter. During the beef production stage, beef may be slaughtered at one facility, shipped to another facility for processing and packaging, then to a wholesale distributor, and finally to grocery stores, restaurants, and other retail or food service establishments (FAO 1996, Lowe and Gereffi 2009). There are many potential supply chain pathways within beef production and not all beef supply chains look the same; for example, larger calves may be shipped from a cow-calf operation directly to feedlot and beef may be shipped from a facility that does slaughter, processing, and packaging directly to a grocery store. Previous studies have found that the cattle production stage is responsible for the greatest portion of beef supply chain GHG emissions (primarily from enteric fermentation and manure management) with changes in land use due to pasture or land for cattle feed crops being the second largest contributor (Poore and Nemecek 2018, Gerber et al 2013). Emissions from beef slaughter/processing tend to make up <5% of GHG emissions associated with beef production (Poore and Nemecek 2018, Gerber et al 2013).

Multiple methodology approaches have been applied to quantify the environmental impacts of products or services (e.g., beef), entire systems (e.g., food system), or specific groups of consumers (e.g., cities). Two assessment methods, life cycle assessment (LCA) and input-output analysis (IOA), and one methodology framework, urban metabolism (UM), are reviewed here. Each approach has its strengths and limitations, with some studies using a hybrid approach that combines multiple assessment types or frameworks to compensate for the drawbacks of using any one method on its own. Use of a hybrid approach can also produce a more comprehensive, spatial explicit representation of the system or entity being studied (Suh et al 2004, Wenz et al 2015, Goldstein et al 2013, Zhang et al 2015).

One of the most common methods used in assessing the full environmental impact of a product or service is the LCA approach (Reap *et al* 2008). LCA studies may vary in what boundaries are used to determine the "beginning" and "ending" of a product supply chain (Muthu 2020, Jiménez-González 2000). A cradle-to-grave LCA study evaluates product lifespan from initial production, to processing and transportation, to distribution and disposal. Other LCA variants include cradle-to-gate (e.g., Roop et al 2014), cradle-to-retail (e.g., Nijdam et al 2012), and gate-to-gate (e.g., Finnegan et al 2017). LCAs are notorious for not being comparable across studies due to differences in system boundaries. In addition, LCAs often struggle to incorporate spatial variation and local environmental uniqueness into impact assessments (Reap et al 2008).

Input-output analysis (IOA) has also been used to assess the environmental impact or GHG footprint of a product (e.g., Kanemoto et al 2016, Fry et al 2018, Reap et al 2008, Bullard et al 1978). IOAs analyze input-output tables produced by the U.S. Bureau of Economic Analysis (BEA) to understand the types and relative contribution of processes across economic sectors that contribute to the production of a particular good or service (Grant 2009, Suh et al 2004). IOA's have been criticized for using data that is aggregated at the national level for individual industries making it difficult to isolate specific commodities of interest for analysis (Lenzen 2011).

Urban metabolism (UM) is a framework that has been used to study the total environmental impact of groups of consumers, primarily cities (Kennedy *et al* 2007, Zhang *et al* 2015). The UM approach is particularly useful for quantifying the GHG emissions emitted from an urban system in order to calculate a city's GHG footprint (Kennedy et al 2011, Goldstein et al 2013). UM studies may use a top-down method such as IOA or (less commonly) a bottom-up method such as LCA (Goldstein *et al* 2013, Ramaswami *et al* 2008). However, common critiques of UM approaches include the lack of standardization and consideration of embedded emissions associated with upstream and downstream flow outside of the specific urban system being studied (Kennedy et al 2011, Goldstein et al 2013, Zhang *et al* 2015).

This study uses a bottom-up LCA approach within an urban metabolism framework to quantify the GHG emissions associated with the spatially explicit beef supply chains that support urban demand for domestic beef in 70 U.S. metropolitan areas. A main goal of this study is to develop a model that applies consistent methodology to enable comparison of GHG footprints attributed to beef supply chains for several of the largest metropolitan areas in the U.S. This study explores the following research questions: (1) what is the U.S. domestic beef production supply chain that supports urban beef demand in 70 U.S. metropolitan areas? (2) what is the GHG footprint of each metropolitan area's domestic beef supply chain? (3) What portion of the national-level beef supply chain contributes most to the GHG footprint nationally and across metropolitan areas? (4) how do domestic beef supply chains and their attributed GHG emissions compare between metropolitan areas? and (5) what specific changes in the domestic beef supply chain for certain metropolitan areas might help reduce their GHG footprint attributed to beef demand? The goal of this study is to establish a novel methodology for analyzing national-level, city-driven product supply chains, and identify future research questions.

2. Methods

Here, we use "beef supply chain" and "beef production" interchangeably to refer to the domestic production and transport of feed for cattle, production and transport of cattle slaughtered in 2012, and the processing and transport of beef to retail (e.g., grocery stores and foodservice). Beef "processing" refers to all slaughter, processing, and packaging activities related to cattle meat for the production of beef products.

2.1 Scope of study

This study seeks to create a spatially and temporally explicit model of the U.S. domestic beef production supply chain and its attributed emissions by using a life cycle assessment approach combined with an urban metabolism framework to analyze detailed commodity flow data. GHG coefficients are applied to the model to generate GHG footprints for domestic beef production at the level of individual supply chains. This study quantifies the GHG emissions in kg CO_2e associated per lb of bone-in retail beef product for each of 70 metropolitan areas.

Metropolitan areas as referenced in this study parallel the Metropolitan Statistical Areas defined by the U.S. Office of Management and Budget.

For this cradle-to-consumer life cycle assessment (LCA), "cradle" is defined as the production of cattle feed and "consumer" is defined as the retail (or food service) point of purchase for consumers. Beef production in the U.S. is a very complex system with many different potential supply chain pathways between when a calf is born and ultimately packaged beef and purchased by consumers. Due to data availability constraints, we use a simplified version of the most common supply chain path within U.S. beef production (Figure 2.1). The following supply chain components are included in this analysis: (1) production of feed for cattle, (2) transport of feed to cattle, (3) raising of cattle, (4) transport of cattle to slaughter, (5) slaughter, processing, and packaging, and (6) transport of beef product to retail and point of consumer purchase. Due to a lack of finer-resolution commodity flow and inventory data, the following transportation steps in the supply chain were excluded: calves to stocker/backgrounding operation, mature cattle to feedlot, carcass to separate processing facility, and beef product to wholesaler warehouse or distribution center. Previous research by Weber and Matthews (2008) suggests that total supply chain transportation for red meat contributes to only 6% of red meat's total GHG impact; it is unlikely that the partial exclusion of supply chain transportation steps will significantly impact analysis results.

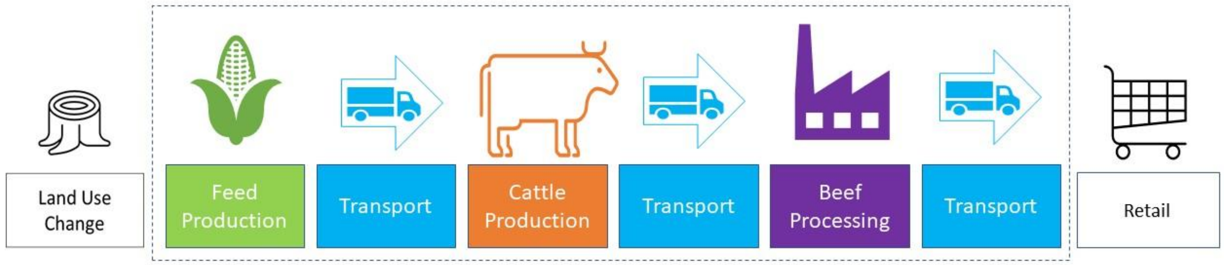

Figure 2.1 Beef production supply chain components included in this study are shown within the dotted line indicating study boundaries. Upstream and downstream supply chain components outside of the dotted line (land use change and retail activity) were excluded.

The spatial scale of analysis begins at the county level before being aggregated to the sub-state level; for states with large metropolitan areas (MA), data is aggregated to the MA level. The baseline year of this study is 2012 which, at the time this study began, coincided with the most recent version of the publicly available Commodity Flow Survey (CFS) and Freight Analysis Framework 4 (FAF4) data. A main focus of this study was method development; 2012 FAF4 data provides an excellent benchmark for method creation. Additionally, due to the frequent use of 2012 FAF4 data in relevant literature, use of the dataset in this study allows for greater comparability across relevant work. The framework for the model created in this study can be easily modified to run on updated FAF datasets as they become available.

Table 2.1 Sources of GHG emissions accounted for in this assessment.

Supply Chain Step	GHG	Included activities/sources	Excluded activities/sources
Feed Production	N_2O	Direct and indirect from: • Application of organic and inorganic fertilizers • Manure application • Crop residue effects	• Biomass burning • Loss of N_2O due to changes in soil carbon
	CO_2 N_2O CH_4	• On-farm energy use including: electricity, fuel, and natural gas. • Crop protection chemicals • Lime application • Transport of feed to cattle	• Changes in soil carbon due to management practices and land use change • Seed production • Embedded energy in equipment and buildings
Cattle production	CH_4	• Enteric fermentation • Manure management	–
	N_2O	• Direct and indirect from manure management	–
	CO_2 N_2O CH_4	• On-farm electricity use for cattle housing • Transport of cattle to slaughter facilities	• Changes in soil carbon stocks on pre-existing or converted rangelands and pasture • On-farm energy use for machinery and heating
Slaughter, processing, and distribution	CO_2 CH_4	• Electricity and natural gas used for slaughter and processing activities • Transport of beef to retail	• Refrigeration during transport

2.2 Input data

In order to create a national level commodity flow network (CFN) that tracks the flow of cattle feed, cattle, and beef between geographic locations, we synthesized a number of public-source datasets including the Commodity Flow Survey (CFS; U.S. Census Bureau 2015) and Freight Analysis Framework version 4 (FAF4; Oak Ridge National Laboratory 2015). CFS and/or FAF data have been utilized in previous research to track the flow of food (Lin *et al* 2018, Zhang and Koylu 2020, Vora *et al* 2021, Weber and Matthews 2008, Sanders and Webber 2014) and virtual water (Rushforth and Ruddell 2018, Garcia *et al* 2020, Richter *et al* 2020). The methodology used in this study builds off the novel methodology used in Rushforth and Ruddell 2018, Garcia *et al* 2020, Richter *et al* 2020. Other databases from the U.S. Department of Agriculture (USDA), the U.S. Bureau of Labor Statistics, and Cattle Buyers Weekly (see Table 2.2) were incorporated into the CFN to improve flow estimates.

Table 2.2 List of major data sources used in this study.

Name	References	Purpose
Commodity Flow Survey (CFS) Public Use Microdata	US Census Bureau (2015)	Framework for the commodity flow leverage network - excludes farm-based flows
Freight Analysis Framework (FAF) version 4	Oak Ridge National Laboratory (2015)	Framework for the commodity flow leverage network - includes farm-based flows
USDA 2012 Census of Agriculture	US Department of Agriculture (2014)	County-level crop production data for cattle feed
USDA NASS QuickStats	US Department of Agriculture (2021)	Characterics of cattle slaughtered for beef in 2012
Cattle Buyers Weekly, Top 30 Beef Packers 2013	Kay (2013)	Slaughterhouse location and number of cattle slaughtered
USDA, Food Safety and Inspection Service (FSIS), Meat, Poultry, and Egg Product Inspection Directory (MPI)	US Department of Agriculture, Food Safety and Inspection Service (2012)	Slaughterhouse location and number of cattle slaughtered

2.2.1 CFS and FAF Data

The CFS is a survey conducted every five years in a collaborative effort between the U.S. Census Bureau and U.S. Department of Transportation's Bureau of Transportation Statistics. The survey is voluntary and targets 100,000 establishments within the manufacturing, mining, wholesale, distribution and warehouse, and some retail and service trade sectors. The CFS compiles survey data to generate a database of national multimodal freight flows of commodities between origin and destination locations according to commodity type, weight, and monetary value. Data regarding commodity shipments from foreign countries and several industries, including farm-based agriculture and most of retail, were considered out-of-scope for the CFS. The FAF4 database is built on the CFS but incorporates additional data from the USDA, Census Bureau, and other sources in order to create a more comprehensive multimodal database of national freight flows. The U.S. is divided into 132 CFS areas or FAF zones (hereinafter referred to as “FAFs”) depending on an area’s population and significance as a transportation gateway for commodities. Some MAs are split across multiple state lines and therefore multiple FAFs (e.g., New York City metropolitan area consists of 4 FAFs, one each in Connecticut, New Jersey, New York, and Pennsylvania). In total there are 70 different metropolitan areas (some split across FAFs, some not) represented in the FAF dataset with the remainder of the U.S. contained in 48 other FAF zones. Commodity shipments in CFS and FAF data are organized by type of commodity according to Standard Classification of Transported Goods (SCTG) codes. The SCTG codes selected for and relevant to this study are displayed in table 2.3; SCTG codes are only specified at the two digit level.

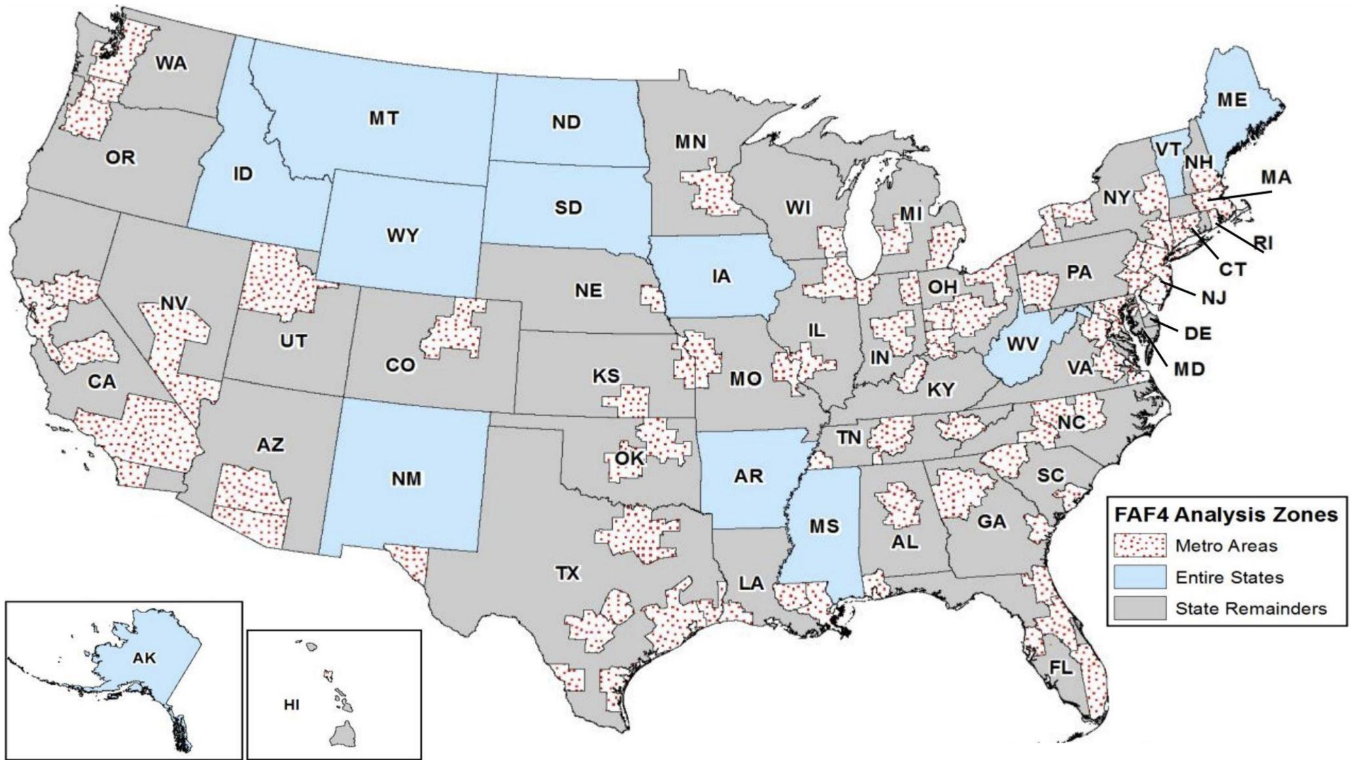

Figure 2.2 Map of all FAF zones in the FAF4 dataset (U.S. DOT 2017).

Table 2.3 SCTG Groups and associated commodities relevant to this study

SCTG Group	Group Title	Relevant Commodities
01	Live Animals and Fish	Live cattle
02	Cereal Grains	Grain corn, barley, grain sorghum, oats, wheat
04	Animal Feed, Eggs, Honey, and Other Products of Animal Origin	Silage corn, hay, haylage, silage sorghum
05	Meat, Poultry, Fish, Seafood, and Their Preparations	Beef (fresh, chilled, frozen, salted, dried, or smoked)

The first two steps in the beef production supply chain are flows of feed from field to feedlot and flows of cattle to slaughter house. As farm-based agriculture, these two steps in the beef production supply chain are considered out-of-scope (OOS) for the CFS but are included in the FAF. In order to isolate data regarding relevant farm-based flows, CFS data is subtracted from the FAF4 dataset leaving only OOS flows. Multiple studies have used FAF data to trace commodity flows; however, the methodology used in this and previous studies (Rushforth and Ruddell 2018, Garcia et al 2020, Richter et al 2020) differs from other (Lin *et al* 2018, Vora *et al* 2021) in that farm-based food flows are separated from industrial food flows when analyzing FAF4 data.

The aggregation of FAF4 commodity flows according to their two digit SCTG code necessitates the use of additional data in order to estimate the portion of each FAF4 farm-based (FB) OOS flow that is related to only beef production. For example, any FAF origin to destination flow of a SCTG 01 good could include live cattle, swine, poultry, fish, or any other live animal leaving a farm; data regarding the demand for cattle at slaughterhouse locations (Kay 2012) is leveraged to estimate what portion of each unique origin to destination SCTG 01 flow is likely live cattle. U.S. Department of Agriculture 2012 Census of Agriculture data is used to determine which FAF zones produced cattle feed and had feedlot cattle in 2012 (USDA 2014). Data provided by *Cattle Buyers Weekly* is used to determine which FAF zones contained slaughterhouses that slaughtered and processed cattle in 2012 (Kay 2012). FAF commodity flows where the activity relevant to a particular step of the beef supply chain is not known to occur are filtered out. Filtering of FAF commodity flow data is done prior to building the commodity flow network for each step of the beef supply chain.

2.3 Commodity Flow Network

2.3.1 Leverage Networks : An overview

CFS and FAF4 data are used to create a relative network of commodities (identified by their two digit SCTG group) flowing between their origins and destinations (see figure 2). Instead of using the total mass or dollar values associated with commodity flows in CFS and FAF data, we use the relative proportion of flows to create a flow network. Due to the coarseness of the CFS and FAF4 datasets, the actual weight or value of specific commodity flows is somewhat unreliable and difficult to disaggregate from bundled commodity groups; however, relative flow proportions are much more likely to accurately represent real-world patterns of commodity movement. This particular method is known as creating a “leverage network” (Wang *et al* 2019); using a leverage network to analyze CFS and FAF data is a methodology adapted from previous studies by Rushforth and Ruddell 2018, Garcia et al 2020, and Richter et al 2020. Additional datasets from USDA and Cattle Buyers Weekly that track the production weight and location of specific commodities are then fed into the relative flow network to provide magnitude of values (mass and U.S. dollars) for relevant origin to destination commodity flows (Table 2.1).

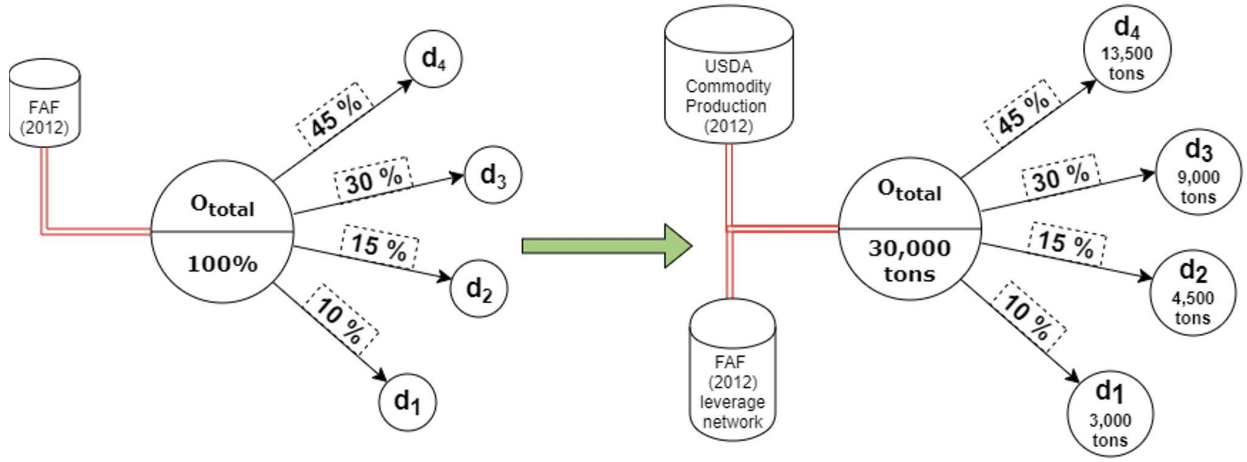

Figure 2.3 Example of an origin-driven leverage network for cattle feed flows; O = commodity origin and d_x = one of multiple commodity destinations. First, a relative flow proportion network is created for each commodity origin, O, using FAF4 data. Then, USDA crop production data for each commodity origin, O, is incorporated to provide absolute commodity weights; the absolute weight of cattle feed crops going to each destination, d_x, is allocated proportionally.

Leverage networks applied in previous studies (Rushforth and Ruddell 2018, Garcia et al 2020, and Richter et al 2020) have focused on the relative distribution of a commodity from origins to destinations (see Figure 2.2); we call these “origin-driven” leverage networks for the purposes of this study. Origin-driven leverage networks are modeled primarily according to known commodity production or supply at an origin. However, disaggregated commodity production data tracking weight and production location does not currently capture all commodities in the beef supply chain. In such cases, the creation of an origin-driven network is less feasible and would necessitate a greater number of data assumptions. To create the cattle flow network, data reporting the number of cattle slaughtered in each FAF zone that was used to create the beef flow network was used to create a “destination-driven” network for cattle flow. Our destination-driven network was modeled based on demand at the destination as opposed to origin supply and uses destination-specific consumption data combined with FAF4 data to estimate the relative flow of a commodity from multiple origins shipped to a destination.

2.3.2 Feed Flow Network

In order to determine the proportion of cattle feed within the FAF4 flows for commodities in SCTG groups 02 (includes grain corn, barley, grain sorghum, oats, wheat) and 04 (includes silage corn, hay, haylage, silage sorghum), an origin-driven leverage network is created using filtered FAF4 farm-based OOS data and 2012 USDA Census of Agriculture crop production data. The Census of Agriculture is conducted every 5 years and collects data regarding farms, ranches, and the people who run them via a voluntary questionnaire. Included in the Census of Agriculture database is the amount of each type of crop that was produced that census year; crop production data is available at the county, state, and national level. County-level crop production data is used for this study and later aggregated up to the FAF zone level. The agricultural crops included in this study are those that make up the majority of feed consumed by beef cattle in the U.S. according to Eshel et al 2015. Cattle feed is generally composed of grazed roughage, harvested/processed roughage, grain concentrates, byproducts, and added supplemental minerals and nutrients. Crops defined as concentrated feed were corn grains, sorghum grains, barley, oats, or wheat; processed roughage consists of corn silage, sorghum silage, hay, and haylage (including greenchop) (Eshel *et al* 2015). FAF4 data is filtered to include only those flows originating at a FAF zone known to produce cattle feed crops and being shipped to destinations known to include cattle on feed; both of these datasets are included in the 2012 Census of Agriculture available through Quick Stats (USDA 2014).

