Carbon footprint analysis of Western Canadian beef production compared to international competitors – Part 1

From: Dr. Vivek Arulnathan, Daniela Dominguez, Dr. Nathan Pelletier (PRISM Consulting)

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Executive summary

Beef is one of the most important livestock-based food products in Canada. Over 45% of Canadian beef is exported to international markets. Among livestock-based food products, beef is generally considered the most resource intensive and environmentally impactful, but the large natural and naturalized pastures used for rearing beef cattle (Prairie grasslands) in Western Canada can also produce important societal and environmental benefits.

Given the competitive nature of international markets and the growing regulatory and societal pressure for sustainably produced food, the Global Institute for Food Security (GIFS) commissioned a study to compare the carbon footprint of the characteristic Western Canadian beef production system against representative beef production systems in key global competitor countries (backgrounding and feedlot finishing in USA and grass-finishing in Brazil).

Data for this analysis was collected using a systematic review of publicly available data sources that were assessed using Life Cycle Assessment (LCA) data quality screening indicators – with descriptors for the indicator scores modified to reflect study-specific data quality goals. Data was preferentially sourced from life cycle inventory (LCI) databases to ensure maximum internal consistency. High quality data to characterize Western Canadian beef production was largely obtained from Statistics Canada and the Canadian Roundtable for Sustainable Beef's (CRSB) National Beef Sustainability Assessments. For the USA, data of generally high quality was sourced primarily from the National Agricultural Statistics Service (NASS) and a series of surveys undertaken as part of the US Beef Sustainability Program (funded by the United States Department of Agriculture and the Cattlemen's Beef Board). Data quality was comparatively lower for Brazil, particularly with respect to completeness and temporal correlation. There was a lack of publicly available data to separately characterize all of Brazil's different production regions in order to develop a nationally representative model. Hence, data representative of Mato Grosso and Mato Grosso do Sul states, the largest