In order to prevent the disclosure of sensitive information regarding individual operations (e.g., only one production facility within that county or state), some crop production data within the 2012 Census of Agriculture was not disclosed for certain counties and certain states. In instances where county-level data was not disclosed, values were estimated for each crop via a backfilling method (see Appendix A).

To prepare the USDA crop production data for use with the FAF4 database, the weights of all crop production totals were converted to thousand tons to match FAF4 shipment weight totals. For some crops, this conversion was straightforward, requiring only a conversion of lbs to tons and/or tons to thousand tons. For other crops such as grain corn, production totals had to be converted from the unit of bushels. Because "bushel" is a unit of volume, the corresponding weight of a bushel is different for every crop. Unique conversion factors for each crop for which production weight was reported in bushels were obtained from the 2013 Agricultural Statistics report produced by the USDA (USDA 2013b). The 2013 Agricultural Statistics report was also used in the FAF4 Methodology to obtain conversion factors for USDA crop production data (Hwang *et al* 2016).

The USDA Census of Agriculture dataset does not include SCTG group codes for agricultural products. Appendix B of the FAF4 Methodology document (Hwang *et al* 2016) lists all agricultural commodities included in the FAF4 categorized by SCTG group and was used to assign an SCTG group to each of the agriculture crops from the USDA crop production data.

2.3.3 Beef Flow Network

The beef commodity flow network tracks the shipment of beef (SCTG 05) from slaughter and processing facilities to grocery stores and other retail locations. Due to data limitations, the flow of beef from slaughter facilities to separate processing facilities, warehouses, and/or distribution centers prior to final retail destinations is not considered in this model. The beef flow network was created prior to modeling the cattle flow network and is later used to aid in the creation of the cattle flow network.

All marketable, commercially slaughtered beef included in this study is produced off-farm in a state or federally inspected commercial facility. To model the beef flow network, the complete FAF4 database was used without isolating farm-based flows and other flows that are considered out-of-scope for the CFS. Commodities in the SCTG 05 group include meat, poultry, fish, seafood, and their preparations. SCTG 05 commodities are meat that has been processed and prepared for retail in one of the following forms: fresh, chilled, frozen, salted, dried, or smoked. All other SCTG commodity flows were excluded from the SCTG 05 origin-driven leverage network. Additional filtering was done to exclude commodity flows for which no weight was recorded and flows of imported beef.

In order to identify beef production origins, a list of the 2013 top 30 U.S. beef packers and their 2012 slaughter statistics was obtained from Cattle Buyers Weekly (CBW; Kay 2013). Slaughter statistics included company names, slaughter plant locations, and the total number of cattle slaughtered by each company in 2012. The top 5 beef packing companies oversee 32 total plants which account for 79% of all commercial slaughter (both federally inspected [FI] and non-federally inspected [NFI]; Kay 2013, USDA). The location and general slaughter volume for all other federally inspected facilities that slaughtered beef in 2012 were obtained from the 2012 USDA Food Safety and Inspection Service (FSIS) Meat, Poultry, and Egg Product Product Inspection Directory (MPI) database. MPI data was used to provide boundaries regarding the amount of federally inspected commercial cattle slaughter that could be allocated to each FAF based on their number of beef slaughtering facilities and each facility's slaughter volume category. An additional CBW resource listing the 72 largest beef plants in January 2012 reported the daily slaughter capacity for each plant; daily slaughter capacity was used to guide allocation for some of the top 5 beef packing companies for which the exact number of cattle slaughtered was not disclosed at the plant level.

USDA National Agricultural Statistics Service (NASS) national and state level data for total number of cattle slaughtered in commercial federally inspected, state-inspected, and custom-exempt facilities in 2012 were used to provide state level boundaries when allocating slaughter at the FAF level. Slaughter data for some states was not disclosed in the USDA NASS dataset and required backfilling. Final slaughter allocation at the FAF-level involved a tedious multi-step process; the patchiness of available data required that some FAF-level allocation be done on a state-by-state basis (see Appendix A for a more detailed step-by-step workflow of slaughter allocation methodology).

Available data from USDA NASS regarding commercial beef slaughter at non-federally inspected facilities combines state-inspected slaughter (marketable within state boundaries) with custom-exempt slaughter (not able to be sold) rendering the two different data types indistinguishable. To remove as much custom-exempt slaughter from analysis as possible, states that had NFI beef slaughter in 2012, but did not have a state inspection program, were assumed to have only custom-exempt slaughter and were excluded from analysis. Comprehensive multi-state data detailing the location of state-inspected slaughter facilities is not known to currently exist. Within each state, the proportions of FI slaughter allocated to each FAF was used to determine FAF-level distribution of NFI slaughter as well.

The allocated number of head of cattle slaughtered at each FAF were converted from number of head slaughtered to total live weight to dressed weight to retail (bone in) weight. State-level values for average live weight/head of cattle slaughtered in 2012 were obtained from USDA NASS QuickStats and used to convert number of head slaughtered to total live slaughter weight for each FAF. A national average dressing percentage was calculated using USDA 2012 national totals for average live weight and average dressed weight. Average U.S. retail (bone-in) beef weight percentage was calculated using data in the USDA ERS Meat Supply and Disappearance data tables for 2012 total beef carcass weight and total beef retail weight. Conversion values are listed in Table 2.4. Weight of retail beef produced at each FAF origin was incorporated into an origin-driven leverage network created using the same methodology outlined in the feed flow network.

2.3.4 Cattle Flow Network

The cattle flow network tracks the shipment of cattle from feedlot and farms to a facility for slaughter. Due to limited data, tracking the movement of cattle between farms, from farm to auction, and from farm to feedlot was not within the scope of this study. Unlike the origin (production) driven networks for feed flows and beef flows (Fig. 2.2), the leverage network created for tracking the flow of cattle to slaughter is destination (demand) driven. Demand for cattle at FAF destinations is determined using the FAF-level slaughter data previously utilized in the creation of the beef flow network

To model the flow of cattle for slaughter, a leverage network is created using commodity flows of SCTG 01 in the FB OOS FAF4 dataset. The SCTG 01 commodity group consists of all live animals and fish; this includes both live animals raised for meat (e.g., pigs, cattle, chickens) and pets. SCTG 01 commodity flows in the FB OOS FAF4 dataset were filtered to exclude flows that had zero or negative weight and imports; FAF-level slaughter data was used to exclude FAF destinations that did not have cattle slaughter in 2012. The resulting estimated number of head of cattle being transported in each origin-destination flow were rounded to the nearest whole number and converted to weight using the U.S. average live weight for commercially slaughtered cattle in 2012; average live weight was obtained from USDA NASS QuickStats.

Table 2.4 Assumptions for U.S. cattle slaughtered in 2012.

Characteristic	Unit	Value	Source
Lifetime[a]	Days	555	USDA NASS 2016 Pennsylvania Beef Council 2018 Drouillard 2018 Farm Credit Knowledge Center 2021 Terry et al 2020 Beef Cattle Extension 2019 Koontz et al 2005 Place and Miller 2020 Cheung and McMahon 2017
Weaning phase[a]	Days	219	
Stocker/ Backgrounding phase[a]	Days	164	
Feedlot phase[a]	Days	168	
Average live slaughter weight (LW)	lbs	1,302	USDA NASS Quick Stats 2022
Dressed weight (DW) percentage	%	60.5	USDA NASS Quick Stats 2022
Retail bone-in beef percentage from DW	%	70	USDA ERS Meat Supply and Disappearance
Retail boneless beef percentage from bone-in	%	96	USDA ERS Meat Supply and Disappearance
Feed consumption - Harvested forage	Lb DM / lb LW	3.01	Rotz et al 2019
Feed consumption - Grain concentrate	Lb DM / lb LW	1.53	Rotz et al 2019

[a]Applies specifically to conventionally raised beef cattle or about 78% of marketable domestic beef slaughtered in 2012.

2.4 Transportation

For each of the three commodity flow networks (cattle feed, slaughter cattle, and commercial beef), the original FAF4 database was used to determine the average distance traveled for each origin to destination commodity flow. The average weighted distance as reported in the original FAF4 database and the flow commodity weight as reported in the generated commodity flow networks were used to calculate the average ton-miles for each flow.

The FAF4 weighted average shipment distance reflects mileage of shipments of farm-based, non-farm-based, and all commodities within each SCTG group including those not relevant to this study. Though use of the FAF4 origin-destination average weighted distance to estimate average shipment distance for commodities relevant to this study is not without limitations, this method is likely more accurate than alternative options identified at this time (i.e., using FAF centroid to FAF centroid routed highway distances).

2.5 Greenhouse Gas Emissions

Intensity factors used in this study for estimating energy consumption and GHGs emitted at each stage in the beef production supply chain are based on sources in the literature. See Appendix A for a more detailed overview of all factors. A review of relevant literature did not reveal comprehensive regionally specific energy use or GHG emissions intensity factors for the majority of activities associated with beef production. Therefore in most cases, national-level averages were used. Due to overall data limitations, some GHG emission intensity factors do not break down emissions by GHG type or specific activity (e.g., fuel use for machinery used in planting feed crops). When emission intensity factors for individual GHGs were available, 100-year time horizon global warming potentials (GWP) from the IPCC Sixth Assessment Report (AR6) were used to calculate emissions in terms of CO_2 equivalence (CO_2e). Total beef supply chain GHG emissions for the US and each individual metro and non-metro area was calculated by summing the GHG emissions of all flows of beef into the FAFs associated with each area.

2.5.1 Transportation

GHG emissions attributed to transportation in this study are restrained to one-way origin to destination commodity shipments and do not consider round trip distance as done in some studies (e.g., Stackhouse-Lawson et al 2012, Rotz et al 2019, Kannan et al 2016) in order to avoid potential double counting. All domestic FAF4 commodity flows relevant to this study are categorized in the FAF4 database as 1 of 5 possible shipment modes: 1 - Truck, 2 - Rail, 3 - Water, 4 - Air (including truck-air), and 5 - Multiple modes & mail (Oak Ridge National Laboratory 2015b). As done in Vora et al 2021, origin to destination commodity flows shipped by mode 5 were reassigned to the most common mode by which that commodity was shipped between the origin to destination pair. If 100% of all commodity shipments between an origin-destination pair were reported as mode 5, the transportation mode was reassigned to truck as the US's preferred method of shipment (Vora et al 2021). According to total shipment weight, commodities that were transported by mode 5 made up ~0.1% of the total weight of all SCTG 05 commodities shipped.

Emission intensity factors for modes 1-4 were sourced from the EPA's April 2022 GHG Emission Factors Hub publication (U.S. EPA 2022). All truck transport was assumed to be medium- and heavy-duty trucks. Emission factors were multiplied by the ton-miles for each commodity flow to calculate CO_2, CH_4, N_2O, and CO_2e emissions for the transportation associated with that commodity flow.

2.5.2 Feed Production

GHG emissions intensity factors for the production of cattle feed were sourced from Adom et al 2012. Emissions factors sourced from Adom et al. 2012 were generalized at the level of specific activity/source and GHG type but provide individual emission factors for five U.S. production regions and six of the 10 cattle feed crops included in this study. Factors for the six relevant cattle feed crops were used to generate average emission factors for SCTG 02 and SCTG 04 commodities in kg CO_2e/kg dry mass feed.

2.5.3 Cattle Production

GHG emission sources and emitting activities related to cattle production within the scope of this study include enteric fermentation, manure management, and on-farm electricity use. Emission intensity factors for enteric fermentation and manure management are based on data from the EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019 released April 2021. EPA emission intensity factors are provided for CH_4 and N_2O on a kg GHG/head/year basis for each cattle type; cattle types are differentiated by gender, purpose (beef or dairy), age, and feeding stage. Emission factors were converted to kg GHG/head/day and incorporated in life stage progression models for each cattle type slaughtered in 2012 to generate lifespan emissions factors. Assumptions used in creating life stage progression models are included in Table 2.4. Data from USDA NASS QuickStats regarding the number of cattle slaughtered in 2012 according to cattle type was used to generate a weighted average emissions factor in kg GHG/head. For the purposes of this study, a value of 0 lifespan emissions is assumed for dairy cull cows slaughtered in 2012; emissions associated with dairy cattle eventually slaughtered for beef are considered impacts of the dairy production system. A more detailed explanation of the methods used for determining cattle production emissions is available in Appendix A.

Numerous LCA studies of cattle or beef production account for emissions attributed to energy use on cattle farms (Roop et al 2014, Southwell and Rothwell 1977, Ryan and Tiffany 1998, Rotz et al 2013, Rotz et al 2015, Dyer et al 2017, Asem-Hiablie et al 2015). Many of the studies evaluated do not report energy use associated with cattle farming separately from feed production and focus on annual cattle emissions rather than lifetime emissions for slaughtered cattle. Due to a lack of available data appropriate for the scope of this study, energy use for cattle farming only accounts for the electricity used for cattle housing as sourced from Asem-Hiablie et al 2018.

Regional-level emission factors for electricity use were obtained from EPA's 2012 eGRID database published in 2015. The emission rate for the eGRID subregion that covered the greatest portion of each FAF was used to estimate the emissions associated with electricity usage in that FAF. The eGRID annual output emission rates are calculated for electricity generation sources but do not account for losses from transmission and distribution infrastructures (U.S. EPA 2015b). In order to account for electricity consumption within each FAF, regional grid gross loss factors were included when calculating the total amount of GHG emissions attributed to electricity usage in each FAF.

2.5.4 Beef Slaughter/Processing

Analysis of the GHG emissions associated with the slaughtering and processing of cattle for beef products focuses on emissions from energy, specifically electricity and natural gas, used to carry out facility operations. A literature review was conducted to obtain specific energy intensity factors per amount of cattle slaughtered. Due to limited data, energy intensity factors represent national as opposed to regional averages.

The amount of electricity consumption associated with beef processing in kwh/kg cattle live weight (LW) was determined by averaging beef processing electricity usage factors from Li et al 2018, Asem-Hiablie et al 2018, Desjardins et al 2012, Parker et al 1997, Ziara et al 2016 and Roop et al 2014. A brief overview of each study's attributes can be found in the Appendix A. The same eGRID electricity emission factors used for estimating the GHG impact of electricity use in the cattle production stage were used for electricity consumption during beef processing.

The amount of natural gas usage associated with beef processing in Btu/kg LW was determined by averaging beef processing natural gas usage factors from Li et al 2018, Asem-Hiablie et al 2018, Desjardins et al 2012, and Parker et al 1997. Emission factors for natural gas combustion were obtained from the EPA's April 2022 GHG Emission Factors Hub publication (U.S. EPA 2022).

2.6 Beef Footprint

A GHG footprint per lb of retail (bone-in) beef was calculated for each final FAF destination at the end of the beef production supply chain. To calculate the GHG footprint of entire beef supply chains for each end destination, GHG emissions for each supply chain step were calculated for flows, summed at FAF destinations/origins, and re-allocated to outflows using an approach similar to the leverage network.

FAF4 tracks commodity flows between a total of 132 individual FAFs. Metro areas are defined in this study as FAFs that consist of a metropolitan area; metro FAFs might represent an entire metropolitan area or only a portion of a larger metropolitan area that spans multiple states (e.g., New York City metropolitan area consists of 4 FAFs, one each in Connecticut, New Jersey, New York, and Pennsylvania). Within the FAF4 dataset, the 84 metro FAFs represent the 70 largest individual U.S. metropolitan areas. Non-metro areas as defined in this study are FAF's that consist of an entire state or the "Remainder of [state]"; the one exception being FAF 441 which includes the entire state of Rhode Island and is also considered part of the larger metropolitan area of Boston.

All results (where applicable) are presented using the functional unit of pounds (lbs) of retail (bone-in) beef. Average GHG footprints in kg CO_2e/lb retail beef were estimated for each metro area by first calculating GHG footprints for each beef inflow then calculating the weighted average GHG footprint. Footprints for individual inflows of beef were weighted according to the proportion each beef inflow that contributes to the total amount of beef (in lbs) shipped to the FAF destination from all FAF origins. Weighted averages for metro vs. non-metro areas and a national-level weighted average were determined following the same method of proportionally weighting the footprint for each relevant individual flow.

2.7 Sensitivity Analysis

A sensitivity analysis was conducted to estimate uncertainty as a result of some of the choices made in the model. The following factors were included in the sensitivity analysis: electricity and natural gas use intensity for slaughter plants, CO_2e intensity factors for production of SCTG 02 and 04 feed crops, lifestage length for cattle (affecting both enteric fermentation and manure management emissions), refrigeration of trucks during beef distribution, and variation in global warming potentials. The best estimate value used in the study is based on the most appropriate or mean value from the literature; however, the sensitivity analysis considers the full range of values reported in the literature.

3. Results and Discussion

3.1 Greenhouse Gas Emissions

3.1.1 U.S. Domestic Beef Production Supply Chains

Metro-destined beef supply chains were examined to determine where cattle feed, cattle, and processed beef were most commonly sourced from. Non-metro Texas, non-metro Kansas, and non-metro Nebraska were the top three areas from which cattle feed, cattle sent to slaughter, and commercial beef were sourced for metro beef supply chains. The top five origin areas for each commodity and the relative proportion each origin contributes are reported in Table 2.5. Supply chains for two individual metropolitan areas (Phoenix, AZ and New York, NY) were analyzed in Table 2.6 to demonstrate the national-scale cross-city comparability of data generated by the model created in this study. A more detailed description of individual FAF zones is provided in Appendix B.

Table 2.5 Top five commodity origins for beef supply chains that end in domestic metro destinations.

	Feed Production		**Cattle Production**		**Beef Processing**	
Rank	*Origin*	*Portion of all DM feed (%)*	*Origin*	*Portion of all LW cattle (%)*	*Origin*	*Portion of all bone-in beef (%)*
1	Rest of NE	14	Rest of NE	15	Rest of TX	18
2	Rest of TX	11	Rest of KS	12	Rest of KS	17
3	Rest of KS	11	Rest of TX	12	Rest of NE	15
4	Rest of CO	6	Rest of CO	6	Rest of WA	5
5	Rest of CA	4	Rest of CA	5	Omaha, NE	4
Top 5	46 %		48 %		59 %	

Table 2.6 Top five commodity origins in beef supply chains that end in Phoenix, AZ vs. New York, NY

		Feed Production		**Cattle Production**		**Beef Processing**	
	Rank	*Origin*	*Portion of all DM feed (%)*	*Origin*	*Portion of all LW cattle (%)*	*Origin*	*Portion of all bone-in beef (%)*
Phoenix, AZ	1	Rest of UT	19	Rest of UT	20	Phoenix, AZ	34
	2	Rest of TX	11	Phoenix, AZ	14	Rest of TX	18
	3	Rest of AZ	9	Rest of TX	11	Rest of UT	13
	4	Phoenix, AZ	8	Rest of KS	8	Rest of KS	13
	5	Rest of KS	7	Tucson, AZ	7	Fresno, CA	5
	Top 5	54 %		61 %		83 %	
New York, NY	1	Rest of KS	17	Rest of KS	19	Rest of KS	32
	2	Rest of NE	10	Rest of PA	12	Rest of TX	13
	3	Rest of PA	10	Rest of NE	11	Rest of PA	9
	4	Rest of TX	7	Rest of TX	8	Philadelphia, PA	9
	5	Rest of OK	5	Iowa	3	Omaha, NE	7
	Top 5	50 %		54 %		69 %	

3.1.2 Beef Supply Chain Emissions Totals

GHG emissions attributed to the domestic production of marketable beef slaughtered and processed in the U.S. in 2012 for domestic consumption totaled 146 million metric tons (MMT) CO_2e. Of this total, 64% or 93 MMT CO_2e can be attributed to metro-destined beef and 36% or 53 MMT CO_2e can be attributed to beef consumed in non-metro areas. As shown in Figure 2.3, the top 10 metro areas responsible for the largest amount of beef supply chain emissions contributed 50 MMT CO_2e, equating to 34% of total U.S. beef supply chain GHG emissions. Half of U.S. beef supply chain GHG emissions can be attributed to the top 22 metro areas out of the 70 evaluated in this study. Figure 2.3 provides the total attributed emissions in MMT CO_2e for each individual metro area.

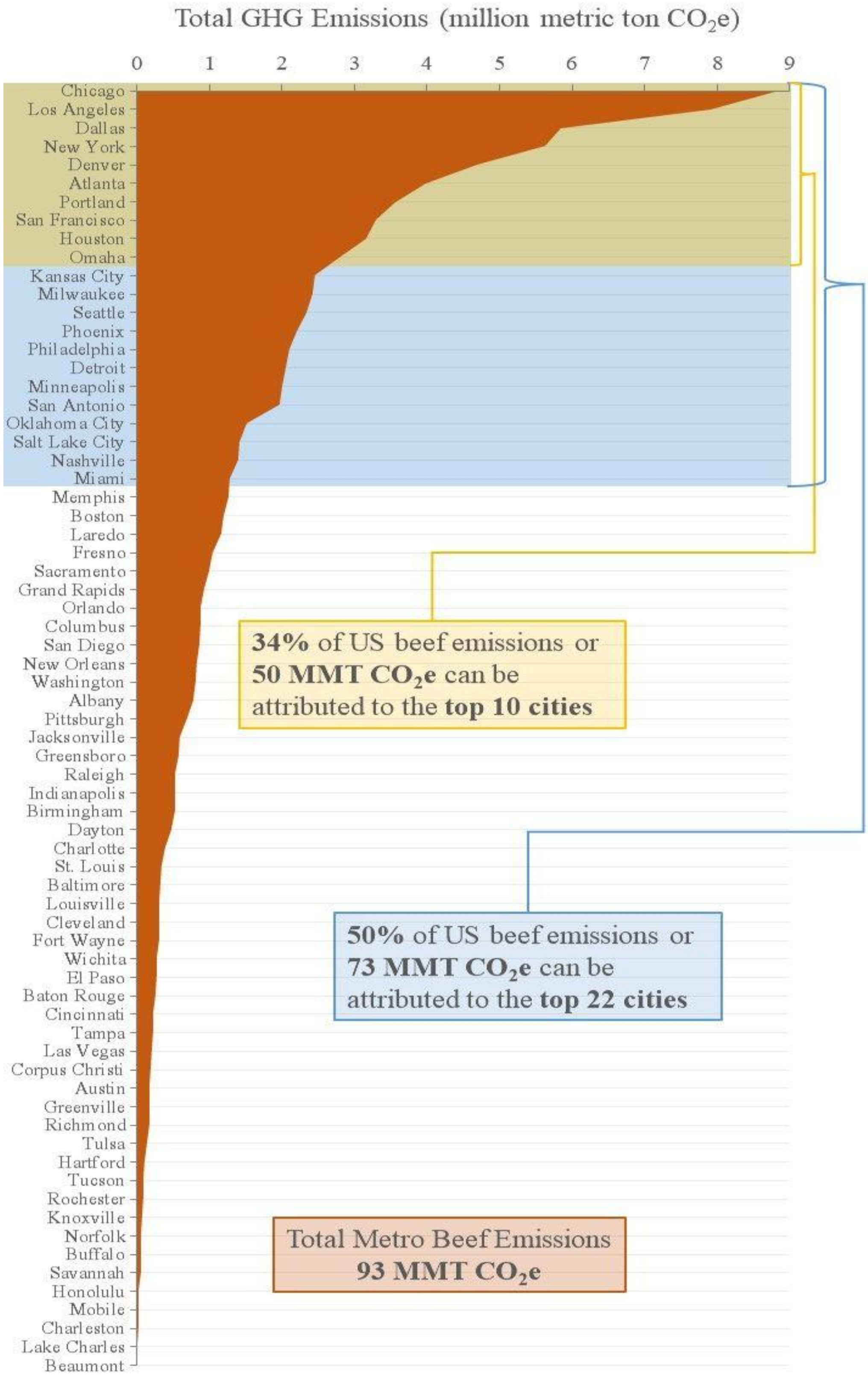

Figure 2.4 GHG emissions attributed to metropolitan beef supply chains by metro area (MMT CO_2e)

GHG emissions for beef supply chains were also evaluated on a per capita basis; for each metro and non-metro FAF area, the attributed beef supply chain GHG emissions were divided by that area's 2012 population. Of the total beef available for consumption in the U.S. in 2012, 8.6% was imported; inclusion of imported beef was outside the study boundaries for the initial version of the U.S. beef supply chain model described herein (USDA ERS 2022). Due to the exclusion of imported beef from the model, the metric of per capita emissions should serve primarily as a comparative metric within the context of this study as opposed to an absolute value for broader application. While national-level per capita GHG emissions attributed to the beef supply chain were 0.5 t CO_2e/person, individual area per capita emissions ranged from a low of 4×10^{-5} tons of CO_2e/person in Beaumont, TX to 4.9 t CO_2e/person in the "Rest of NE" FAF zone. Of the 118 metro and non-metro areas evaluated, the majority (89%) had a per capita GHG footprint of < 1 t CO_2e per person. Only four (3%) of the 118 areas evaluated had a per capita emissions > 3 t CO_2e/person - Rest of NE, Laredo,TX, Rest of KS, and Omaha, NE.

3.1.3 GHG Footprints Attributed to Beef Supply

The functional unit of 1 lb retail beef (bone-in) was used to calculate the GHG footprint of domestic beef available for consumption in each metro and non-metro area across the U.S. according to each area's unique beef supply chain. GHG footprints calculated at both the national and sub-regional level are the average of all relevant individual supply chain systems that contribute to the end destination of interest; averages are weighted according to the portion of beef (by weight) each individual supply chain contributes to the total beef available at the final destination.

At a national level, the weighted average GHG footprint of U.S. domestic beef was 8.70 kg CO_2e/lb retail beef. The average GHG footprints for grouped metro vs. non-metro areas were similar (8.72 and 8.66 kg CO_2e/lb retail beef respectively). Footprints across metro areas ranged from 8.04 to 10.88 kg CO_2e/lb retail beef. Footprints for all individual origin to destination commodity flows ranged from 8 to 16 kg CO_2e/lb retail beef. Areas with the highest GHG footprints (10 kg CO_2e/lb retail beef or more) are listed in Table 2.5. A full list of GHG footprints for all individual metro and non-metro areas can be found in Appendix C.

Table 2.7 Metro and non-metro areas with GHG footprints ≥ 10 kg CO_2e/lb retail beef

Metro		*Non-Metro*	
Mobile, AL	11	West Virginia	11
Charleston, SC	10	Rest of New Hampshire	10
Knoxville, TN	10	Alaska	10
Lake Charles, LA	10	Rest of Hawaii	10
Savannah, GA	10		
Honolulu, HI	10		

The lack of significant variation in GHG footprints across locations can be explained in part by the lack of regionally specific model inputs, due to limited data availability, incorporated into primarily the life cycle analysis portion of this study (e.g., using U.S. average energy intensity factors for every beef slaughterhouses), as well as aspects of the beef production model (e.g., using U.S. average live weight instead of regional for cattle at all cattle origins). Variation that does exist in footprints across individual areas is a result of regional differences in cattle live weight at slaughter (less beef produced per cow results in more emissions per lb of beef), transportation mileage for commodities, and the application of regionally specific emission factors for feed production (when available).

3.1.4 GHG Emissions by Supply Chain Activity

Emissions can be attributed to segments of the beef production process (with all transportation considered separately from production) as follows: 19% feed production, 75% cattle production, 1% beef production, and 4% transportation (Figure 2.4). At a national level, the majority (66%) of beef supply chain emissions in 2012 is attributed to the occurrence of enteric fermentation in cattle over their lifetime prior to slaughter. The activities and processes associated with the production of feed for cattle were responsible for 19% of total supply chain emissions. Ideally feed production emissions would be broken down according to specific activity instead of grouped; however, the GHG emissions intensity factors used in this study for feed production though general in terms of activity were regionally specific. The use of regionally specific GHG emissions data in the model increases the model's ability to account for local uniqueness. The management of manure produced by cattle over their lifecycle accounted for 8% of beef supply chain emissions. Remaining sources of emissions included electricity use on cattle farms (0.8%), electricity and natural gas use for beef processing (1.2%), and vehicle transport of commodities from origin to destination (4 %). A summary of beef supply chain emissions according to emission source and relative portion is captured in Figure 2.4.

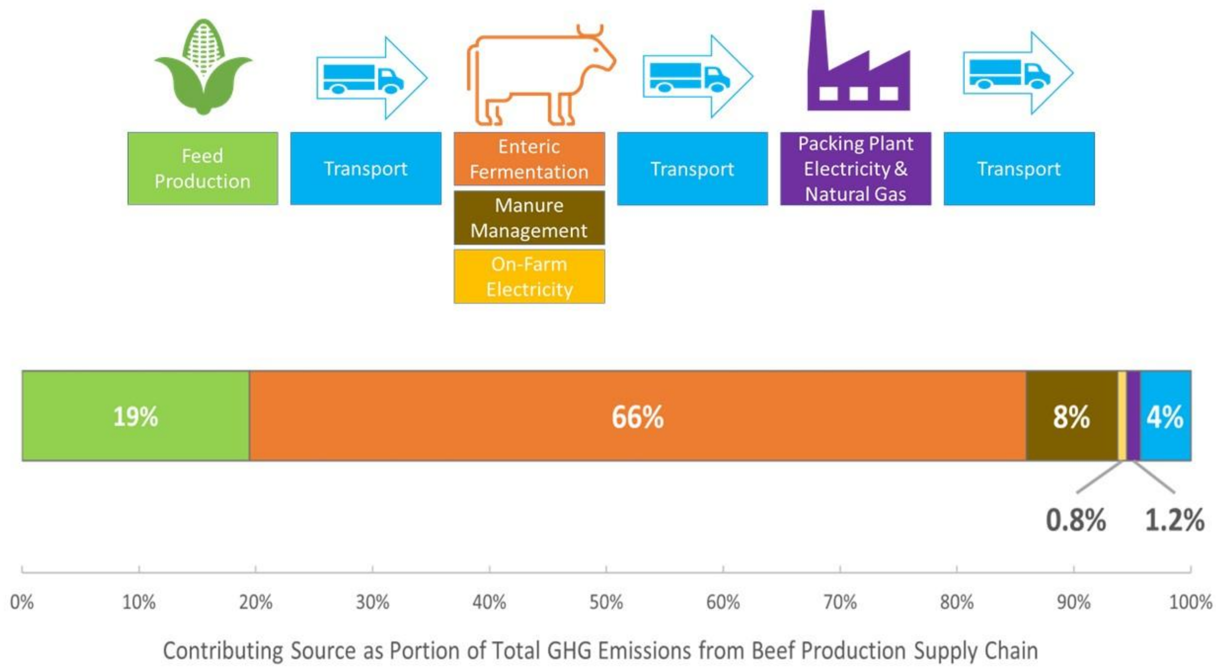

Figure 2.5 Beef production supply chain emissions by contributing activity or source

No significant variation in emissions by segment of the supply chain was found when comparing grouped metro vs. non-metro areas to the national average. Across all individual metro and non-metro areas, emissions per supply chain segment ranged from 18% to 22% for feed production, 69% to 78% for cattle production, 0.7% to 1.4% for beef production, and 1% to 12% for transportation. When excluding Alaska and Hawaii and focusing on the contiguous 48 states, emissions per supply chain segment ranged less for cattle production (72%-78%) and transportation (2%-8%) but did not change for feed production and beef production. For each metro and non-metro area, the greatest portion of GHG emissions was attributable to enteric fermentation.

3.2 Sensitivity Analysis

Total U.S. beef supply chain emissions and footprints had a relative uncertainty of ± 35%. When considering potential variability in emission factors, energy intensity, beef lifespan, global warming potentials, and truck refrigeration, total 2012 U.S. beef supply chain emissions ranged from 100-179 MMT CO_2e (146 ± 51 MMT CO_2e;Table 2.8). The U.S. GHG footprint of beef in 2012 was 8.7 ± 3 kg CO2e/lb.

Results regarding the sensitivity of the model to individual factors is displayed in Table 2.9. Upper and lower bound adjustment of cattle lifestage as it relates to the production of enteric methane had the largest impact (± 23%) on model outputs. Model outputs were secondarily most sensitive to inputs for feed production emissions intensity (± 8%). Adjustments to the energy intensity for electricity and natural gas use in the slaughtering and processing phase had the least impact on model outputs (each ± 0.4 %).

Table 2.8 Results of sensitivity analysis and uncertainty bounds

	Best estimate	Lower	Upper	Absolute difference	Relative difference
Total U.S. Beef Emissions (MMT CO_2e)	146	100	179	± 51	35%
U.S. Beef Footprint (kg CO_2e/lb beef)	8.7	6.0	10.7	± 3	

Table 2.9 Results of sensitivity analysis and contribution of each factor to uncertainty

Factor	**Uncertainty Impact**
Global Warming Potential (GWP)	± 5%
Beef Processing - Electricity	± 0.4%
Beef Processing - Natural Gas	± 0.4%
Feed Production - Emissions	± 8%
Cattle Production - Enteric Fermentation	± 23%
Cattle Production - Manure Management	± 2%
Transportation - Refrigerated Beef	+ 0.6%

3.3 Cross-study Comparison

GHG footprints for beef as determined by other studies were obtained for comparison; footprints, study locations, and study boundaries are available in Table C.2 of Appendix C. The GHG footprint of 8.7 ± 3 kg CO_2e/lb retail (bone-in) beef determined by this study is lower but not unreasonable when compared to the range of 8 kg CO_2e/lb retail beef (Desjardins et al 2012) to 16 kg CO_2e/lb retail beef (Pelletier et al 2010) found in relevant literature (Table C.2). When evaluating supply chain emissions across all individual origin to destination commodity flows of beef, this study found that the GHG footprints for individual beef supply chains ranged from 8 to 16 kg CO_2e/lb retail beef.

A review of the literature revealed a significant range across studies in how emissions attributed to beef production were dispersed across sources and supply chain stages (Table C.3). Emissions attributed to feed production ranged from 17% - 55% of total beef production emissions, enteric fermentation 23% - 60%, and manure management 8% - 30%. Beef processing emissions made up ~1.8% of total beef production emissions in the few relevant studies that accounted for emissions post farm-gate. Like this study, the majority of relevant literature found that enteric fermentation accounted for the greatest portion of GHG emissions attributed to the beef production supply chain. In both this study and the majority of literature, the aggregate emissions associated with feed production were found to be the second largest contributor to beef supply chain emissions following enteric fermentation.

3.4 Impact reduction opportunities

Three approaches to reducing the GHG impact of a commodity or system might be: (1) adjust aspects of the current system by opting for lower-emitting practices while maintaining the same amount of output, (2) reduce overall production and output thereby reducing the total emissions, and/or (3) shift demand for the higher-impact commodity away to a different lower-impact commodity. Each of these approaches could be used in tandem depending on a particular commodity or system of focus (e.g., a system could reduce production, adopt lower-impact practices, and see demand partially shift to a different commodity and system entirely). An example policy option involving all three approaches might be the implementation of a carbon or GHG emissions tax. Adding an additional tax to goods with higher GHG footprints (such as beef), could possibly shift consumer demand toward alternative products due to higher retail beef prices, reduce beef production due to decreased demand, and/or shift production toward lower-emitting practices as they become the more cost-efficient option (Popp et al 2010). The overall feasibility of implementing any of these approaches to GHG reduction successfully may depend on what policy options are actionable given social, geographic, and financial restraints.

The majority of public attention in regards to reducing the GHG impact of beef production has often focused on the second and third approach - reduced production of beef by shifting demand toward meats with a lower GHG footprint (e.g., chicken) or plant-based protein sources. Studies have shown that shifting to a vegetarian or vegan diet would result in lower dietary GHG emissions, while remaining nutritionally comparable and increasing health benefits (Fresan and Savate 2019, Goldstein et al 2017, Eshel et al 2016). However, a large-scale shift towards reduced meat consumption has been met by both psychological and economic barriers (Goldstein et al 2017).

As an alternative to, or in conjunction with, efforts to reduce GHG emissions through dietary change, changes within the beef production system itself should also be pursued. With over half of emissions from the 2012 U.S. domestic beef supply chain attributed to enteric fermentation (66%), the most impactful solutions for reducing the GHG footprint of beef should focus primarily on reducing direct emissions from cattle as opposed to energy consumption, energy efficiency, or transportation. Production intensity of enteric methane (and manure) is heavily influenced by cattle lifespan, size, and diet (Terry et al 2021, Gerber et al 2013). Producing larger frame cattle that reach slaughter weight quickly is inherently a more efficient method as it means more beef for less number of cattle and at a faster rate generally leading to lower GHG emissions per amount of beef (Terry et al 2021). Genetic selection of specific traits to increase relative beef production and use of dietary supplements to aid in feed digestibility are promising mitigation strategies for reducing beef supply chains emissions from enteric fermentation (Gerber et al 2013).

4. Conclusion

One of the key motivators for creating the beef production supply chain network and emissions model was the need to first determine and then allocate total GHG emissions associated with retail beef in different U.S. metro areas to specific locations and sources within the supply chain. The study sought to create a dynamic, cohesive, and comprehensive spatially explicit method for determining total and relative GHG emissions of individual beef supply chains in a way that allowed for comparison between cities or regions.

Creation of the U.S. beef production supply chain network revealed the heavy concentration of supply chain activity in non-metro Kansas, non-metro Texas, and non-metro Nebraska; these three regions are responsible for producing 36% of cattle feed, 39% of cattle, and 50% of processed beef. Model outputs showed that 70 metropolitan areas in the U.S. are responsible for the majority (64%) of U.S. GHG emissions from the beef supply chain from a consumption-based accounting perspective. This finding emphasizes the significant relative concentration of power of urban areas in terms of producing or reducing total GHG emissions. The U.S. GHG footprint for retail beef was 8.7 ± 3 kg CO2e/lb retail beef; the GHG footprint for individual metro areas ranged from 8 to 11 kg CO2e/lb retail beef. Footprints for metro and non-metro areas were very similar indicating that beef production supply chains are rather homogeneous in terms of emissions produced regardless of where end consumption is occurring.

Enteric fermentation was the largest source (~66%) of GHG emissions within the beef supply chain followed by all feed production activities (~19%). Between individual metro and non-metro areas, the relative portion of emissions attributed to individual sources ranged the most for transport (7%), enteric fermentation (6%), and feed production (3%) with all other sources varying less than 3%. Transport, enteric fermentation, and feed production are the main drivers for differences in GHG footprints between beef consumption areas. Though transport as a emissions source had the greatest range in emissions relative to other sources in individual beef supply chains, at the national level transportation only accounts for 4% of beef supply chain emissions. This finding underscores the importance of addressing feed and cattle production practices, particularly enteric fermentation as the largest emissions source, as opposed to focusing only on reducing vehicle miles traveled within the supply chain.

Future research should prioritize improving the ability of the beef production supply chain network to capture regional uniqueness in production practices and climatic variability. As data becomes available, regionally-specific emission and resource intensity factors should be incorporated into the model replacing national-level values. Emission and energy intensity factors based on weight instead of head should be used where applicable to increase inclusion of regional variability in cattle weight.

Variation across LCA studies in system boundaries (e.g., cradle-to-farm-gate vs. cradle-to-slaughter-gate), GHG emissions included (e.g., land use change, off-farm transport, refrigeration, etc.), functional unit (e.g., kg live weight vs. kg retail boneless edible beef), emissions allocation (e.g., cattle byproducts or by cattle type), and scope (e.g., annual emissions for all beef cattle vs. lifetime emissions for all cattle slaughtered for beef in 2012) make cross comparison between studies difficult. This study and the spatially explicit beef production network model created allow us to explore GHG emissions of the U.S. beef production supply chain in a way that is comprehensive of the entire U.S. and comparable between individual metropolitan and non-metropolitan areas across the U.S.

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CHAPTER 3:

CONCLUSION

As the disastrous current and looming impacts of anthropogenic induced climate change become more apparent, attempts to both mitigate and adapt to climate change have increased. Although climate action continues to move slowly at the federal level, cities and communities have shown growing interest in pursuing climate action strategies on their own (Astor 2022). Cities are the central drivers of resource use and thus greenhouse gas (GHG) emissions. In 2018, 55% of the world's population was living in urban areas and consuming the majority (~75%) of the world's natural resources; this indicates a large concentration of buying power governed by a relatively small number of local governments (UNEP 2013, UN DESA 2018, Moran et al 2018). The urban population is expected to increase to 68% of the global population by 2050 (UN DESA 2018). From a consumption-based accounting perspective, approximately 60-70% of GHG emissions can be attributed to cities (UN-HABITAT 2011, IEA 2008). Our ability as a collective society to meet global GHG emission reduction targets will be determined by the success of city-driven GHG mitigation (Mohareb et al 2018, Mohareb et al 2014, Hoornweg et al 2011).

3.1 Sustainable Urban Food Systems

Research has shown that producing and consuming less meat and livestock products, particularly beef, would lower GHG emissions attributed to agriculture significantly (Popp et al 2010). However, for a city trying to reduce the environmental impacts of their food system, the process is less than straightforward. More data is needed to inform cities about what aspects of their food supply chains should be prioritized when it comes to changing how, where, and what food is sourced. Analysis for sustainable food systems must occur at the local scale for supply chains specific to each city. The model created and results generated from this study can aid cities in understanding their unique beef supply system and compare their systems with other cities to generate shared knowledge.

3.2 Climate Change Adaptation

In addition to mitigating climate change, there is a drastically growing need to implement measures that adapt food systems to climate change impacts. Regional changes in temperature and precipitation patterns as a result of anthropogenic induced global climate change are likely to have adverse effects on livestock production across the entire supply chain as shown in Figure 3.1 (Godde et al 2021). Although certain crops will be positively impacted by increased atmospheric CO_2 levels for at least a period of time and higher latitude growing regions may benefit from increased temperatures (Reeves et al 2017), a majority of climate related impacts will be negative. Potential negative impacts of climate change on livestock production include increased risk of disease and pests, heat stress to laborers, crops, and livestock, water stress to crops and livestock, crop loss due to flooding, and supply chain disruptions due to extreme weather events (Godde et al 2021, Rojas-Downing et al 2017). As a result of the net impacts of climate change, shifts in production regions for cattle feed, rangeland, and pasture as well as cattle operations can be expected (Brown et al 2015).

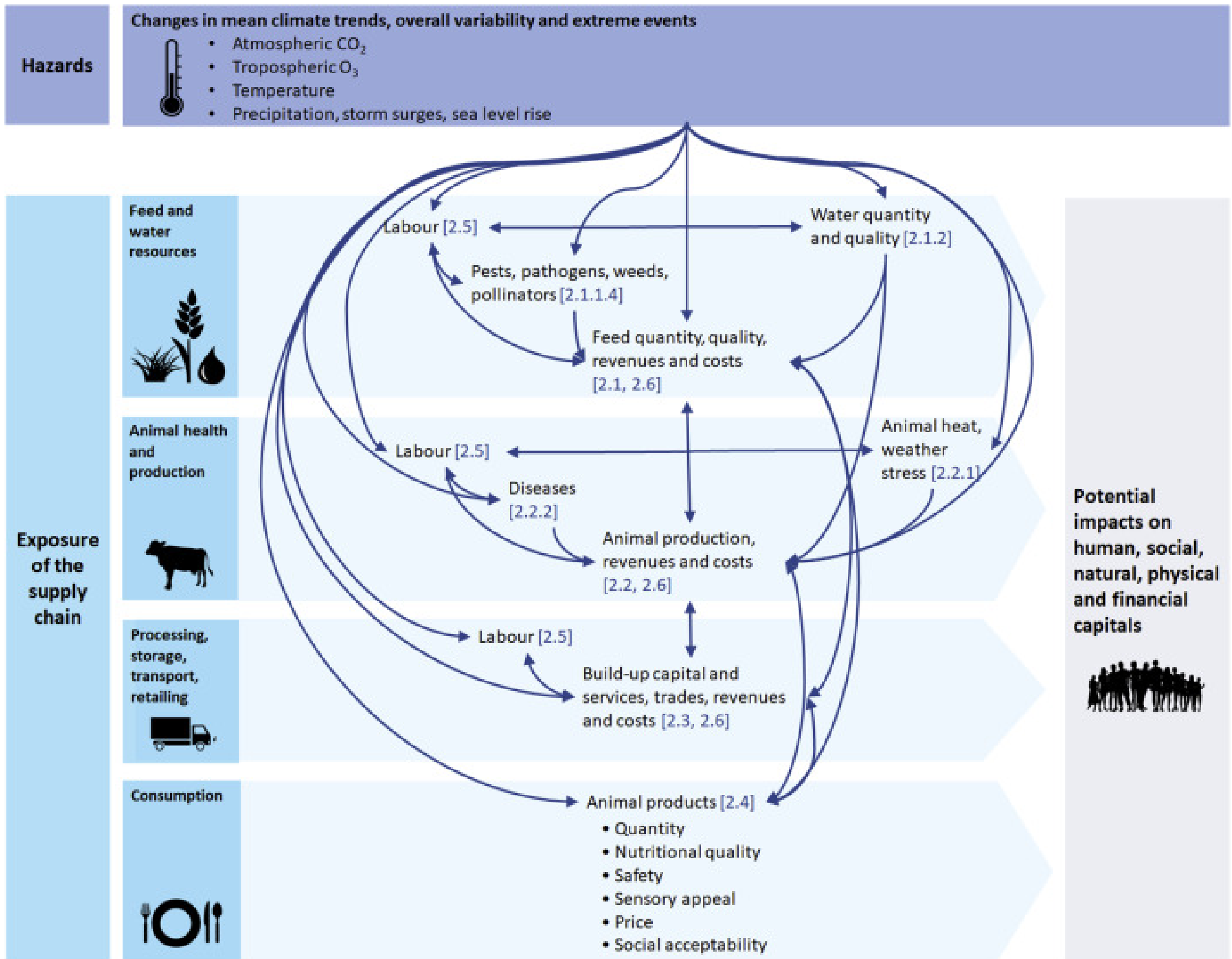

Figure 3.1 Potential climate change impacts on each stage of the livestock production supply chain (Godde et al 2021).

Spatially explicit models of food production supply chains, like the model created in this study, could play a critical role in the strategic design and implementation of climate change adaptation measures within supply chains. Such models, and more spatially detailed and explicit data, could greatly benefit cities and communities working on building more resilient food systems. Much of our food production occurs in rural communities and non-metro areas, a trend supported by the results of this study in regards to beef production. As patterns of food production shift in response to climate change impacts and demand driven climate mitigation and adaptation policies, many rural communities may suffer without the facilitation of a just transition (Woodhill et al 2022). Spatially explicit food production models could be used to preemptively direct federal and state level support for rural communities most vulnerable to agricultural volatility (Gowda et al 2018).

3.3 Suggestions for Future Research

This novel study offers a plethora of opportunities for improvement and expansion. Limitations to this study are derived mainly from lack of spatially (and temporally) explicit data - a common limitation for LCA studies (Reap *et al* 2008). Though numerous detailed European LCA studies were identified, there is an overt lack of inventory data for inputs into the beef production supply chain (including feed production and beef processing) that is based on production within the U.S. Future work should prioritize the incorporation of finer scale, regionally specific data as it becomes available. There is a strong need for finer scale, higher quality data that accurately tracks the complex intra- and international flow of goods while continuing to protect the privacy of individual operations as necessary. Innovative solutions for meeting such demands could include the use of blockchain technology to help track the carbon footprint of food products as attributed to production and transportation stages (Shakhbulatov et al 2019).

Model estimations for cattle feed consumption could be significantly improved by incorporating data regarding the on-farm finishing weight of cattle and typical feed ratios in each region. At the time of this study, only data regarding the weight of cattle at slaughter could be found; because cattle may be raised in one location and slaughtered in another, it can not be assumed that slaughter weight and cattle on-farm finishing weight are the same for a given region. Additionally, the feed type proportions in cattle diets are known to vary by region according to what crop is most economical to grow. Incorporation of regionally specific data regarding cattle diets and on-farm finishing weights could also be used to increase the location-based specificity of GHG emissions from enteric fermentation. Emissions from manure management could be estimated at the regional level by incorporating local climate data and regional manure management styles. Current literature does not document the regional variability in energy use and intensity across U.S. beef processing plants; this data could be very beneficial in understanding GHG emissions associated with slaughter and processing at a local level.

The sensitivity analysis conducted for this study could be significantly improved by expanding it to include on-farm finishing weight of cattle (lbs) and feed consumption intensity (DMI lbs/finishing weight lbs). Despite both of these factors having a significant impact on model end results, they were excluded from the sensitivity analysis at this time due to the tediousness and time-demanding nature of the procedure. Feed consumption intensity and on-farm finishing weight of cattle were used to create the leverage network for SCTG 02 & 04. As a result of the current model structure, altering these factors for a sensitivity analysis would have required reworking the entire model. The exclusion of these two particular factors from the sensitivity analysis is a limitation to this study; future models should be structured in such a manner as to ensure that a thorough sensitivity analysis can be conducted in a more efficient manner.

Due to limited data availability, the total amount of transportation-related emissions associated with the beef production supply chain are almost certainly underestimated by the current model. Future work should prioritize better tracking of cattle movement within the production stage from cow-calf operation, to backgrounder/stocker phase, to feedlot. Improvements to commodity flow tracking should also look to account for the shipment of beef from slaughterhouse to future processing, distribution, and/or wholesale prior to retail. Truck refrigeration for shipped beef should be more thoroughly evaluated and incorporated in the LCA portion of this model.

Future work could explore the possibility of creating a hybrid LCA-IOA model to expand on (and likely improve the accuracy of) the methodology used in the study by incorporating an input-output approach. National input–output make and use tables could be used to expand system boundaries of the current model by capturing a greater and more comprehensive range of commodity interdependencies within the beef production system (Garcia et al 2020). For example, sparse inventory data and scientific literature specifying energy use on cattle farms could be supplemented by using input-output tables to determine the total amount of electricity and natural gas used by the beef cattle farming industry. Because input-output tables are created at the national-level, energy use data would need to be thoughtfully disaggregated; however, the total amount of energy used would be more complete (Lenzen 2011). The use of a hybrid LCA-IOA model could also potentially help reduce any truncation errors while expanding the comprehensiveness of the beef system production model (Fry et al 2019, Suh et al 2004).

LCA system boundaries should be expanded both upstream and downstream to account for emissions related to land use change and soil carbon as well as food waste. In 2012, 4.3% of beef produced was lost as waste at the processing and retail level (US ERS 2020). The model created in this study does not account for waste; instead, the model makes a direct conversion between cattle live weight and retail beef without considering loss.

The model created in this study relies on 2012 data as, at the time of this study, these were the most recent FAF4 and CFS datasets available. Future versions of this model should be run using the latest 2017 data and results analyzed for comparison with the 2012 results. Doing so will expand understanding of "bigger picture" trends across time. Finer scale models could be used in such time series studies to track how commodity flow networks change over time in response to changing consumer demand, economic transitions, climate change impacts, and policy implementation in individual cities (Kennedy et al 2011).

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APPENDIX A:

SUPPORTING INFORMATION

S-1 Overview

The methodology presented herein creates a static model of greenhouse gas emissions associated with the major steps in the beef production supply chain. Supply chain steps included in this model were: production of cattle feed, production of cattle, slaughter, processing, and packaging of cattle meat (beef processing), and transportation between all steps of production.

The majority of the methodology for this study involved the construction of a network tracking the flow of major commodities involved in beef production in the U.S from origin to destination locations; this commodity flow network (CFN) also tracks attribute information for the shipment transportation between origins and destinations.

This study seeks to create a comprehensive national-level model detailed at the sub-regional level for beef that could be purchased by consumers at a commercial establishment. The model created is unable to account for all aspects of the US beef production system. Data limitations and study constraints necessitated a narrower scope when modeling certain system aspects and oversimplified assumptions for other aspects of the system. In several cases, the model assumes that attributes reflective of the majority of US slaughtered cattle are true for all cattle slaughtered. For example, 97% of cattle slaughtered in the US are raised in conventional systems where they feed on grain (in addition to other feed types) at some point in their life; only 3% of cattle are raised in alternative systems where cattle do not consume grain at any point in their life or where organic practices are used. The model created in this study does not account for alternative systems and assumes all cattle are raised in conventional systems. Table ____ outlines some of the necessary assumptions made in the model; other assumptions are tracked within the methodology recorded in this document.

Table S-1 Attribute data for US Beef Industry vs. assumptions included in model for all slaughtered cattle

Component	Included		Excluded	
Production System[1, 2]	97%	Conventional, grain fed	3%	Alternative system (e.g. grass fed, organic)
Cattle Type[3]	29% 50% 2% 10%	Heifers Steers Bulls (dairy and beef) Cows (non-dairy)	10%	Cows (dairy)
Slaughter Type[3]	98.1% <1.6 %	Commercial - Federally Inspected Commercial - State Inspected and some Custom Exempt[a]	0.3% <1.6%	Farm Custom Exempt[a]
Feed Type[4]	23% 12%	Harvested forage Grain concentrate	59% 7%	Grazed forage or pasture Other (byproducts or food scraps)

a - Some custom exempt is excluded but exact proportion is unknown, 1 - Mathews and Johnson 2013, 2 - Cheung and McMahon 2017, 3 - USDA NASS Quick Stats 2022, 4 - Rotz *et al* 2019

S-2 Developing the Commodity Flow Network Baseline

Data quantifying the flow of commodity goods within the U.S. (including imports and exports) was obtained from the U.S. Census Bureau, 2012 Commodity Flow Survey (CFS) and the 2012 Freight Analysis Framework version 4 (FAF4) produced by the Bureau of Transportation Statistics, Federal Highway Administration, and Oak Ridge National Laboratory (ORNL). CFS data tracks the flow of commodities primarily from the manufacturing, mining, and wholesale sectors. These commodity "flows" are tracked as individual shipments from businesses. FAF4 builds in farm-based agriculture flows and international trade which are considered out-of-scope in the CFS data. The scope of this study was constrained to 2012, the most recent complete CFS and FAF4 datasets, at the time of this analysis. As of now, 2017 data is publically available for both CFS and FAF (as FAF5).

Commodity shipments included in CFS data are organized by type of commodity according to Standard Classification of Transported Goods (SCTG) codes. Commodities in the CFS dataset are further classified into greater detail according to the North American Industry Classification System (NAICS).

Table S-2 Commodities relevant to this study grouped by SCTG as outlined in the FAF4 Methodology - Appendix B.

SCTG Group	Group Title	Relevant Commodities
01	Live Animals and Fish	Live cattle
02	Cereal Grains	Grain corn, barley, grain sorghum, oats, wheat
04	Animal Feed, Eggs, Honey, and Other Products of Animal Origin	Silage corn, hay, haylage, silage sorghum
05	Meat, Poultry, Fish, Seafood, and Their Preparations	Beef (fresh, chilled, frozen, salted, dried, or smoked)

The farm-based commodities recorded in Table _____ (e.g. cattle, grain corn, hay) are not included in the CFS SCTG groups as the CFS does not include any farm-based flows. By subtracting the CFS dataset from the FAF4 dataset, farm-based flows in each relevant SCTG group can be isolated; the methodology for this procedure is explained in detail in S-2.4. Farm-based data was not isolated when modeling SCTG 05 flows as this study is concerned only with the production of marketable beef produced off-farm in commercial facilities.

S-2.1 Commodity Flow Survey (CFS) Data

The following steps were taken to prepare CFS data for use in this study.

1) Download 2012 CFS Public Use Microdata File in CSV File format. The CSV file was imported into Microsoft Access.
2) Shipment record data was extracted from Access for the following SCTG codes: 01, 02, 04, and 05 and imported into Microsoft Excel.

a) Data for which SCTG detail has been reduced to a range value (either as 01-05 or 06-09) was not included. Shipment data that is not associated with a specific SCTG code and only assigned a SCTG range was deemed too coarse of detail to be useful within the analysis and was thus excluded; data must be associated with specific SCTG code. Shipments with SCTG code recorded as a range value were excluded because at the time of this study, there was no known methodology for distributing the data from records associated with a SCTG code range to individual SCTG codes without introducing or reinforcing bias.
   i) *For the cumulative shipment data that either through individual SCTG code or general SCTG range fell within SCTG 01-05, shipments assigned the 01-05 range made up 3% of the total value and 5% of the total weight.
b) From this subset of data, shipment records for which transportation mode is listed as truck were extracted.
c) Data for shipment records related to exported goods remained in the CFS dataset used in this analysis.

3) The end-goal of this methodology is to create a crosswalk between CFS and FAF4 data so that farm-based data included in the FAF4 dataset can be isolated and utilized for further analysis. The FAF4 farm-based data is considered "out-of-scope" (OOS) data not included in the CFS and contains details of shipments "from the field (i.e., farm) to grain elevator, distribution or processing center, or slaughterhouse[1]". The FAF4 farm-based OOS data provides information regarding the first and second step of the beef production supply chain by providing shipment records for cattle feed and live cattle. The following formatting changes were made to CFS data in order to facilitate a crosswalk with FAF4 data and extract the FAF4 farm-based OOS data:
   a) Conversion of CFS shipment origin and shipment destination codes to FAF origin and destination codes. Crosswalk done using the CFS Area Code - FAF4 Zone ID lookup table published by the Oak Ridge National Laboratory and available online with FAF4 data.
   b) Shipment data collected by the Census Bureau for the CFS is considered confidential and can not be released in its raw form as it may provide sensitive information about individuals or establishments that contributed their data to the survey (2012 CFS methodology). Before releasing data for public use, the CFS used disclosure avoidance techniques (specifically Noise Infusion) to protect any confidential information about individual survey respondents. In order to make estimates of total shipment value, total shipment tonnage, total shipment distance routed, and total shipment ton-miles from the Public Use Microdata (PUM) file, the user must multiply the values by their corresponding shipment tabulation weighting factor. The formulas used for this process can be found in the CFS 2012 PUMF Users Guide.
      i) When calculating the average of any type of record for a given domain, each value in the domain of interest must be multiplied by their corresponding weight factor, summed, then divided by the sum of all weight factors in that domain. For example, this method was used when calculating the average miles per shipment.

[1] Building the FAF4 Regional Database: Data Sources and Estimation Methodologies, 2016

ii) Units for value and weight were then converted to million dollars and thousand U.S. short tons (respectively) in order to align with FAF4 units for value and weight.

c) An index code was created for each shipment record by combining the shipment origin, destination, and SCTG code separated by hyphens (e.g. 101-101-1).

d) Multiple CFS shipment records that had the same index code were consolidated into one shipment record by summarizing their value, weight, and ton-miles.

S-2.2 Freight Analysis Framework version 4 (FAF4) Data

The following steps were taken to prepare FAF data for use in this study.

1) Relevant FAF4 data was extracted from the FAF4 Regional Database for 2012 in Microsoft Access format. Shipment records for the following SCTG codes were extracted: 01, 02, 04, and 05.
    a) From this subset of data, extract shipment records for domestic shipments and shipments records for which domestic mode is listed as truck. Because the vast majority of farm-based agricultural shipments are moved by truck, when creating the FAF4 dataset all farm-based agricultural shipments were automatically assigned a transportation mode of truck.[2]
2) As referenced earlier in this methodology, in order to create a crosswalk between 2012 FAF4 data and 2012 CFS data, a few formatting changes had to be made to each dataset.
    a) An index code was created for each shipment record by combining the shipment origin, destination, and SCTG code separated by hyphens (e.g. 101-101-1).

S-2.3 Export and Import Data in CFS and FAF

S-2.3.1 CFS Exports and Imports

- The CFS dataset does not capture data regarding the import of commodities into the U.S. at their U.S. entry point. However, the CFS dataset does include data regarding commodities that were originally imported but are now being shipped from one U.S. location to another. These commodities are not identified as being originally imported however and are recorded as domestic shipments. Imported commodities are "hidden" within the CFS data as domestic goods.
- The CFS data does capture data regarding the export of commodities from the U.S.. When a shipment of commodities ends at a U.S. exit point to then continue onward to a foreign destination, CFS data captures the domestic travel of those commodities to the exit point, but does not track the shipment once it leaves the U.S.. Shipments of commodities that end at a U.S. exit point are identified as "exports" in the CFS dataset; the foregin destination of those exported commodities is also identified in the CFS dataset.

S-2.3.2 FAF Exports and Imports

- In the FAF dataset, commodities that are shipped into the U.S. are identified according to the foreign country (or region) they were imported from and the mode that was used to import them. When the imported commodities are shipped from the U.S. FAF zone entry point to a different FAF zone, the foreign shipment information is attached to the commodities' domestic shipment record. However, after the first domestic shipment of

[2] Building the FAF4 Regional Database: Data Sources and Estimation Methodologies, 2016

the imported commodity from its U.S. entry point to another FAF zone, whether or not the commodity was imported is no longer tracked.

- Similar to import data, in the FAF dataset, commodities that are exported from the U.S. are identified according to the foreign county (or region) they were exported to and the mode that was used to export them. This export information is attached to the domestic shipment record of those commodities when the commodities are shipped from a domestic FAF zone to the FAF zone.

S-2.4 Isolation of Farm-Based Out-of-Scope Flows

- A combined index was created by combining index numbers from CFS and FAF and then deleting any duplicates. For each index, the CFS shipment value and weight associated with that index was subtracted from the associated FAF value and weight.
- Theoretically if an index exists in both FAF4 and CFS, the FAF4 shipment record for that index should have the same if not greater value and weight as the corresponding CFS shipment records. However, because CFS data undergoes an intensive data quality check process before being used in the creation of the FAF4 dataset, it was necessary that some adjustments be made to the CFS data to fix any errors; this adjusted CFS dataset is not available to the public. The PUM file CFS data used in this methodology has not undergone this same intensive data quality review process and therefore has some inconsistencies with the final CFS dataset used in the creation of the FAF4 dataset. As a result, when subtracting the PUM file CFS data from the FAF4 data, some indexes returned a negative difference (indicating that for that index, the CFS data in the PUM file was greater in value and weight than the adjusted CFS incorporated in the FAF4 dataset. For these occurrences, negative differences returned in the CFS-FAF subtraction process were assumed to be zeros as they would be if the adjusted CFS dataset used in the creation of the FAF4 had been used in the CFS-FAF subtraction process instead of the CFS PUM file.
- 2012 USDA data regarding the national totals for farm-based agricultural shipments according to commodity type were used as benchmark values to check that FAF farm-based OOS flows had been successfully isolated from CFS data. Shipment totals were summarized for each of the following commodity groups SCTG 01,02, and 04 then compared to the 2012 USDA national totals; results of this comparison are shown in Table _____. The summation method used treated negative differences between FAF data and CFS data as 0’s.

Table S-3 Comparison of national level estimates for agricultural production as reported by the USDA vs. calculated estimates of farm-based out-of-scope FAF4 data.

National Level Estimates for Agricultural Production						
	Weight (thousand tons)			Value (million dollars)		
SCTG	USDA Totals	Calculated FAF OOS	% Difference	USDA Totals	Calculated FAF OOS	% Difference
1	90,460	96,688	7%	146,746	156,573	7%

2	451,736	453,296	0.3%	88,797	89,410	1%
4	55,472	58,185	5%	3,261	5,316	63%
Total	**597,668**	**608,169**	**2%**	**238,804**	**251,299**	**5%**

S-2.4.1 Method Limitations

For the data used in this study, there are slight inconsistencies between the CFS published estimates vs. tabulations done using the Public Use Microdata (PUM) file. These inconsistencies are in part due to the amount of additional "noise" added into the PUM file data to protect the confidentiality of CFS survey respondents. In some cases, the level of detail for shipments was reduced, first at the mode or commodity level then at the geographic level if necessary. Some shipments of commodities that would have been relevant to the scope of this study (SCTG 01, 02, 04, & 05) were reduced at the commodity level and recorded as an SCTG group ("01-05"). Shipments for which commodity detail was reduced to the SCTG group of "01-05" account for 3% of the total value and 5% of the total weight of all shipments (reduced detail and not) of commodities in the SCTG 01-05 range. Shipments that were reduced at the commodity level were excluded from this study; therefore in this study the summed value and summed weight for all shipments of commodities in the SCTG 01-05 range is an average underestimate of 3-5%. As a result of these (and other) limitations, the PUM file data best captures the general pattern of how commodities flow in the U.S. rather than the exact amounts of commodities flowing.

S-3 Beef Flow Network

S-3.1 Cattle Slaughter & Processing FAF-Level Allocation

S-3.1.1 Method Overview

Data Used [primary]:

- US Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) Quick Stats (http://quickstats.nass.usda.gov)
    - 2012 Federally Inspected (FI) and Non-Federally Inspected (NFI) cattle slaughter
    - US State totals
    - US National totals
- US Department of Agriculture (USDA) Food Safety and Inspection Service (FSIS) 2012 Meat, Poultry, and Egg Product Inspection Directory (MPI) (https://www.fsis.usda.gov/inspection/establishments/meat-poultry-and-egg-product-inspection-directory)
    - Location of FI facilities that slaughtered beef in 2012
    - Slaughter volume of FI facilities that slaughtered beef in 2012
- Kay S 2013 Top 30 Beef Packers 2013 *Cattle Buyers Weekly* (http://www.themarketworks.org/sites/default/files/uploads/charts/Top-30-Beef-Packers-2013.pdf)
    - Estimated number of cattle slaughtered by 25 of the top 30 US beef packing companies in 2012

Data Used [secondary]:

- USDA 2012 Livestock Slaughter Summary - published April 2013
- US Geological Survey (USGS) US Board on Geographic Names 2021 National File (https://www.usgs.gov/u.s.-board-on-geographic-names/download-gnis-data)

Method Boundaries and Overview

- Due to the scope of this study, analysis of cattle slaughter was limited to commercial cattle slaughter and excluded farm slaughter (commercial vs. farm slaughter as defined in the USDA 2012 Livestock Slaughter summary report). Beef produced from cattle slaughtered on farms in 2012 was assumed to be primarily consumed on the farm where slaughter occurred and not sold or transported for commercial purposes. In 2012, cattle slaughtered on farms made up <0.3% of total cattle slaughter as reported by the USDA.
- Data regarding the number of cattle slaughtered commercially (both all commercial and FI specifically) in 2012 is available at the national and state level from the USDA's QuickStats online database used for accessing data published by the NASS.
    - For both the state level all commercial cattle slaughter and the state level FI commercial cattle slaughter datasets, slaughter totals for certain states were not disclosed. When compared to national level summary data, a little over 5% of data was non-disclosed in each of the two state level datasets.
- Federally inspected (FI) slaughter made up >98% of commercial cattle slaughter in 2012 and non-federally inspected slaughter (NFI) <2% (USDA QuickStats). FI slaughter was allocated at the FAF level prior to allocating NFI slaughter at the FAF level to generate total 2012 commercial cattle slaughter for each FAF.

S-3.1.2 Federally Inspected (FI) Commercial Slaughter

- City and state locations for FI facilities that slaughtered cattle to produce beef in 2012 were pulled from the FSIS's 2012 MPI Directory dataset paired with the MPI Directory Supplement: Establishment Demographic Data. City, state locations were assigned FAF locations using data from the USGS US Board on Geographic Names, county to CFS metro area lookup table, and CFS to FAF zone lookup table.
    - If a facility was recorded as slaughtering cattle for beef, even if that facility was also recorded as slaughtering other types of animals for meat, the facility was included in this analysis.
    - Slaughter facilities in the Virgin Islands and Puerto Rico were excluded from this analysis.
- Four sources of data were used for estimating the number of cattle slaughtered at each FAF in 2012.
    - "Top 30 Beef Packers 2013" list published by Cattle Buyers Weekly (CBW) contains estimates for the number of cattle slaughtered in 2012 by each of the top 30 beef packers in the US. Total 2012 slaughter estimates are not disclosed at all

for five of the 30 companies. For the top five beef packers with >1 slaughter plant, slaughter estimates are summed at the company level. These top 5 beef packing companies oversee 32 beef slaughter plants and made up approximately 79% of all commercial cattle slaughter and 80% of commercial, FI cattle slaughter in 2012 (USDA NASS, CBW Top 30). For 20 beef packers with only one slaughter plant, the total number of cattle slaughtered in 2012 was provided at the level of the individual plant. Slaughter estimates for individual plants were automatically allocated to the FAFs in which the slaughter plants were located to generate partial slaughter totals at the FAF level.

- "Largest U.S. Beef Plants" list published by CBW in 2012 contains estimates for the daily slaughter capacity of the largest 72 individual beef plants as it were January 31st 2012. Daily capacity was used to allocate slaughter at the FAF level for the 32 plants owned by the top 5 beef packers.
- USDA FSIS 2012 MPI Directory with Establishment Demographic Data in addition to containing the names and locations of FI facilities that slaughtered cattle, also assigns a Slaughter Volume Category (SVC) number ranging from 1-5 "based on aggregated head slaughtered for the last 360 days". In cases where a slaughter plant slaughters more than one type of animal, the SVC reflects the sum of all animals slaughtered. However, the 56 FI slaughter plants included on the CBW Top 30 Beef Packers list all had SVC values of 2,3, or 4 (4 being the highest SVC for a beef slaughtering facility) and were not reported in the MPI as slaughtering any animals other than cattle.
  - All but one of the companies included in the CBW Top 30 list matched with an establishment record within the MPI directory; it was assumed the omission of this Top 30 company from the MPI directory indicated the company was not FI. The total 2012 cattle slaughter for this company was also not disclosed. This company was omitted from the analysis and allocation of commercial, FI cattle slaughter.
- USDA NASS national and state level data for total number of cattle slaughtered in a commercial, FI facility in 2012 were used to provide national and state level data boundaries for allocation of slaughter at the FAF level.
  - Slaughter totals were not reported for 11 of the 50 states reported by the USDA NASS as having slaughtered cattle (commercial, FI) in 2012. For two of the eleven states with non disclosed data, the USDA FSIS MPI directory held no records of establishments that slaughtered cattle in 2012 in those states.These two states were not allocated any commercial, FI cattle slaughter leaving nine states with USDA non-disclosed slaughter.

- The sum of cattle slaughter estimates for companies listed in the CBW Top 30 list was subtracted from the USDA national total for commercial, FI cattle slaughter. The remaining number of head of cattle was considered “unallocated slaughter”. Unallocated slaughter was then methodically distributed to FAFs based on the number and SVC of beef slaughter plants in each FAF that were not included or did not have disclosed estimates in the CBW Top 30 list. When summed at a state level, FAF slaughter could not exceed USDA commercial, FI cattle slaughter totals for each state. SVC values were weighted [Table _] and the amount of available unallocated slaughter distributed to each FAF according to the FAF’s portion of weighted SVC out of total weighted SVC.

Table S-4 Overview of slaughter volumne category in MPI database and use in study analysis

USDA MPI Slaughter Volume Category (SVC)				Study Analysis	
Establishments that slaughter animals were grouped into five categories based on aggregated head slaughtered for the last 360 days				Weights were assigned in relation to the median of the range for each SVC value	
Code	*Description*	*Lower*	*Upper*	*Median*	*Weight*
1	< 1,000	>0	999	499.5	1
2	≥ 1,000 and < 10,000	1,000	10,000	5,499.5	11
3	≥ 10,000 and < 100,000	10,000	100,000	54,999.5	110
4	≥ 100,000 and < 10,000,000	100,000	10,000,000	5,049,999.5	10,110

- The first portion of FAF level slaughter allocation was conducted on a state by state basis according to the amount of disclosed data from USDA and CBW Top 30 list available for each state:

(1) For seven states, USDA total state slaughter was known and only one FAF in each state was recorded in the MPI as having a FI facility that slaughtered beef. For each of these seven states, all USDA state slaughter was allocated to the one FAF with FI beef slaughtering facilities.

(2) For eight states, USDA slaughter totals were summed to the level of two regional groups rather than individual states: the Maryland/Delaware group and the New England group (consisting of CT, MA, ME, NH, RI, and VT). None of these states had plants or companies with estimated cattle slaughter included in the CBW Top 30 list. The USDA regional group slaughter total was distributed to the FAF’s within each regional group according to the portion of weighted SVC total.

(3) Ten states had known USDA slaughter totals, no companies or plants with estimated cattle slaughter included in the CBW Top 30 list, and multiple FAFs with beef slaughter. For each of these states, USDA state slaughter totals were allocated to FAFs according to their portion of weighted SVC state total.

(4) One state had known USDA slaughter totals, some estimated slaughter from a plant in the CBW Top 30 list, and did not have a slaughter plant owned by one of the top 5 beef packers. For this state, available unallocated state slaughter was calculated by subtracting the estimated slaughter for the plant in the CBW Top 30 list from the USDA state slaughter total. The remaining unallocated state slaughter was dispersed at the FAF level according to the portion of weighted SVC total.

(5) One other state had known USDA slaughter totals, some estimated slaughter from a plant in the CBW Top 30 list, and did not have a slaughter plant owned by one of the top 5 beef packers; however, the CBW estimated slaughter exceeded total state slaughter as reported by the USDA by 0.3%. The CBW estimate was disregarded and instead only weighted SVC total was utilized to proportionally distribute available unallocated state slaughter to each FAF.

- The 21 remaining states fit one or both of the following descriptions: USDA total state slaughter was not disclosed or the state contained a slaughter plant owned by one of the top 5 beef packing companies. CBW Top 30 list includes estimates for 2012 cattle slaughter for the top 5 beef packing companies only at the company level and not the individual plant level. The following multi-step process was utilized to distribute the remaining unallocated slaughter and slaughter from the top 5 beef packing companies at the FAF level for 21 remaining states:

(1) The remaining portion of unallocated slaughter that had not already been distributed to the 27 states earlier in the FAF level allocation process was distributed to the remaining 21 states. The method of weighting SVC for plants not included in the CBW top 30 list was utilized to distribute the remaining unallocated slaughter to FAFs based on each FAFs proportion of aggregateed weighted SVC for all 21 states.

(2) Slaughter estimated by CBW for individual beef plants was allocated to each FAF based on the location of each beef plant.

(3) Fifteen remaining states contained a beef plant owned by one of the top 5 beef packers and required further slaughter allocation.

    (a) For three of these states, USDA 2012 slaughter totals were not disclosed. The current amount of allocated slaughter was summed for all states that did not have disclosed USDA slaughter totals and subtracted from the total USDA commercial, FI cattle slaughter that was not disclosed at the state level. The remaining unallocated slaughter for states with non-disclosed USDA data was distributed at the FAF level according to the daily slaughter capacity of plants owned by one of the top 5 beef packers. Daily slaughter capacity (DC) values for individual plants were sourced from CBW's "Largest U.S. Beef Plants" list current for January 2012. DC for individual plants was summed at the state level and remaining slaughter for non-disclosed states distributed according to each FAF's portion of aggregate DC for the three states.

(b) For the final 12 states, all remaining slaughter was allocated at the FAF level by again utilizing the DC of plants owned by the top 5 beef packers. DC for these plants was summed at the FAF level and for all 12 states; slaughter was allocated according to each FAF's portion of DC out of aggregate DC for the 12 states.

Exceptions

- Five establishments in the MPI directory were recorded as having slaughtered cattle in 2012 and having a SVC of 3 or 4 but were on neither the CBW Top 30 Beef Packers 2013 list nor the CBW 2012 Largest U.S. Beef Plants list. Because these CBW lists cover all other beef slaughter facilities recorded in the MPI with a SVC of 3 or 4 and some with a SVC of 2, it was assumed that the SVC value for four of these five establishments was very likely a reflection of the pork and/or chicken slaughter reported at each establishment. An online review of each establishment further supported the assumption that these four establishments focus primarily on poultry or pork slaughter with beef slaughter making up a minority. For the purposes of this analysis, SVC values for four of the five establishments were re-assigned a value of 2 (the lowest SVC for plants included in the CBW lists).
    - One of these five establishments was located in Michigan and was reported in the MPI Directory to have slaughtered sheep and lamb in addition to beef. When performing the final slaughter allocation step for Michigan and having re-assigned the above referenced establishment to a SVC 2 from the MPI assigned SVC 3, the amount of slaughter allocated indicated that a beef plant located in one of the FAFs had utilized 102% of it's daily slaughter capacity in 2012. No US beef plant has ever utilized 100% of their daily slaughter capacity (Ishmael, 2017) and to produce over the DC would be almost impossible as DC reflects the innate physical limitations of each plant. When the above referenced establishment that was recorded in the MPI but not the CBW lists was allowed to maintain the MPI assigned SVC of 3, resulting slaughter allocation did not indicate that plant DC utilization had been a highly unlikely 100% or more. Further online research revealed that in 2014, the above referenced establishment produced 1.8 million lbs of ground beef over a 2.5 week period (The Cattle Site, 2014) indicating that the establishment likely carries out a significant amount of cattle slaughter. (If we assume a 5.5 day work week and an average fed steer produces about 185 lbs of ground beef, a little over 600 cattle would have been slaughtered each day).

S-3.1.3 Non-Federally Inspected (NFI) Commercial Slaughter

- USDA reported cattle slaughter that is commercial but not federally inspected (NFI) consists of state-inspected slaughter plants and custom-exempt slaughter plants. State inspected slaughter plants sell and transport meat intrastate only. Custom-exempt facilities perform commercial slaughtering and processing of meat for the meat animal's owner/s but that meat may not be sold after (USDA 2012 Summary Livestock Report, April 2013). The USDA NFI cattle slaughter dataset makes no distinction between slaughter totals for state inspected slaughter and custom exempt. Attempts were made to eliminate some custom-exempt slaughter; however, removing custom-exempt slaughter totally was not within the scope of this study.

  - USDA commercial, NFI cattle slaughter data for states reported by the USDA to no longer have a state inspection program for slaughter as of 2012 was excluded from analysis. Remaining slaughter included all state-inspected slaughter and custom-exempt slaughter in states with state inspection programs; remaining NFI slaughter accounted for <1.4% of total commercial cattle slaughter in 2012. I
  - Further attempts to separate out custom-exempt slaughter were not within the scope of this study and therefore some over-allocation of state-inspected slaughter exits; however, as noted above, the portion of remaining NFI slaughter is <1.4% of total commercial cattle slaughter in 2012.

- At the time of this study, no known resource existed which listed the locations of state-inspected or custom-exempt plants that slaughtered cattle in 2012. Due to limitations in available data, the majority of remaining commercial, NFI slaughter was assumed to be state-inspected slaughter and allocated at the FAF level using the same distribution pattern as commercial, FI slaughter. For the purpose of this study, it was assumed that cattle slaughter plants (both FI and NFI) are likely to reside in similar interstate geographic locations due to similar access to: cattle, land for infrastructure, and trade routes.

  (1) Like the USDA commercial, FI cattle slaughter totals, USDA data for commercial, NFI cattle slaughter contained grouped data for certain regions, specifically New England and Maryland/Delaware. According to general methodology for USDA NASS livestock slaughter estimates (USDA 2012 Livestock Slaughter Report, April 2013), New England consists of CT, MA, ME, NH, RI, and VT. However, Not all of these states had state inspection programs for meat slaughter ("meat" excludes poultry) at the time of data collection in 2012. Within the New England group, only Maine and Vermont have state inspection programs; within the Maryland/Delaware group, only Delaware has a state inspection program (State Inspection Programs, USDA).

    (a) USDA NFI slaughter for the New England group was distributed to Vermont and Maine (each of which only had one FAF with a FI slaughterhouse recorded in the 2012 FSIS MPI Directory) according to each state's portion of weighted SVC total (as determined by the previous method for FI slaughter).

    (b) USDA NFI slaughter for the Maryland/Delaware group was distributed in total to the one FAF in Delaware that had a FI slaughterhouse recorded in the 2012 FSIS MPI Directory.

(2) Four states had non-disclosed USDA commercial, NFI slaughter data and three of those four states had state-inspection programs. All non-disclosed USDA commercial, NFI slaughter data was assumed to be state-inspected slaughter. Slaughter was distributed at the FAF level among the three states with state inspection programs according to each state's portion of weighted SVC total (as determined by the previous method for FI slaughter).

(3) Two states (Wyoming and Louisiana) had disclosed USDA NFI slaughter but did not have FI slaughter.

  (a) Wyoming has only one FAF and thus all NFI slaughter for Wyoming was allocated to that one FAF.

  (b) No resource could be identified that listed specifically state inspected cattle slaughter plants in 2012 in Louisiana. The Louisiana Department of Agriculture and Forestry provides a list of current state inspected red meat slaughter plants; this list does not include details regarding the amount of slaughter performed by each facility. The number of state inspected red meat slaughter plants was calculated for each LA FAF. USDA NFI slaughter for LA was distributed at the FAF level according to each FAF's portion of LA state inspected red meat slaughter plants.

(4) For all remaining states with state inspection programs and disclosed USDA commercial, NFI slaughter, NFI slaughter was allocated at the FAF level within each state according to each FAF's portion of allocated FI slaughter (out of state total).

S-3.2 SCTG 05 Leverage Network

- The SCTG 05 network tracks flows of beef from slaughterhouse to grocery and retail destination.
- The vast majority (99.7%)[3] of cattle slaughter occurs in commercial facilities and not on farms. The SCTG 05 network created for this study tracks only those flows of beef from federally inspected and state inspected commercial slaughterhouses and excludes the 0.4% of beef that is produced by farming operations. The SCTG 05 network also excludes ~0.3% of commercial cattle slaughter that is custom exempt. Actual amount of custom exempt slaughter is likely slightly greater but <1.6% of total commercial cattle slaughter; however, there was no known way to separate out all custom exempt slaughter from the USDA non-federally inspected commercial cattle slaughter dataset which includes state-inspected slaughter as well.
  - Farm and (most) custom exempt slaughter were excluded from analysis as the beef produced is not legally able to be sold to other users at all, especially not through a grocery or retail location.
- Data selection

[3] USDA NASS Quick Stats

    - To create the leverage network for SCTG 05, the complete FAF4 database was utilized without isolating FAF4 flows that were out-of-scope for the CFS. Most of the commodity flows involving the retail sector were considered out-of-scope for the CFS but are built into the FAF4. The FAF4 also includes a more comprehensive and accurate account of import and export commodity flows.
    - SCTG 05 commodity flows include meat, poultry, fish, seafood, and their preparations. Weights of SCTG 05 commodities in the FAF database reflect the weight of livestock meat that has been processed and prepared for retail in one of the following forms: fresh, chilled, frozen, salted, dried, or smoked. All other SCTG commodity flows were excluded from the SCTG 05 leverage network.
    - Commodity origins were filtered to exclude FAFs that did not have allocated 2012 commercial cattle slaughter.
    - Removed commodity flows that were imports from foreign destinations. Analysis of imported beef is outside the scope of this study.
    - Removed commodity flows for which shipment weight was recorded as “0”; though these flows did not have recorded shipment weight, 3% of them had recorded value. Total $ value of removed flows with “0” weight made up < 0.0001% of the total value of flows in the filtered SCTG 05 data.
- Assumption of same-facility processing
    - Due to limited data availability, for the purposes of this study it was assumed that cattle slaughtered at a facility were processed into beef at the same facility (or a facility located in the same FAF) then shipped to a retail or food service location.
    - The beef production supply chain is complex; there are multiple possible pathways between a cattle animal being slaughtered and beef being sold to consumers [Image ___].

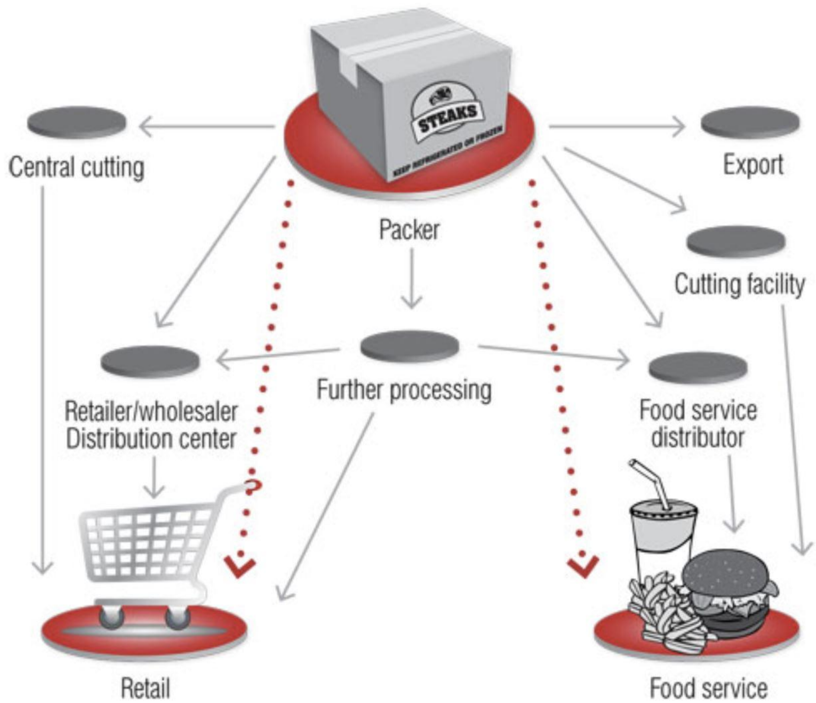

Figure S-1 Potential pathways for beef from packer to commercial consumer (Ismael, 2013[4])

- FAF data tracks commodities according to their SCTG code but is not detailed enough to track commodities in their inter industry transactions. As mentioned earlier, SCTG code 05 for meat, includes all meat, poultry, fish, seafood, and their preparations in any of the following forms: fresh, chilled, frozen, salted, dried, or smoked. FAF data does not allow for differentiation between steps in the supply chain - if meat moves from a slaughterhouse to a separate facility for further processing to a wholesaler then to a grocery store, FAF data will simply show the total amount of SCTG 05 commodity being moved from one location to the next. The lack of available data that could be utilized to separate FAF SCTG 05 flows according to facility type at origin and destination necessitated that for this study, we assume all SCTG 05 flows move from FAF slaughter origin to FAF demand destination.
- The 2012 MPI Directory does record what all activities each facility is allowed to operate including: ID Warehouse, Processing, Slaughter, or Slaughter and Processing. Though the 2012 MPI Directory provides information regarding what type and general amount of animal slaughter was conducted at each facility in 2012, it does not provide this level of detail for processing activities. However, it was noted that of the 586 facilities that slaughtered cattle in 2012, > 98% were listed as conducting both slaughter and processing. All facilities that conducted

[4] https://www.beefmagazine.com/retail/middlemen-retailers-food-service-parcel-peddle-beef

beef slaughter that had a slaughter volume capacity of 3 or 4 (the highest SVC for beef slaughter plants) were reported as conducting both slaughter and processing. Without additional information, it can not be assumed that beef slaughtered at facilities that conduct both slaughter and processing was therefore also processed at those facilities. However, this analysis of slaughter and processing activity in the MPI data may support the assumption that the largest beef slaughter facilities also process beef further before shipping it to a wholesale facility or retail location.

- Cattle Slaughtered to Beef Conversion
  - The assumption was made that beef shipped from packing plants was shipped as retail cuts as opposed to dressed carcasses. This assumption is supported by a fact sheet from the North American Beef Institute titled "Case-Ready Meats Modified Atmosphere Packaging"[5].
  - Number of cattle slaughtered at each FAF origin was previously determined during the FAF-level allocation of slaughter methodology earlier. For use in the SCTG 05 network, the number of head of cattle slaughtered was converted to total live weight, then to total dressed weight, and then to total retail weight (lbs).
  - Conversion of number of head of cattle slaughtered to FAF total live slaughter weight was done on a state by state basis. 2012 data regarding the average live weight in lbs/head for each state with cattle slaughter was obtained through USDA NASS QuickStats database. Number of head slaughtered in each FAF was multiplied by the appropriate state average lb/head, live basis to calculate FAF total live weight for slaughtered cattle.
    - Average lb/head, live basis was not disclosed for Florida, Illinois, Iowa, and South Dakota. For these 4 states, the regional average was used. Regions were defined the same as in USDA NASS 2012 Survey multi-state regional data for cattle slaughter available through the USDA NASS QuickStats tool.
    - The average lb/head, live basis value for New Hampshire was used for Connecticut, Maine, Rhode Island, Massachusetts, and Vermont as data for all these states is automatically grouped into a "New England" data unit in the USDA NASS survey data.
    - The average lb/head, live basis value for Maryland was used for Delaware as data for these two states is automatically grouped into a "Maryland/Delaware" data unit in the USDA NASS survey data.
  - An average dressing percentage was calculated using USDA 2012 national totals for commercial cattle slaughter and beef production; average dressed weight was divided by average live weight to calculate a dressing percentage of 60.5%. This

[5] https://www.meatinstitute.org/inde.g.php?ht=a/GetDocumentAction/i/125374

dressing percentage was multiplied by total live weight (lbs) for each FAF to generate each FAF's total dressed weight (lbs).

  - 2012 beef data from the USDA ERS Meat Supply and Disappearance data tables was used to calculate what percentage of dressed weight would become weight for retail cuts. Under the 2012 beef per capita disappearance (lbs) data subsection, retail weight was divided by carcass weight to calculate a retail weight of 70% (of dressed weight). This retail percentage was multiplied by total dressed weight (lbs) for each FAF to generate each FAF's total production weight (lbs) of retail beef.
  - [See results data in Cattle_Beef_Conversion tab of SCTG 05 Leverage Network spreadsheet for an summary analysis of the accuracy of this beef conversion process at the FAF level compared to USDA ERS Supply and Disappearance national level benchmark data]
- Leverage Network Creation
  - An origin-driven leverage network was created in a method similar to that done for SCTG 2 and SCTG 04 commodity flows. For each unique origin-to-destination commodity flow, the proportionally commodity weight of each individual flow out of the total commodity weight flowing out of that origin was calculated.
  - The proportional weight of each individual flow out of an FAF origin was used to proportionally determine where retail beef produced at the FAF origin was flowing to.
- Leverage Network Results
  - The resulting SCTG 05 leverage network included a small number of unique origin-to-destination flows that had a weight of <1 lb. These 305 flows made up 2.8% of total number of flows and approximately 0.000001% of summed weight of all flows. Due to the negligent contribution of these 305 flows to the GHG footprint at any step of the supply chain and in order to consolidate the data analyzed, these 305 flows were excluded from analysis. The SCTG 05 Leverage Network was recalculated to account for the exclusion of these 305 flows.

S-4 Cattle Flow Network

S-4.1 Slaughter Cattle Production FAF-Level Allocation

- 2012 county-level data regarding the number of cattle was obtained from the USDA Census of Agriculture using the online Quick Stats data search and download tool. Cattle inventory data from the 2012 Census of Agriculture data details the number of cattle (per head) on each cattle operation on the date of December 31st, 2012. At the county-level 2012 Census of Agriculture cattle inventory data is broken down into the six following groups:
  - Cattle, (Excluding Cows)
  - Cattle, Cows

- Cattle, Cows, Beef
- Cattle, Cows, Milk
- Cattle, Including Calves
- Cattle, On Feed

More detailed descriptions of each of these groups are available in the Census of Agriculture Methodology, Appendix B: General Explanation and Census of Agriculture Report Form[6], pg.11. Class of cattle included and excluded from each group was further clarified through correspondence with a USDA Census of Agriculture statistician.

- Like the 2012 Census of Agriculture crop production data, 2012 Census of Agriculture cattle inventory data has undergone a comprehensive disclosure review resulting in the suppression of some data in the public dataset. Those values in the 2012 cattle inventory data that were suppressed and replaced with a "(D)" were assigned estimated values using the same backfilling methodology used with the 2012 crop production dataset. National-level totals for each cattle inventory group were used to estimate the percentage of data values that were backfilled due to suppression and non-disclosure.

Table S-5 Portion of cattle production data that was backfilled

	% of data backfilled based on national-level totals	
Cattle inventory group	**State-level**	**County-level**
Cattle, (Excluding Cows)	0	0.56
Cattle, Cows	0	0.23
Cattle, Cows, Beef	0.26	21.63
Cattle, Cows, Milk	0.03	4.81
Cattle, Including Calves	0	0.19
Cattle, On Feed	0.07	20.57

- For the purposes of this study, the following cattle inventory groups were used: (1) Cattle, (Excluding Cows), (2) Cattle, Cows, Beef, and (3) Cattle, Cows, Milk
- As with the 2012 Census of Agriculture crop production data, each data record in the 2012 Census of Agriculture cattle inventory data has the following location details: state name, state ANSI, county name, and county ANSI. Each cattle inventory data record was assigned a FAF Zone location using the same location crosswalk methodology as used for the USDA crop production data.

[6] https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Volume_1,_Chapter_1_US/usappxb.pdf

S-4.2 SCTG 01 Leverage Network

Data

- FAF Farm-Based Out-of-Scope (FAF FB OOS)
  - Created by subtracting CFS flows from FAF flows
- Results of the FAF-level slaughter allocation analysis [see above]
- USDA NASS Cattle Inventory - Dec 2012
  - Used for comparison to gauge relative success of the demand-driven leverage network for SCTG 01

Filtering

- Removed FAF FB OOS flows that had zero or negative weight (see justification for this above in methodology for previous leverage networks created)
- Removed FAF FB OOS flows that had international origins.
- FAF4 FB OOS data for SCTG 01 group was filtered to include only those FAF zone destinations that were estimated to have had domestic cattle slaughter in 2012 as determined previously by FAF-level allocation of USDA state totals for commercial, federally inspected and state inspected cattle slaughter.
- Filtering of FAF zone origins was not done as all FAF zones reported having sales of cattle in 2012 according to USDA data. Filtering origins that have reported sales of cattle on feed for select destinations where slaughterhouses processed only fed cattle, was explored and determined ineffective due to the insignificant impact on number of flows included in the analysis.
  - Additionally, **sales data should not be relied on** as data synonymous with # of cattle sent to slaughter. If a feedlot is owned by the same company as the beef packing plant to which cattle are being shipped, there may be no "sale" of cattle or monetary transaction so those cattle would not be captured in USDA cattle sales data. e.g. JBS was #2 biggest beef packer in 2012 and in 2015 owned 11 feedlots making it the largest feedlot company.

Creating the Destination-driven Leverage Network

- To create the destination-driven network, the total amount of weight flowing into each FAF destination was calculated by summing all individual flow weights according to their FAF destination. The proportion each individual flow into or around a FAF destination made up of total flow into/around a FAF destination was calculated by dividing the individual flow weight by the total weight of flow into/around a FAF destination.
- The proportion or percentage that each individual flow contributed to total flow into/around a FAF destination was multiplied by the total demand for slaughter cattle (# head) at that FAF destination; the resulting proportion of cattle for slaughter is assumed to be sourced from the FAF origin of each individual flow.
- # head of cattle for each individual flow was rounded to the nearest whole number to eliminate fractions of live cattle flowing through the network. After rounding, 19

individual origin-destination flows were recorded as transporting zero cattle and excluded from the leverage network.

Success of Leverage Network Results

- Data from the USDA Cattle Inventory from Dec 2012 was used as a benchmark to compare the success of the SCTG 01 demand-driven (or destination-driven) leverage network.
    - USDA Cattle Inventory data is estimated through surveys administered by the NASS. Cattle inventory data reflects the total number of cattle present at a specific point in time and is not reflective of the total number of cattle present throughout the year.
    - USDA cattle inventory data specifically used for comparison was the estimated total number of cattle on feed at the county, state, and national level. Cattle on feed totals were analyzed to determine what % of the national total of cattle on feed was present in each county and state. Proportions were used instead of actual values as leverage network values represent total number of cattle moved from an origin to a destination over the span of a year and USDA cattle inventory values represent the number of cattle on feed present at an origin on a specific day in December 2012.

Table S-6 Results of benchmark comparison - State Origins

Top 10 State Origins for Leverage Network Cattle Flows (live cattle for slaughter)			
State	*Leverage Network*	*USDA Cattle Inventory*	% Difference
	% of total cattle flowing out/around origins	% of US Cattle on Feed Inventory	
Texas	17.3%	19.1%	-1.8%
Nebraska	17.0%	18.4%	-1.4%
Kansas	15.0%	15.7%	-0.7%
Colorado	8.2%	7.0%	1.2%
Minnesota	5.2%	3.7%	1.5%
California	4.9%	3.4%	1.5%
Oklahoma	4.2%	2.5%	1.7%
Iowa	3.7%	10.8%	-7.1%
Wisconsin	2.7%	1.9%	0.8%
Utah	2.7%	0.2%	2.5%
Top 10 States Total	81%	83%	-2%
Remainder 40 States Total	19%	17%	2%

Table S-7 Results of benchmark comparison - FAF Origins

Top 10 FAF Origins for Leverage Network Cattle Flows (live cattle for slaughter)			
FAF	*Leverage Network*	*USDA Cattle Inventory*	% Difference

		% of total cattle flowing out/around origins	% of US Cattle on Feed Inventory	
Rest of NE	319	16.5%	17.8%	-1.3%
Rest of KS	209	12.8%	15.1%	-2.3%
Rest of TX	489	11.4%	18.1%	-6.8%
Rest of CO	89	6.2%	5.2%	1.0%
Rest of MN	279	4.6%	2.9%	1.7%
Iowa	190	3.7%	10.8%	-7.1%
Rest of OK	409	2.8%	2.2%	0.6%
Rest of CA	69	2.7%	3.1%	-0.3%
Rest of WI	559	2.4%	1.6%	0.8%
Houston	486	2.2%	0.2%	1.9%
Top 10 FAFs Total		65%	77%	-12%
Remainder FAFs Total		35%	23%	12%

- Some discrepancies appear to exist in regards to where cattle on feed are proportionally located in the US (according to USDA point-in-time cattle inventory, Dec 2012) and where cattle for slaughter are estimated to be sourced from proportionally (according to results of generated SCTG 01 leverage network).
- Some probable reasons for discrepancies:
  USDA Cattle Inventory level
  1) Because the USDA Cattle Inventory data is an estimate of the number of cattle present on one particular day of the year, it does not necessarily reflect annual patterns.
  2) The “cattle on feed” category as defined by the USDA includes heifers and steers on feed to be sold to processing facilities; this definition excludes bulls, cows, and other cull cattle that may end up on feedlots before being slaughtered. Cull cattle typically contribute about 20% +/- of US commercially available beef [7] [8] [9]. According to the USDA 2012 Livestock Slaughter Summary report, 21.6% of commercial cattle slaughter was dairy cows, other cows, and bulls in 2012. Not all cattle headed to slaughter are captured in the USDA Cattle on Feed Inventory.
  3) USDA Cattle Inventory data has been backfilled at the county and state level. All cattle inventory data for Iowa was disclosed at the county level so Iowa discrepancies can not be attributed to data backfilling. Texas county-level cattle inventory data was backfilled, (21% of data for Rest of Texas FAF 489 was backfilled).

  Leverage Network level
  1) Underreporting in CFS/FAF data (in the case of Iowa especially)

[7] https://www.bqa.org/Media/BQA/Docs/nbqa-exec-summary_cowbull_final.pdf
[8] https://www.sites.ext.vt.edu/newsletter-archive/livestock/aps-99_10/aps-0132.html
[9] Profitable Cattle Marketing for the Cow-Calf Producer, University of Georgia Extension

2) Hard to separate cattle from other animal ag in some states (Iowa especially)...too much noise in the data.

- Head to Weight Conversion
  - At the time of this study, there was no known record of the average finished live weight of beef cattle from each state in 2012. USDA 2012 livestock slaughter state level data reports the average live weight of cattle before slaughter at slaughter destination; however, this data does not determine the average live weight of finished cattle in their state of origin. In order to maintain consistency and avoid incorporating additional bias, the national average live weight for commercially slaughtered cattle (1,302 lbs) was used to convert the number of slaughter cattle at each FAF origin to tons of live weight when shipped to slaughter at FAF destination.

S-5 Feed Flow Network

Cattle feed crops used in this study were selected after consulting a literature review of other similar studies analyzing only those cattle feed crops that make up the majority of feed intake by cattle and cows in the US. Cattle feed is composed of concentrated feed and roughage (which includes both pasture and processed roughage). This study considers the main cattle feed crops included in a 2015 livestock feed partitioning study conduted by Eshel et al. Crops included in this study are as follows:

- Grain concentrates: corn grains, sorghum grains, barley, oats, or wheat
- Harvested roughage: corn silage, sorghum silage, hay, and haylage (including greenchop)

S-5.1 Feed Production FAF-Level Allocation

Data regarding county-level production of crops grown for cattle feed in 2012 was obtained from the United States Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) via the online Quick Stats Tool. Annual county level production data was obtained for all cattle feed crops represented in the 2012 Census of Agriculture.

S-5.1.1 Backfilling of USDA Disclosure Data

- In order to prevent the disclosure of sensitive information regarding individual operations, certain crop production data within the 2012 USDA Census was suppressed and replaced with a “(D)”. Due to the effects of this disclosure review, crop production totals were not initially available for all counties or states. For instances where county-level data was not disclosed, extrapolated values were calculated for each crop via the following process:
  1. 2012 USDA Census national-level totals were obtained
  2. 2012 USDA Census state-level totals were obtained
  3. State-level totals were summed to calculate national total
  4. The difference between the national total calculated from state-level summation and the national-level total reported directly by the Census was calculated. This difference was then split evenly among states that were included as records in the state-level data but had had their crop production values suppressed as part of the disclosure review.

    a. For each crop included in this study, the data backfilled at the state-level represented 0.001% - 1.8% of the crop's national-level total as reported directly by the Census.
5. The state-level dataset was updated to include these backfilled values for those states with non-disclosed crop production values.

- After USDA census data was backfilled at the state-level, the updated state-level dataset was used to backfill county-level data using the same methodology.
    1. County-level totals were summed to obtain totals for each state.
    2. For each state in the county-level data, the difference between the state total calculated from county-level summation and the state total reported in state-level Census data (post-state-level backfilling) was calculated. For each state in the county-level data, this difference was then split evenly among counties that were included as records but had had their crop production values suppressed as part of the disclosure review.
        a. For each crop included in this study, the data backfilled at the county-level represented 0.034%- 20.5% of the crop's national-level total as reported directly by the Census. However, for 82% of the crops, backfilled data represented only 0.034%-4.7% of the national-level total for each crop. Backfilled data represented a significantly larger percentage of the total data for haylage and sorghum silage.
    3. The county-level dataset was updated to include these backfilled values for those counties with non-disclosed crop production values.

  As part of the USDA disclosure review, calculated coefficients of variation (CVs) were suppressed and replaced with a "(D)" if the associated value was not disclosed. New CVs were not calculated for extrapolated data and remain marked with a "(D)".

S-5.1.2 USDA Data Conversions

- In order to prepare the USDA crop production data for analysis, the weights of all crop production totals were converted to thousand tons to match FAF4 shipment weight totals. For some crops, this conversion was straightforward, requiring only a conversion of lbs to tons and/or tons to thousand tons. For other crops such as corn (grain), production totals had to be converted from bushels of corn (grain) to tons and then to thousand tons. Because "bushel" is a unit of volume, the corresponding weight of a bushel is different for every crop. Unique conversion factors for each crop for which production weight was reported in bushels were obtained from the 2013 Agriculture Statistics report produced by the USDA. The 2013 Agriculture Statistics report was also utilized in the FAF4 Methodology to obtain conversion factors for USDA crop production data.
- The USDA Census of Agriculture dataset does not include SCTG group codes for agricultural products. Appendix B of the 2016 FAF4 Methodology document lists all agricultural commodities included in the FAF4 categorized by SCTG group. Appendix B was used to assign an SCTG group to each of the animal feed crops included in the USDA crop production data used in this study.
- American National Standards Institute codes (ANSI codes) are standardized codes assigned to geographic entities across the U.S. and used within the federal government to ensure uniform identification of locations. County-level USDA Census of Agriculture

data includes the following details regarding location: state name, state ANSI, county name, and county ANSI. The U.S. Census Bureau provides a lookup table[10] listing which U.S. counties make up each CFS Area; state and county ANSI codes are included in this table and associated with each county. The Bureau of Transportation provides a CFS Area Code - FAF4 Zone ID lookup table[11] published by the Oak Ridge National Laboratory. These two lookup tables were used to provide an associated FAF Zone ID for each crop production record in the USDA dataset according to the records state and county ANSI code.

S-5.1.3 FAF4 SCTG Group Commodity Composition

- In the FAF4 dataset, agricultural commodity flows of SCTG 02 (Cereal Grains) and SCTG 04 (Animal Feed, Eggs, Honey, and Other Products of Animal Origin) may include crops other than those of interest to this study. Through analysis of USDA 2012 crop production data for all commodities included in both SCTG 02 and SCTG 04 in the FAF4 dataset, it was determined that the animal feed crops relevant to this study were the overwhelming majority of weight in each SCTG group.
- SCTG 02 group also includes: buckwheat, emmer and spelt, rice, rye, wild rice, popcorn, millet, safflower, and triticale. These crops made up < 3% of the total 2012 national level production weight of all SCTG 02 agricultural commodities as defined in the FAF4 Methodology. SCTG 04 group also includes: Wool, honey, and mohair. These commodities made up <0.03% of the total 2012 national level production weight of all SCTG 04 agricultural commodities as defined in the FAF4 Methodology.

S-5.2 SCTG 02 & 04 Leverage Network

- The FAF relative flow network (or leverage network) for SCTG 2 & 4 was built using the FAF4 farm-based (FB) out-of-scope (OOS) flows previously isolated using the methodology outlined prior.
    - FAF4 import data was not utilized in the creation of the FAF relative flow network. All import data was removed at the point where it entered a domestic destination. However, after entering the US, domestic shipments of imported commodities are reported as domestic goods in the FAF4 database. Export data was utilized in the creation of the leverage network in order to track the portion of domestically grown feed crops leaving the US
    - Any flows that had negative, zero, or unknown (the presence of some amount of flow is reported in FAF4 but the amount is unknown or undisclosed) were removed from the FAF4 farm-based OOS dataset used to create the relative flow network.
    - Data regarding SCTG 3 was not included in the creation of the leverage network. In 2016/2017 about 31.2 million tons of soybean meal was fed to livestock; however, less than 4% of this went to beef cattle[12]. Of the total dry matter feed annually consumed by all beef cattle in the U.S. (Eshel et al. 2015) soybean meal and hulls makes up less than 0.5%.

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[10] https://www.census.gov/programs-surveys/cfs/technical-documentation/geographies.2012.html

[11] https://www.bts.gov/faf

[12] https://www.soymeal.org/wp-content/uploads/2018/11/LOW-RES-FY2018-Soybean-Meal-Demand-Analysis-1.pdf

    - USDA Quick Stats online data query tool does not reveal a way to access data specifically for Washington D.C. (FAF 111 in the FAF4 dataset). It is additionally highly unlikely that Washington, DC is responsible for a significant portion of cattle feed crop production. For these reasons, FAF 111 was removed from the FAF origins included in the FAF SCTG 02 leverage network.
- The assumption was made that at every FAF zone origin, production of cattle feed agricultural commodities at that origin either flowed out (outflow) or around (intraflow) the FAF zone. For each FAF-SCTG (origin) index, intraflow and outflow of commodities in each SCTG group was summed for each FAF zone origin, "FAF origin production". The proportion of SCTG commodity flowing out of (to another FAF destination) or around the FAF origin was calculated for each individual flow according to commodity shipment weight. This calculation was done separately for SCTG 02 and SCTG 04 so each has slightly different leverage networks.
    - For example, if in the FAF4 FB OOS data, there were 4 flows of SCTG 02 transported from FAF 89 to other FAF destinations and 1 flow of SCTG 02 transported around FAF 89 - the weight of the flow from FAF 89 to FAF 50 may make up 20% of the total weight of SCTG being shipped out or around FAF 89. This calculation is done for each of the 5 flows adding up to 100% of all flows of SCTG 02 shipped out/around FAF 89.
- USDA crop production data (in 1,000 short tons) for animal feed crops of interest to this study in STCG groups 2 & 4 had previously been summed at the FAF-level using county, state, and national level data. The amount of each SCTG 02 and SCTG 04 crop produced at and flowing out/around each FAF was estimated by allocating USDA crop production data to the FAF origin, and splitting production weight up into flows proportional to the leverage network created from the FAF4 FB OOS dataset.
- USDA crop production data was incorporated at the level of the specific SCTG 02 and SCTG 04 crop. It was assumed that all flows out of/around a FAF were composed of the same proportion of specific crops as what was produced at the FAF origin.
    - e.g. According to USDA 2012 data, FAF 499 produced a total of 178 thousand short tons of SCTG 02 commodities. Of this production weight, barley made up %16.68, Corn grain %45.87, Oats %1.48, Sorghum grain %0.05, and Wheat %35.93. As determined by the leverage network, flows out/around FAF 499 each have a different proportion of the total overall SCTG 02 crop production weight, but each contain the same proportion of the specific SCTG 02 agricultural crops produced at FAF 499.
- Inflow to each FAF-SCTG (destination) is the sum of destination-specific outflow from each FAF-SCTG (origin) that has used the leverage network to incorporate USDA production data. In this way, USDA crop production was incorporated into each origin-to-destination commodity flow in the FAF leverage network according to original proportions of flows in the FAF4 farm-based OOS dataset.
- The total weight of available cattle feed at each FAF destination was calculated by summing the weight of domestic commodity flows into or around each FAF zone; weight of commodity flows that were shipped to a FAF domestic destination but then exported to a foreign country were not included when calculating total available cattle feed at FAFs.

S-5.3 Allocation of Feed for Slaughtered Cattle

- The USDA crop production data utilized in this analysis records the weight of crops on an as-fed basis, meaning the weight of the crop reflects the weight when the feed is normally fed to animals. On an as-fed basis, weight of feed will include both the weight of the dry matter and the weight of moisture in the feed[13]. Feed intake for cattle is often reported on a dry matter (DM) basis. In order to estimate the amount of feed available for cattle at each FAF destination, weight of feed crops was converted to DM basis. The conversion of as-fed to DM weight was done using the USDA Crop Production 2012 Summary report for hay and haylage and the 2012 Feed Composition Tables from Beef Magazine[14] for all other feeds.
    - In some cases, decisions had to be made regarding which conversion factor was most relevant. For example, barley grain could be converted into DM basis by using the DM% for barley grain, barley grain - steam flaked, barley grain - steam rolled, barley grain 2-row, barley grain 6-row, barley feed pearl byproduct, etc. In order to aid in selection of the correct conversion factor, thorough online research was conducted to determine in what form each crop was most often fed to cattle. Information from published and non-published academic sources in addition to agricultural extension websites and reports. The DM% for the two or three most common feed forms were averaged for each crop to generate an average DM%.
- Total relevant feed demand at each FAF was estimated according to (1) the number of cattle shipped from that FAF to slaughter in 2012 as determined by the SCTG 01 leverage network and (2) average estimated lifetime feed consumption for a US beef cattle (Place and Miller 2020, Rotz et al. 2019).
    - The feed consumption factor used from Rotz et al. 2019 and Place & Miller 2020 represents the feed consumed across the three main phases of an average US beef cattle's life - cow-calf, stocker or backgrounding, and finishing. Feed consumption by cull cows and bulls from cow-calf operations that eventually become beef as well as finished steers and heifers is included. Dairy cows represented ~10% of commercial cattle slaughter in 2012 but are not accounted for in estimated feed demand. For the purposes of this study, GHG emissions and resource use related to the portion of dairy cows that were slaughtered for beef in 2012 are considered to be impacts of the dairy industry, not the beef industry.
    - The beef cattle feed consumption factor as calculated in Rotz et al. 2019 breaks down consumption by feed type: grazed forage, harvested forage, grain concentrate, and other (byproduct feeds and food waste). For the purposes of this study, only feed consumption of harvested forage (SCTG 04) and grain concentrate (SCTG 02) are included in analysis. When including grazed forage from pastures, harvested forage and grain concentrate represent ~33% of all feed consumed by the average US beef cattle over their lifespan; however, these two feed types represent 84% of all commercially farmed agriculture crops consumed by cattle in their lifespan. [See summary table below]
    - The feed consumption factors used were in the unit of (lb DM / lb cattle live weight). The total live weight of slaughter cattle sourced from each FAF was determined by multiplying the number of cattle by the 2012 average live weight

[13] USDA Crop Production 2012 Summary, January 2013
[14] 2012 Feed Composition Tables, Aug 13, 2012, Beef Magazine

for commercially slaughtered cattle as reported by the USDA, 1302 lbs[15]. Total lbs of dry matter feed demand for the total live weight of slaughter cattle at the FAF was calculated then converted to 1,000 short tons. Feed demand was determined separately for SCTG 02 and SCTG 04.

Table S-8 Feed consumption factors for beef cattle over their lifespan. “Other” includes byproduct and food waste feeds. (Rotz et al. 2019, Place & Miller 2020)

Beef Cattle Feed Consumption by Feed Type		
Feed Type	**lbs DM/ lbs live weight**	**% of non-grazed feed**
Grazed forage	7.79	
Harvested forage	3.01	84 %
Grain concentrate	1.53	
Other	0.89	16 %
Total	*13.16*	

- Approximately 97% of cattle slaughtered annually are produced through a conventional grain-fed and/or grain-finished system[16] [17]. Nine sources concerning beef production from either peer-reviewed academic journals or agriculture extension agencies published over the last 17 years were reviewed to calculate the average lifespan of a beef cattle in the U.S. beef industry. A beef cattle (heifer or steer) could live anywhere from 15-22 months or an average of 18 months before slaughter. A calf may become weaned after 172-267 days prior to which they consume mostly milk before switching to pasture and starter feed composed of grains[18]. After weaning, cattle raised for beef may spend 149-185 days feeding on one or a combination of grazed forage, harvested forage, and concentrates (including grain or byproduct feeds)[19]. The cattle will then be moved to a feedlot for 138-208 days where they are fed a diet heavy in concentrates to gain weight for slaughter[18].
    - On average, a beef cattle’s lifespan will last over a year; the animal may be fed some portion of harvested forage or grain concentrate anywhere from 4 to 11[20] [18] [21] months of its life. This study acknowledges that beef cattle’s lives and feed consumption (and therefore feed production and feed shipment) may extend over more than a 1 year timescale. For the purposes of this study, it is assumed that the FAF origin to destination commodity flow network of harvested forage and grain

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[15] USDA quick stats
[16] Back to Grass: The market potential for U.S. Grassfed Beef Cheung and McMahon April 2017
[17] Place and Miller 2020
[18] Capper 2012 Is the grass always greener? Comparing the environmental impact of conventional, natural, and grass-fed beef production systems. *Animals* 2:2 127-143
[19] Overview of the U.S. Cattle Industry, USDA, 2016, Rotz et al 2019, Place and Miller 2020, Pennsylvania Beef Council 2018, Drouillard 2018, Farm Credit Knowledge Center 2021, Terry et al. 2020, Beef Cattle Extension 2019, Koontz et al. 2005, and Cheung and McMahon 2017
[20] Overview of the U.S. Cattle Industry, USDA, 2016
[21] CORN-FED VERSUS GRASS-FED BEEF, NAMI, 2015

concentrate feed present in 2012 will closely parallel flows of cattle feed a year prior during which cattle feed was transported and consumed by cattle slaughtered in 2012. This study acknowledges that all cattle feed consumed by cattle slaughtered in 2012 may not have been transported from farm to cattle in 2012; however, 2012 data may be assumed to be representative of similar patterns of cattle feed flow over the most recent prior years.

- After determining the feed demand for 2012 slaughter cattle at each FAF, perceived feed deficiencies at each FAF were calculated by subtracting DM feed demand (both for SCTG 02 & 04 separately) from the amount of DM SCTG 02 & 04 feed available at each FAF (according to the cattle feed leverage network). At the FAF level, there was a perceived feed deficiency of about 23% of feed demanded over the entire lifespan of all cattle slaughtered for beef in 2012. This perceived deficiency is likely due to one or multiple of the following factors: (1) feed not shipped in 2012 was shipped and/or consumed in 2011 for some cattle slaughtered in 2012 (2) a portion of feed demand was met by feed stocks from previous years, (3) FAF4 database may not account for all cattle feed, (4) feed was imported, (5) not all feed was shipped from a farm and therefore there flows do not appear in the FAF FB OOS dataset, or (6) some roughage crops may not have been included in the feed model.
    1) Because beef cattle live an average of 18 months, it is likely some cattle were consuming feed in 2011 that is not included in the 2012 cattle feed leverage network.
    2) According to data from the USDA Feed Grains Database, feed stocks for grain (SCTG 02) and hay (SCTG 04) at the beginning of 2012 totalled 45,807 10^3 short tons. This amount of feed stocks is a little over double the perceived FAF-level feed deficiency for slaughter cattle in 2012.
    3) Cattle feed produced on or in close association with a cattle feeding operation may not be included in the FAF4 database as it is not traded or transported a significant distance. The failure to include all cattle feed in the FAF4 Database would decrease the ability for the SCTG 02 & 04 leverage network to accurately estimate how much cattle feed is available in each FAF.
    4) Due to limited resources, inclusion of data regarding cattle feed that is imported within the SCTG 02 & 04 leverage network is not within the scope of this study at this time. Future work should seek to incorporate import data. According to the USDA Feed Grains Database, the amount of imported SCTG 02 cattle feed crops (corn, barley, oats, sorghum) was double that of the perceived FAF-level SCTG 02 deficiency estimated by this analysis. However, imported SCTG 02 crops only represented ~3% of the total amount of SCTG 02 feed produced and available domestically in FAF's in 2012[22]. At this time, information regarding the import of SCTG 04 feed crops could not be located; while the U.S. is a significant exporter of SCTG 04 crops such as alfalfa hay[23], it is unlikely that the U.S. imports a significant amount
    5) Some feed may have been shipped from the site of production to a commercial feed mill, processed, and then shipped to the cattle farm or feedlot; because this shipment is not considered a farm-based flow, it would be excluded from the

[22] USDA ERS Feed Grains Database 2022
[23] Tyng,2012 Record Forage Exports Despite Record Domestic Prices USDA FAS

FAF4 FB OOS dataset. However, many large farms and feedlots have feed mills onsite[24] and receive feed directly from farms.

6) Other roughage crops not included in this study but consumed by cattle include: wheat silage, corn stalks, wheat straw, or other crop residues[25]. These crops are not listed in the agricultural products included for SCTG 04 in the FAF4 dataset (FAF Methodology Appendix B); FAF level shipment data for these commodities does not currently exist for 2012.

- In FAF's with perceived feed demand deficiencies, feed demand was assumed to have been met by feed shipped and/or consumed in the FAF in 2011 or feed shipped to the FAF in previous years and stored. The extra feed required to meet feed demand for 2012 slaughter cattle was assumed to have been shipped to the FAF destination in previous years from the same relative proportion of FAF origins. Extra feed was back-allocated separately for each SCTG according to DM basis.
    - For example, if FAF 499 had a feed deficiency of 100 tons of DM SCTG 02 feed, this amount might be back-allocated 20% to FAF origin 20, 30% to FAF origin 61, and 50% to the FAF origin 499 (intraflow).
- After the back-allocation of extra feed to FAF origin-destination flows, total DM feed demanded and consumed at each FAF by cattle slaughtered in 2012 was split and attributed to FAF origins proportional to the total amount of SCTG 02 or 04 DM feed the FAF destination received from each origin.
    - For example, FAF 20 received 50% of their total SCTG 02 feed supply from FAF 61; therefore, 50% of the 2012 slaughter cattle feed demand at FAF 20 was estimated to be sourced from FAF 61.
    - This step is necessary to determine the weight and shipping distance of feed relevant to this analysis.
- The estimated DM weight of SCTG 02 and 04 feed flowing from each origin specifically to satisfy slaughter cattle feed demand at each FAF destination was converted back to an as-fed basis to accurately reflect shipping weight. Due to resource limitations, the exact proportion of cattle feed crop types used to satisfy demand at each FAF is not considered in this analysis at this time. To convert SCTG 02 & SCTG 04 DM feed back to an as-fed basis, an average DM% is used for each SCTG group.
    - For SCTG 02 the average DM% was calculated by averaging all five crops (barley, corn grain, oats, sorghum grain, and wheat) equally as the DM% for each crop falls within a 3% difference.
    - For SCTG 04, DM% differed significantly more among the four crops. This difference in crop DM% necessitated that the average DM% be weighted according to the proportion each crop likely accounted for in total SCTG 04 feed consumption by beef cattle. Weights for each SCTG 04 crop were determined by using Eshel et al. 2015 data to estimate what portion of roughage diet may be composed of each roughage feed type. Dairy and beef cattle can consume the same types of roughage materials[26] but what they end up consuming may be determined by regional availability and price. For the purpose of this study, it was

[24] Coffey et al. 2016 Review of the feed industry from a historical perspective and implications for its future *Journal of Applied Animal Nutrition*, Wagner, Archibeque, and Feuz 2014 The Modern Feedlot for Finishing Cattle *Annu. Rev. Anim. Biosci.* **2:535-54**

[25] Wagner, Archibeque, and Feuz 2014 The Modern Feedlot for Finishing Cattle *Annu. Rev. Anim. Biosci.* **2:535-54**

[26] https://dairy-cattle.extension.org/effective-fiber-for-dairy-cows/

assumed that on average the proportional feed type composition for beef and dairy cattle roughage diets was the same. In the Eshel et al. 2015 study, primarily dairy and beef (95%) and a small amount of other livestock (horses, goats, sheep, 5%) consumed all processed roughage feed available annually for livestock. Beef cattle consumed 83% of all processed roughage feed consumed by livestock on average from 2000-2010. For simplification, it was assumed that beef cattle consumed 83% of the total weight consumed by livestock within each processed roughage feed crop category (hay, haylage, corn silage, and sorghum silage). The estimated weight of each roughage feed crop consumed by beef cattle proportional to the total weight of all roughage feed consumed annually by beef cattle was used to calculate a weighted DM% average for SCTG 04 roughage feed crops.

SCTG 02 & 04 Leverage Network - Notes

- The FAF4 FB OOS dataset did not include any flows of SCTG 04 with a domestic destination of FAF 20; there were no flows available in the leverage network to back allocate SCTG 04 cattle feed that was deficient in 2012. For the purposes of this study, it was assumed that FAF 20 met requirements for roughage cattle feed (SCTG 04) through commodities not captured in the FAF4 FB OOS dataset.

S-6 Transportation

- For each of the three commodity flow networks (cattle feed, slaughter cattle, and commercial beef), the FAF4 database was used to determine average distance traveled for commodities in each origin to destination flow.
    - The Cattle Feed Flow Network (SCTG 02 & 04) and the Slaughter Cattle Flow Network (SCTG 01) are developed using only the isolated farm-based out-of-scope data from FAF4. However, the average weighted distance data recorded in the FAF4 dataset for each origin-destination averages shipment distances for both farm-based and non-farm-based flows. Use of the FAF4 weighted average distance for origin-destination commodity flows in the Beef Flow Network (SCTG 05) presents similar issues. The FAF4 origin-destination average weighted distance may not be a completely accurate reflection of the average shipment distance for the select origin-destination flows included in this analysis - however, this method for determining average shipment distance is likely more accurate than alternative options identified at this time (such as using FAF centroid to FAF centroid routed highway distance).
    - Average weighted distance and shipment weight was used to calculate the average ton-miles for each commodity flow.

S-7 Life Cycle Assessment

- Energy consumption intensity and greenhouse gases emitted at each stage in the beef production process are based on sources in the literature. Ideally, energy consumption and GHG emissions data used in the beef production model would be detailed at the level of:

(1) individual US states or regions, (2) individual GHGs (specifically CO_2, N_2O, and CH_4), and (3) specific activity or source (e.g. Diesel used for cattle farm machinery). Due to limited data availability, energy consumption and GHG emissions data used in the life-cycle analysis portion of this study does not reflect all three levels of detail previously listed. In some cases, a particular level of detail was prioritized over others (e.g. data that was general at the level of activity and GHG type but detailed at the level of individual US regions was used to calculate emissions from cattle feed production).

- 100-year time horizon global warming potentials (GWP) for each greenhouse gas were sourced from the IPCC Sixth Assessment Report (AR6) and used when calculating CO2 equivalence (CO2e). In AR6, separate GWPs are provided for methane emissions based on whether they originate from fossil fuels (e.g. coal burned to generate electricity) or from a non-fossil fuel source (e.g. livestock enteric fermentation).
- An overview of all energy intensity factors and GHG emission factors used in this study are in Table _____.

Table S-9 Energy intensity factors and GHG emission factors utilized in the life cycle assessment.

Activity	**Factor**	**Unit**	**Sources**	**Notes**
Transportation				
Truck	0.211 0.002 0.0049	kg CO_2/ton-mile g CH_4/ton-mile g N_2O/ton-mile	US EPA 2022	No significant adjustments.
Rail	0.022 0.0017 0.0006	kg CO_2/ton-mile g CH_4/ton-mile g N_2O/ton-mile		
Water	0.041 0.0183 0.0008	kg CO_2/ton-mile g CH_4/ton-mile g N_2O/ton-mile		
Air	1.165 0.0359	kg CO_2/ton-mile g N_2O/ton-mile		
Feed Production				
SCTG 02	505	kg CO_2e/US ton DM	Adom et al 2012	Factors are presented for individual crops and are regionally specific for 5 US production regions. Factors for individual crops included in this study were used to generate separate averages for SCTG 02 and 04 feed commodity groups. SCTG 02 included corn grain, oasts, and winter wheat. SCTG 04 included alfalfa hay, corn silage, and grass hay. Factors in this table represent unweighted national averages; regional averages were used in this study.
SCTG 04	209	kg CO_2e/US ton DM		

Cattle Production				
Enteric fermentation	0.1288	short ton CH_4/head	US EPA 2021	EPA factors in kg GHG/head/year for each cattle type were used to calculate lifespan emission factors for each type of cattle slaughtered in 2012.
Manure management	0.0038 0.0011	short ton CH_4/head short ton N_2O/head		
On-farm electricity use	0.09	kwh/kg live weight	Asem-Hiablie et al 2018	Factor includes electricity for cattle housing only. No significant adjustments.
Beef Processing				
Electricity	0.081	kwh/kg live weight	Ziara et al 2016 Asem-Hiablie et al 2018 Desjardins et al 2012 Roop et al 2014 Parker et al 1997 Li et al 2018	Factors sourced from literature review and averaged.
Natural gas	792	Btu/kg live weight	Asem-Hiablie et al 2018 Desjardins et al 2012 Li et al 2018 Parker et al 1997	Factors sourced from literature review and averaged.
Energy				
Electricity	1,163 0.031 0.015	lb CO_2/MWh lb CH_4/MWh lb N_2O/MWh	US EPA 2015	Factors in this table represent national unweighted average emission rates; regional averages that accounted for gross grid loss were used in this study.
Natural gas	53.06 0.001 0.0001	kg CO_2/mmBtu kg CH_4/mmBtu kg N_2O/mmBtu	US EPA 2022	No significant adjustments.

S-7.1 Transportation

- GHG emissions attributed to transportation in this study are restrained to one-way origin to distance commodity shipments and do not consider round trip distance as done in some studies (Stackhouse-Lawson et al 2012[27], Rotz et al 2019, Kannan et al 2016[28]).
- All commodity shipments relevant to the beef production flow network were reported in the FAF as being transported via 1 of 6 possible modes. The 6 FAF mode codes and corresponding mode description are as listed: 1 - Truck, 2 - Rail, 3 - Water, 4 - Air

[27] Stackhouse-Lawson et al 2012 Carbon footprint and ammonia emissions of California beef production systems
[28] Kannan et al 2016 Estimation of Energy Consumption and Greenhouse Gas Emissions of Transportation in Beef Cattle Production

(including truck-air), 5 - Multiple modes & mail, and 7 - Other and Unknown. In depth descriptions of each mode type are available in Table 1 of the FAF4 User Guide[29].

- In the creation of the FAF4 database, all farm-based shipments were assumed to travel by truck and automatically assigned to mode 1[30]. All 6 modes previously listed were represented in the transport of beef from slaughter/processing origin to retail destination.
- Mode 7 is mostly movement via conveyor belt[31] and applied only to shipment of relevant commodities for export or import. Analysis of emissions produced by transportation for imported and exported goods is outside the scope of this study; commodity flows recorded as mode 7 were not included in this analysis.
- Origin to destination commodity flows that were reported as mode 5 - Multiple modes & mail were reassigned to an alternate mode using the methodology outlined in Vora et al. 2021[32]. According to total shipment weight, commodities that were transported by mode 5 made up ~0.1% of the total weight of all SCTG 05 commodities shipped.
    - If <100% of all SCTG 05 commodity flows between an origin-destination pair were transported via mode 5, the dominant alternative mode for all SCTG 05 flows for that origin-destination pair was determined and assigned to any origin-destination mode 5 transport. For example, if all SCTG 05 flows (not assigned mode 5) between FAF 61 to FAF 131 were 20% mode 1 and 80% mode 2, all mode 5 SCTG 05 flows between FAF 61 to FAF 131 would be reassigned to mode 2.
    - If 100% of all SCTG 05 commodity flows between an origin-destination pair were transported via mode 5, these flows were reassigned to mode 1 as "truck is the preferred mode of shipment in the US"[33]. SCTG 05 commodity flows between an origin-destination pair where mode 5 represented 100% of all transport represented ~0.01% of all SCTG 05 commodity flow weight.
- Emission factors for all remaining modes: 1 - Truck, 2 - Rail, 3 - Water, and 4 - Air were pulled from the EPA's April 2022 GHG Emission Factors Hub publication[34]. All truck transport was assumed to be done by medium- and heavy-duty trucks. Emission factors were multiplied by the average ton-miles for each commodity flow to calculate CO2, CH4, N2O, and CO2e emissions for the transportation associated with that commodity flow.

[29] https://www.bts.gov/archive/subject_areas/freight_transportation/faf/users_guide
[30] THE FREIGHT ANALYSIS FRAMEWORK VERSION 4 (FAF4) Building the FAF4 Regional Database: Data Sources and Estimation Methodologies
[31] THE FREIGHT ANALYSIS FRAMEWORK VERSION 4 (FAF4) Building the FAF4 Regional Database: Data Sources and Estimation Methodologies
[32] doi:10.1021/acssuschemeng.1c00776
[33] Vora et al. 2021 Supporting Info https://pubs.acs.org/doi/10.1021/acssuschemeng.1c00776.
[34] https://www.epa.gov/climateleadership/ghg-emission-factors-hub#:~:text=The%20most%20recent%20version%20of,product%20transport%2C%20and%20employee%20commuting.

S-7.2 Feed Production

- GHG emission factors for the production of cattle feed were sourced from Adom et al. 2012. Emissions data sourced from Adom et al. 2012 was generalized at the level of specific activity/source and GHG type but provided individual emission factors for five US production regions and six of the 10 cattle feed crops included in this study.
- The six relevant feed crops were divided according to the SCTG group. Within each SCTG group, emission factors for relevant feed crops were averaged to generate unweighted average SCTG 02 and SCTG 04 emission factors for each production region.
- Emission factors were applied to the amount of dry mass SCTG 02 and SCTG 04 feed in each commodity flow according to the flow's FAF origin production region.
    - A production region was assigned to each FAF according to information found from the supplemental material for Adom et al. 2012.
- Initially, origin-to-destination commodity flows of cattle feed were separated depending on whether commodities were SCTG 02 or SCTG 04. After calculating the GHG emissions associated with each flow according to SCTG 02 or 04 commodity type, domestic flows with the same origin, destination, and mode (but different SCTG commodity types) were combined to generate total weight of as-fed and dry mass feed being transported. Total GHG emissions for feed production were summed for each SCTG-combined flow.

S-7.3 Cattle Production

- GHG emission sources and emitting activities related to cattle production within the scope of this study include enteric fermentation, manure management, and on-farm energy use.

S-7.3.1 Enteric Fermentation & Manure Management

- Emission factors for enteric fermentation and manure management are based on data from the EPA GHG Inventory 1990-2019 released April 2021. EPA emission factors are provided for each cattle type (i.e. beef calves, dairy cow, beef cow, heifer stocker, feedlot cattle, not on feed heifer, etc.) on a kg GHG/head/year basis for CH_4, N_2O, and CO_2e. Factors were converted to kg GHG/head/day.
- According to USDA NASS QuickStats data for 2012, cattle slaughtered in 2012 can be divided by cattle type in the following proportions: heifers 29%, steers 50%, cows (dairy) 10%, cows (other) 10%, and bulls 2%. Typical lifespans and amount of time spent in each life stage were generated for each type of cattle that was slaughtered in 2012. Data used to generate these life stage progression models for each cattle type were obtained through a literature review (i.e. USDA NASS 2016, Pennsylvania Beef Council 2018, Drouillard 2018, Farm Credit Knowledge Center 2021, Terry et al 2020, Beef Cattle Extension 2019, Koontz et al 2005, Place and Miller 2020, Cheung and McMahon 2017). The average of all values for the amount of time spent in each life stage as sourced from literature was used when creating life stage progression models.

- EPA emission factors for kg GHG/day were applied to life stage progression models for each cattle type according to the amount of time spent in each lifestage in order to calculate the total emissions produced over a typical lifespan for that cattle type.
  - For example - beef heifers spend an average of 7 months (219 days) in the calf stage; after weaning, beef heifers spend about 5 months (164 days) in a stocker/backgrounding program, then 6 months (168 days) in a feedlot before being slaughtered. EPA per head emissions factors for each of these stages were as follows: beef calves 0.03 kg CH_4/day, heifer stocker/backgrounding (average of heifer stocker/heifer not on feed and feedlot cattle as backgrounders are included in feedlot category) 0.13 kg CH_4/day, and feedlot cattle 0.12 kg CH_4 kg/day. EPA emission factors group backgrounder cattle into the “feedlot cattle" category because of similarity in diet and waste management systems for drylots. Due to a lack of publicly accessible data outlining what percent of beef cattle enter a stocker program vs. a backgrounding program, heifer and steers slaughtered for beef are assumed to have a 50/50 chance of having been in a stocker or backgrounding program prior to entering the feedlot.
- Lifespan emission factors for each cattle type were weighted according to the percent of each cattle type slaughtered in 2012 in order to calculate the weighted average lifespan emissions factor for all cattle slaughter in 2012.
  - For example, in 2012 ~29% of slaughtered cattle were heifers; the average lifespan emissions factor for all slaughtered cattle is weighted so that the lifespan emissions factor for heifers contributes to 29% of the average value.
- For the purposes of this study, the average lifespan emissions factor used in the beef production model for cattle slaughtered 2012 assumes a value of 0 for the lifespan emissions factor for dairy cull cows slaughtered in 2012. Emissions associated with dairy cattle eventually slaughtered for beef are considered impacts of the diary production system and not the beef production system.

S-7.3.2 On-Farm Energy Use

- Though many LCA studies of cattle or beef production account for emissions attributed to energy use on cattle farms (Roop et al. 2014, Southwell and Rothwell 1977, Ryan and Tiffany 1998, Rotz et al. 2013, Rotz et al. 2015, Dyer et al. 2017, Asem-Hiablie et al. 2015) a review of literature revealed a lack of available data that reports energy use at the level of detail and in the appropriate units necessary for use in this study. Instead of averaging several values sourced from literature for energy use associated with cattle farming, this study includes only the electricity used for cattle housing as sourced from Asem-Hiablie et al. 2018. Numerous other studies were evaluated but these studies either did not report energy use for cattle farming separately from feed production or energy use was calculated within study boundaries that did not align with the boundaries for this study.

- Regional-level emission factors for electricity use were obtained from EPA's 2012 eGRID database[35]. The 2012 eGRID data reports annual total output emission rates in lb/MWh or GWh for CO2, CH4, N2O, and CO2e at several levels including state and sub-region. As recommended in the eGRID 2012 Technical Support Document, total output emission rates for the 26 sub-regions were used to calculate scope 2 emissions from electricity usage. The emission factor for the eGRID subregion that covered the greatest portion of each FAF was used to estimate the emissions produced from the electricity used for activities in that FAF.
- The eGRID annual output emission rates are calculated for generation sources but do not account for losses from transmission and distribution infrastructures[36]. In order to account for electricity consumption within each FAF, regional grid gross loss was included in calculations when estimating the total amount emitted by relevant activities in each FAF.

S-7.4 Slaughter & Processing

- For the purposes of this study, analysis of the GHG emissions associated with the slaughtering and processing of cattle for beef products focuses on emissions from energy usage, specifically electricity and natural gas, to run facility operations.
- A literature review was conducted to obtain specific energy intensity factors per amount of cattle slaughtered.
    - The study boundaries for most life-cycle greenhouse gas assessments of beef include the "cradle-to-farm gate" or "farm gate-to-farm gate" portion of the beef supply chain but do not analyze emissions associated with post-farm gate activities (i.e. slaughtering, processing, packaging, distribution, retail, preparation, and food waste) (Rotz et al 2019, Pelletier et al 2010, Stackhouse-Lawson et al 2015[37], Phetteplace et al 2001, Beauchemin et al 2010[38], Casey and Holden 2006, Cederberg and Stadig 2003[39], Nguyen et al 2011[40]). Many relevant beef production studies that do include post-farm gate emissions are European and not US-based (Mogensen et al. 2016[41], Genné & An Derden 2008, Ramírez and Blok

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[35] https://www.epa.gov/egrid/download-data
[36] 2012 eGRID Technical Support Document, pg. 3
[37] Stackhouse-Lawson KR, Rotz CA, Oltjen JW, and Mitloehner FM 2015 Carbon footprint and ammonia emissions of California beef production systems *J. Anim. Sci* **90**:4641-4655
[38] Beauchemin KA, Janzen HH, Little SM, McAllister TA, and McGinn SM 2010 Life cycle assessment of greenhouse gas emissions from beef production in western Canada: A case study *Agricultural Systems* **103**:371-379
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[40] Nguyen, Thu Lan T., Hermansen, John E., Mogensen, Lisbeth, 2010. Environmental consequences of different beef production systems in the EU. J. Cleaner Prod. 18, 756–766
[41] Mogensen et al. 2016 Environmental impact of beef sourced from different production systems - focus on the slaughtering stage: input and output

2006[42], Schroeder et al 2012[43]). Due to the lack of available data, energy intensity factors represent national averages as opposed to regional averages.

S-7.4.1 Electricity

- Six studies, 5 based in the US and 1 based in Canada, were used to determine the average beef processing electricity intensity in kwh/kg LW (Table ____). These studies cover a 20 year time period from 1996-2016. Due to limited data availability, the studies used to determine electricity intensity for beef processing represent majorly medium and large facilities in western US-
- The same electricity emission factors used for on-farm electricity use in the cattle production stage were used for electricity use in beef processing.

Table S-10 Studies used to determine the beef processing electricity intensity factor.

kwh/kg LW	Study	Geographic Area	Year	Facility size
0.107	Li et al. 2018	US - Midwest	2016	Large
0.049	Asem-Hiablie et al. 2018	US	2011 & 2013	Small - Large
0.073	Desjardins et al. 2012	Canada	2006	National average
0.100	Parker et al. 1997	US - Southern High Plains	1996-1997	Large
0.031	Ziara et al. 2016	US - Midwest	2014-2015	Medium
0.127	Roop et al. 2014	US - Northwest	2006	Medium
0.081	**Average kwh/kg LW**			

S-7.4.2 Natural Gas

- Four studies, three based in the US and one based in Canada, were used to determine the average beef processing natural gas intensity in Btu/kg LW (Table ____). These studies were also used to determine beef processing electricity intensity.
- Emission factors for natural gas combustion were obtained from the EPA's April 2022 GHG Emission Factors Hub publication.

Table S-11 Studies used to determine the beef processing natural gas intensity factor

Btu/kg LW	Study	Geographic Area	Year	Facility size
881	Li et al. 2018	US - Midwest	2016	Large
284	Asem-Hiablie et al. 2018	US	2011 & 2013	Small - Large

[42] https://doi.org/10.1016/j.energy.2005.08.007
[43] Roberto Schroeder1, Luís Kluwe Aguiar2 and Richard Baines 2012 Carbon Footprint in Meat Production and Supply Chains Journal of Food Science and Engineering 2 (2012) 652-665

653	Desjardins et al. 2012	Canada	2006	National average
1,349	Parker et al. 1997	US - Southern High Plains	1996-1997	Large
792	**Average Btu/kg LW**			

S-7.5 Final Footprint Estimation

S-7.5.1 Emissions Tracking

- A GHG footprint per lb of retail (bone-in) beef was calculated for each final FAF destination at the end of the beef production supply chain. To calculate the GHG footprint of entire beef supply chains for specific locations, GHG emissions for each step in the supply chain were allocated and summed using an approach similar to the leverage network. Beginning with the feed flow network, GHG emissions associated with each origin to destination commodity flow were summed at FAF destinations for feed. FAF destinations for feed become origins for commodity flows in the cattle flow network.
- The summed GHG emissions for feed at each FAF feed destination are proportionally allocated to each outgoing cattle flow according to the percent each flow contributes to all outgoing cattle flows at that FAF origin. For example, number of slaughter cattle flowing from FAF 319 to FAF 209 make up 19% of all slaughter cattle flowing out of FAF 319; the outflow to 209 would then be allocated 19% of all emissions associated with the feed consumed by slaughter cattle at FAF 319. Each outflow of cattle is also associated with GHG emissions produced from cattle transportation and cattle farming activities; emissions from the production of those cattle, the feed consumed by those cattle, and the transportation of feed and cattle are attached to each cattle outflow.
- The combined emissions from feed and cattle associated with each cattle flow are summed at the cattle destination/beef origin FAF. The same method used at the cattle origin is used to proportionally allocate summed feed and cattle emissions to beef produced at the cattle destination/beef origin. Feed and cattle emissions proportionally allocated to each outflow of beef are combined with emissions generated by the production and transportation of the retail bone-in beef (in lbs) flowing out. Each inflow of beef to a final domestic FAF destination tracks the emissions generated by the feed production, cattle production, beef processing, and supply chain transportation associated with the amount of beef being delivered.
    - Flows of beef shipped for export were included when allocating GHG emissions at FAF origins for beef to outflows of beef.

S-7.5.2 Grouped Metro Areas

- FAF4 tracks commodity flows between a total of 132 individual FAFs. Metro areas are defined in this study as FAFs that consist of a metropolitan area; metro FAFs might represent an entire metropolitan area or only a portion of a larger metropolitan area that spans multiple states (e.g. New York City metropolitan area consists of 4 FAFs, one each in Connecticut, New Jersey, New York, and Pennsylvania). Within the FAF4 dataset, the 84 metro FAFs represent the 70 individual metropolitan areas listed in Table ____.

Table S-12 The 70 individual metropolitan areas accounted for in the FAF4 database.

1. Boston	19. Phoenix	37. Indianapolis	
2. Chicago	20. Charlotte	38. Jacksonville	55. Pittsburgh
3. Cincinnati	21. Cleveland	39. Knoxville	56. Raleigh
4. Kansas City	22. Columbus	40. Lake Charles	57. Richmond
5. New York	23. Corpus Christi	41. Laredo	58. Rochester
6. Philadelphia	24. Dallas	42. Las Vegas	59. Sacramento
7. Portland	25. Dayton	43. Los Angeles	60. Salt Lake City
8. St. Louis	26. Denver	44. Louisville	61. San Antonio
9. Washington	27. Detroit	45. Memphis	62. San Diego
10. Albany	28. El Paso	46. Miami	63. San Francisco
11. Atlanta	29. Fort Wayne	47. Milwaukee	64. Savannah
12. Austin	30. Fresno	48. Minneapolis	65. Seattle
13. Baltimore	31. Grand Rapids	49. Mobile	66. Norfolk
14. Baton Rouge	32. Greensboro	50. Nashville	67. Tampa
15. Beaumont	33. Greenville	51. New Orleans	68. Tucson
16. Birmingham	34. Hartford	52. Omaha	69. Tulsa
17. Buffalo	35. Honolulu	53. Oklahoma City	70. Wichita
18. Charleston	36. Houston	54. Orlando	

- Total GHG emissions for each metro area was estimated by summing the GHG emissions of all flows of beef into the FAFs associated with each metro area. GHG footprints in kg CO_2e/lb retail beef were estimated for each metro area by first calculating GHG footprints for each beef inflow then calculating the weighted average GHG footprint. Footprints for individual inflows of beef were weighted according to the proportion each beef inflow contributed to the total amount of beef (in lbs) shipped to the FAF destination from all FAF origins.

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APPENDIX B:

FAF4 DOMESTIC ZONES DEFINITIONS

FAF Zone	State	Corresponding CFS Area Name	Grouped Name	Type
11	Alabama (AL)	Birmingham-Hoover-Talladega, AL	Birmingham	Metro
12	Alabama (AL)	Mobile-Daphne-Fairhope, AL	Mobile	Metro
19	Alabama (AL)	Remainder of Alabama	Rest of AL	Non-Metro
20	Alaska (AK)	Alaska	Alaska	Non-Metro
41	Arizona (AZ)	Phoenix-Mesa-Glendale, AZ	Phoenix	Metro
49	Arizona (AZ)	Remainder of Arizona	Rest of AZ	Non-Metro
42	Arizona (AZ)	Tucson-Nogales, AZ	Tucson	Metro
50	Arkansas (AR)	Arkansas	Arkansas	Non-Metro
65	California (CA)	Fresno-Madera, CA	Fresno	Metro
61	California (CA)	Los Angeles-Long Beach, CA	Los Angeles	Metro
69	California (CA)	Remainder of California	Rest of CA	Non-Metro
62	California (CA)	Sacramento-Roseville, CA	Sacramento	Metro
63	California (CA)	San Diego-Carlsbad-San Marcos, CA	San Diego	Metro
64	California (CA)	San Jose-San Francisco-Oakland, CA	San Francisco	Metro
81	Colorado (CO)	Denver-Aurora, CO	Denver	Metro
89	Colorado (CO)	Remainder of Colorado	Rest of CO	Non-Metro
91	Connecticut (CT)	Hartford-West Hartford-East Hartford, CT	Hartford	Metro
92	Connecticut (CT)	New York-Newark, NY-NJ-CT-PA (CT Part)	New York	Metro
99	Connecticut (CT)	Remainder of Connecticut	Rest of CT	Non-Metro
101	Delaware (DE)	Philadelphia-Reading-Camden, PA-NJ-DE-MD (DE Part)	Philadelphia	Metro
109	Delaware (DE)	Remainder of Delaware	Rest of DE	Non-Metro
121	Florida (FL)	Jacksonville-St. Marys-Palatka, FL-GA (FL Part)	Jacksonville	Metro

122	Florida (FL)	Miami-Fort Lauderdale-Port St. Lucie, FL	Miami	Metro
123	Florida (FL)	Orlando-Deltona-Daytona Beach, FL	Orlando	Metro
129	Florida (FL)	Remainder of Florida	Rest of FL	Non-Metro
124	Florida (FL)	Tampa-St. Petersburg-Clearwater, FL	Tampa	Metro
131	Georgia (GA)	Atlanta-Athens-Clarke County-Sandy Springs, GA	Atlanta	Metro
139	Georgia (GA)	Remainder of Georgia	Rest of GA	Non-Metro
132	Georgia (GA)	Savannah-Hinesville-Statesboro, GA	Savannah	Metro
151	Hawaii (HI)	Urban Honolulu, HI	Honolulu	Metro
159	Hawaii (HI)	Remainder of Hawaii	Rest of HI	Non-Metro
160	Idaho (ID)	Idaho	Idaho	Non-Metro
171	Illinois (IL)	Chicago-Naperville, IL-IN-WI (IL Part)	Chicago	Metro
179	Illinois (IL)	Remainder of Illinois	Rest of IL	Non-Metro
172	Illinois (IL)	St. Louis-St. Charles-Farmington, MO-IL (IL Part)	St. Louis	Metro
181	Indiana (IN)	Chicago-Naperville, IL-IN-WI (IN Part)	Chicago	Metro
183	Indiana (IN)	Fort Wayne-Huntington-Auburn, IN	Fort Wayne	Metro
182	Indiana (IN)	Indianapolis-Carmel-Muncie, IN	Indianapolis	Metro
189	Indiana (IN)	Remainder of Indiana	Rest of IN	Non-Metro
190	Iowa (IA)	Iowa	Iowa	Non-Metro
201	Kansas (KS)	Kansas City-Overland Park-Kansas City, MO-KS (KS Part)	Kansas City	Metro
209	Kansas (KS)	Remainder of Kansas	Rest of KS	Non-Metro
202	Kansas (KS)	Wichita-Arkansas City-Winfield, KS	Wichita	Metro
211	Kentucky (KY)	Cincinnati-Wilmington-Maysville, OH-KY-IN (KY Part)	Cincinnati	Metro
212	Kentucky (KY)	Louisville/Jefferson County-Elizabethtown-Madison, KY-IN (KY Part)	Louisville	Metro
219	Kentucky (KY)	Remainder of Kentucky	Rest of KY	Non-Metro

221	Louisiana (LA)	Baton Rouge, LA	Baton Rouge	Metro
222	Louisiana (LA)	Lake Charles, LA	Lake Charles	Metro
223	Louisiana (LA)	New Orleans-Metairie-Hammond, LA-MS (LA Part)	New Orleans	Metro
229	Louisiana (LA)	Remainder of Louisiana	Rest of LA	Non-Metro
230	Maine (ME)	Maine	Maine	Non-Metro
241	Maryland (MD)	Baltimore-Columbia-Towson, MD	Baltimore	Metro
249	Maryland (MD)	Remainder of Maryland	Rest of MD	Non-Metro
242	Maryland (MD)	Washington-Arlington-Alexandria, DC-VA-MD-WV (MD Part)	Washington	Metro
251	Massachusetts (MA)	Boston-Worcester-Providence, MA-RI-NH-CT (MA Part)	Boston	Metro
259	Massachusetts (MA)	Remainder of Massachusetts	Rest of MA	Non-Metro
261	Michigan (MI)	Detroit-Warren-Ann Arbor, MI	Detroit	Metro
262	Michigan (MI)	Grand Rapids-Wyoming-Muskegon, MI	Grand Rapids	Metro
269	Michigan (MI)	Remainder of Michigan	Rest of MI	Non-Metro
271	Minnesota (MN)	Minneapolis-St. Paul, MN-WI (MN Part)	Minneapolis	Metro
279	Minnesota (MN)	Remainder of Minnesota	Rest of MN	Non-Metro
280	Mississippi (MS)	Mississippi	Mississippi	Non-Metro
291	Missouri (MO)	Kansas City-Overland Park-Kansas City, MO-KS (MO Part)	Kansas City	Metro
299	Missouri (MO)	Remainder of Missouri	Rest of MO	Non-Metro
292	Missouri (MO)	St. Louis-St. Charles-Farmington, MO-IL (MO Part)	St. Louis	Metro
300	Montana (MT)	Montana	Montana	Non-Metro
311	Nebraska (NE)	Omaha-Council Bluffs-Fremont, NE-IA (NE Part)	Omaha	Metro
319	Nebraska (NE)	Remainder of Nebraska	Rest of NE	Non-Metro
321	Nevada (NV)	Las Vegas-Henderson, NV-AZ (NV Part)	Las Vegas	Metro
329	Nevada (NV)	Remainder of Nevada	Rest of NV	Non-Metro

331	New Hampshire (NH)	Boston-Worcester-Providence, MA-RI-NH-CT (NH Part)	Boston	Metro
339	New Hampshire (NH)	Remainder of New Hampshire	Rest of NH	Non-Metro
341	New Jersey (NJ)	New York-Newark, NY-NJ-CT-PA (NJ Part)	New York	Metro
342	New Jersey (NJ)	Philadelphia-Reading-Camden, PA-NJ-DE-MD (NJ Part)	Philadelphia	Metro
350	New Mexico (NM)	New Mexico	New Mexico	Non-Metro
361	New York (NY)	Albany-Schenectady, NY	Albany	Metro
362	New York (NY)	Buffalo-Cheektowaga, NY	Buffalo	Metro
363	New York (NY)	New York-Newark, NY-NJ-CT-PA (NY Part)	New York	Metro
369	New York (NY)	Remainder of New York	Rest of NY	Non-Metro
364	New York (NY)	Rochester-Batavia-Seneca Falls, NY	Rochester	Metro
371	North Carolina (NC)	Charlotte-Concord, NC-SC (NC Part)	Charlotte	Metro
372	North Carolina (NC)	Greensboro--Winston-Salem--High Point, NC	Greensboro	Metro
373	North Carolina (NC)	Raleigh-Durham-Chapel Hill, NC	Raleigh	Metro
379	North Carolina (NC)	Remainder of North Carolina	Rest of NC	Non-Metro
380	North Dakota (ND)	North Dakota	North Dakota	Non-Metro
391	Ohio (OH)	Cincinnati-Wilmington-Maysville, OH-KY-IN (OH Part)	Cincinnati	Metro
392	Ohio (OH)	Cleveland-Akron-Canton, OH	Cleveland	Metro
393	Ohio (OH)	Columbus-Marion-Zanesville, OH	Columbus	Metro
394	Ohio (OH)	Dayton-Springfield-Sidney, OH	Dayton	Metro
399	Ohio (OH)	Remainder of Ohio	Rest of OH	Non-Metro
401	Oklahoma (OK)	Oklahoma City-Shawnee, OK	Oklahoma City	Metro
409	Oklahoma (OK)	Remainder of Oklahoma	Rest of OK	Non-Metro

402	Oklahoma (OK)	Tulsa-Muskogee-Bartlesville, OK	Tulsa	Metro
411	Oregon (OR)	Portland-Vancouver-Salem, OR-WA (OR Part)	Portland	Metro
419	Oregon (OR)	Remainder of Oregon	Rest of OR	Non-Metro
423	Pennsylvania (PA)	New York-Newark, NY-NJ-CT-PA (PA Part)	New York	Metro
421	Pennsylvania (PA)	Philadelphia-Reading-Camden, PA-NJ-DE-MD (PA Part)	Philadelphia	Metro
422	Pennsylvania (PA)	Pittsburgh-New Castle-Weirton, PA-OH-WV (PA Part)	Pittsburgh	Metro
429	Pennsylvania (PA)	Remainder of Pennsylvania	Rest of PA	Non-Metro
441	Rhode Island (RI)	Boston-Worcester-Providence, MA-RI-NH-CT (RI Part)	Boston	Metro
451	South Carolina (SC)	Charleston-North Charleston-Summerville, SC	Charleston	Metro
452	South Carolina (SC)	Greenville-Spartanburg-Anderson, SC	Greenville	Metro
459	South Carolina (SC)	Remainder of South Carolina	Rest of SC	Non-Metro
460	South Dakota (SD)	South Dakota	South Dakota	Non-Metro
473	Tennessee (TN)	Knoxville-Morristown-Sevierville, TN	Knoxville	Metro
471	Tennessee (TN)	Memphis, TN-MS-AR (TN Part)	Memphis	Metro
472	Tennessee (TN)	Nashville-Davidson--Murfreesboro, TN	Nashville	Metro
479	Tennessee (TN)	Remainder of Tennessee	Rest of TN	Non-Metro
481	Texas (TX)	Austin-Round Rock, TX	Austin	Metro
482	Texas (TX)	Beaumont-Port Arthur, TX	Beaumont	Metro
483	Texas (TX)	Corpus Christi-Kingsville-Alice, TX	Corpus Christi	Metro
484	Texas (TX)	Dallas-Fort Worth, TX-OK (TX Part)	Dallas	Metro
485	Texas (TX)	El Paso-Las Cruces, TX-NM (TX Part)	El Paso	Metro
486	Texas (TX)	Houston-The Woodlands, TX	Houston	Metro
487	Texas (TX)	Laredo, TX	Laredo	Metro

489	Texas (TX)	Remainder of Texas	Rest of TX	Non-Metro
488	Texas (TX)	San Antonio-New Braunfels, TX	San Antonio	Metro
499	Utah (UT)	Remainder of Utah	Rest of UT	Non-Metro
491	Utah (UT)	Salt Lake City-Provo-Orem, UT	Salt Lake City	Metro
500	Vermont (VT)	Vermont	Vermont	Non-Metro
512	Virginia (VA)	Virginia Beach-Norfolk, VA-NC (VA Part)	Norfolk	Metro
519	Virginia (VA)	Remainder of Virginia	Rest of VA	Non-Metro
511	Virginia (VA)	Richmond, VA	Richmond	Metro
513	Virginia (VA)	Washington-Arlington-Alexandria, DC-VA-MD-WV (VA Part)	Washington	Metro
532	Washington (WA)	Portland-Vancouver-Salem, OR-WA (WA Part)	Portland	Metro
539	Washington (WA)	Remainder of Washington	Rest of WA	Non-Metro
531	Washington (WA)	Seattle-Tacoma, WA	Seattle	Metro
111	Washington D.C. (DC)	Washington-Arlington-Alexandria, DC-VA-MD-WV (DC Part)	Washington	Metro
540	West Virginia (WV)	West Virginia	West Virginia	Non-Metro
551	Wisconsin (WI)	Milwaukee-Racine-Waukesha, WI	Milwaukee	Metro
559	Wisconsin (WI)	Remainder of Wisconsin	Rest of WI	Non-Metro
560	Wyoming (WY)	Wyoming	Wyoming	Non-Metro

Source: Oak Ridge National Laboratory 2015a Freight Analysis Framework Version 4 (FAF4)
https://www.bts.gov/archive/subject_areas/freight_transportation/faf/users_guide

APPENDIX C:

ADDITIONAL RESULTS TABLES AND DISCUSSION

Table C.1 GHG Footprints of Beef Supply Chains for Metro and Non-metro Areas

Metro Area	**CO_2e kg/lb retail beef (bone-in)**	**Non-Metro Area**	**CO_2e kg/lb retail beef (bone-in)**
Mobile, AL	10.54	West Virginia	10.88
Charleston, SC	10.25	Rest of NH	10.18
Knoxville, TN	10.13	Alaska	9.87
Lake Charles, LA	10.06	Rest of HI	9.67
Savannah, GA	10.00	Rest of AL	9.48
Honolulu, HI	10.00	Vermont	9.44
Orlando, FL	9.33	Rest of CT	9.44
Greensboro, NC	9.31	Montana	9.19
Buffalo, NY	9.28	Rest of SC	9.19
Norfolk, VA	9.17	Rest of GA	9.12
Corpus Christi, TX	9.15	Rest of OR	9.09
Hartford, CT	9.13	Rest of LA	9.09
Beaumont, TX	9.12	New Mexico	9.08
Memphis, TN	9.07	Rest of FL	9.06
Miami, FL	9.05	Rest of TX	9.02
Tampa, FL	9.04	Rest of TN	8.99
Jacksonville, FL	9.03	Rest of NC	8.98
Nashville, TN	9.03	Rest of NY	8.97
Fort Wayne, IN	9.03	Maine	8.97
Atlanta, GA	8.99	Mississippi	8.91
San Antonio, TX	8.98	Rest of WA	8.86
Raleigh, NC	8.91	Arkansas	8.85
Rochester, NY	8.91	Wyoming	8.82
San Diego, CA	8.89	Rest of MD	8.80
Philadelphia, NJ	8.88	Rest of PA	8.78
Greenville, SC	8.88	Rest of CA	8.77
Pittsburgh, PA	8.87	South Dakota	8.75
El Paso, TX	8.87	Rest of VA	8.74
Tulsa, OK	8.86	Idaho	8.70

Austin, TX	8.86
Baltimore, MD	8.85
New York, CT	8.84
Los Angeles, CA	8.84
Portland, OR	8.84
Dallas, TX	8.82
San Francisco, CA	8.82
Richmond, VA	8.78
Seattle, WA	8.78
Oklahoma City, OK	8.77
New Orleans, LA	8.75
Charlotte, NC	8.75
Birmingham, AL	8.75
Washington, DC	8.74
Laredo, TX	8.74
Cleveland, OH	8.73
Boston, MA	8.73
Houston, TX	8.71
Louisville, KY	8.71
Fresno, CA	8.69
Kansas City, KS	8.69
Phoenix, AZ	8.68
Detroit, MI	8.64
Indianapolis, IN	8.63
Sacramento, CA	8.61
Baton Rouge, LA	8.60
Dayton, OH	8.59
Las Vegas, NV	8.56
Tucson, AZ	8.56
Albany, NY	8.54
Columbus, OH	8.51
Chicago, IL	8.51
Salt Lake City, UT	8.50
St. Louis, MO	8.48
Cincinnati, KY	8.48
Denver, CO	8.46
Milwaukee, WI	8.41
Rest of DE	8.68
Rest of NV	8.67
Rest of AZ	8.67
Rest of KY	8.66
Rest of OK	8.64
Rest of IN	8.64
Rest of MO	8.62
Rest of OH	8.61
Rest of MA	8.58
Rest of KS	8.53
Rest of WI	8.50
Rest of CO	8.41
North Dakota	8.40
Iowa	8.38
Rest of NE	8.36
Rest of IL	8.36
Rest of MI	8.24
Rest of MN	8.18
Rest of UT	8.04

Grand Rapids, MI	8.41
Wichita, KS	8.38
Omaha, NE	8.31
Minneapolis, MN	8.22

C.2 Cross-study Comparison

GHG footprints for beef as determined by other studies were obtained for comparison; footprints, study location, and study boundary are available in Table C.2. Geographical representation across relevant literature was biased towards Europe. Many of the U.S. based LCA beef production studies included in the comparative literature review have a study boundary of cradle-to-farm-gate; supply chain steps beyond the farm-gate are frequently emitted from studies of beef production. Because of the low contribution (<2%) of the beef production stage to GHG emissions footprint for beef (Asem-Hiablie et al 2018, Roop et al 2014), footprints determined by cradle-to-farm-gate studies are appropriate for comparison despite the exclusion of activities that occur in the beef supply chain once cattle leave the farm for slaughter.

Table C.2 Literature review of GHG footprints for beef

Study	Footprint (kg CO_2e/ lb retail beef)	Location	Boundary
Rotz et al 2019	14	US average	cradle-to-farm-gate
Pelletier et al 2010	16	Midwest US	cradle-to-farm-gate
Johnson et al 2003	14	Midwest US	cradle-to-farm-gate
Beauchemin et al 2010	14	Western Canada	cradle-to-farm-gate
Stackhouse-Lawson et al. 2012	11	California, US	cradle-to-farm-gate
Desjardins et al 2012[a]	8	Canada average	cradle-to-slaughterhouse-gate
Roop et al 2014	11	Northwestern US	cradle-to-processing-gate
Asem-Hiablie et al 2018[a]	15	Great Plains US	cradle-to-consumer

Sanders and Webber 2014	14	US average	cradle-to-consumption
This study	*9*	*US average*	*cradle-to-consumer*

[a]Some emissions are allocated to by-products of beef production such as hides, bone meal, and tallow.

The GHG footprint of 8.7 ± 3 kg CO_2e/lb retail (bone-in) beef determined by this study is lower but not unreasonable when compared to the range of 8 kg CO_2e/lb retail beef (Desjardins et al 2012) to 16 kg CO_2e/lb retail beef (Pelletier et al 2010) found in relevant literature (Table C.2). When evaluating supply chain emissions across all individual origin to destination commodity flows of beef, this study found that the GHG footprints for individual beef supply chains ranged from 8 to 16 kg CO_2e/lb retail beef.

Reported values on the relative proportion of GHG emissions attributed to each stage or source in the beef supply chain were gathered through a literature review for comparison; proportion of beef supply chain stage or source emissions out of total, study location, and study boundary are available in Table C.3.

Table C.3 Literature review of beef supply chain emissions by stage or source

Study	Feed Production	Enteric Fermentation	Manure Management	Beef Processing	Other	Location
Asem-Hiablie et al 2018	17 %	53 %	30 %	1.9 %		Great Plains US
Roop et al 2014	55 %	23 %	8 %	1.6 %	1 %	Northwestern US
Rotz et al 2019	<26%	56 %	18 %	N/A	<26%	US average
Pelletier et al 2010	34 %	39 %	24 %	N/A	3 %	Midwestern US
Sykes et al 2019	25 %	48 %	21 %	N/A	1 %	UK
Stanley et al 2018	37 %	31 %	30 %	N/A	2 %	Midwestern US
Casey and Holden 2006	26 %	60 %	10 %		4 %	Ireland
This study	*22 %*	*66 %*	*8 %*	*2 %*	*2 %*	*US average*

As with the GHG footprint of beef, cross-study comparisons for beef supply chain emissions by stage or source was somewhat impractical due to lack of consistency in study boundaries. Results were often presented without enough detail to allow data to be re-framed for comparison across studies with parallel but slightly different research objectives. Given study and data limitations, Table C.3 may be regarded as a comprehensive though imperfect summary of the literature as is currently available.

A review of the literature revealed a significant range across studies in how emissions attributed to beef production were dispersed across sources and supply chain stages. Emissions attributed to feed production ranged from 17% - 55% of total beef production emissions, enteric fermentation 23% - 60%, and manure management 8% - 30%. Few studies accounted for emissions post farm-gate; Asem-Hiablie et al 2018 and Roop et al 2014 reported beef processing emissions to make up 1.9% and 1.6% of total beef production emissions respectively. For five out of the seven studies reviewed in Table C.3, enteric fermentation alone accounted for the greatest portion of GHG emissions attributed to the beef production supply chain. Emissions from activities associated with feed production were found to be most commonly reported as an aggregate sum rather than itemized according to individual sources. For five of the seven studies reviewed, the aggregate emissions associated with feed production were found to be the second largest contributor to beef supply chain emissions following enteric fermentation.

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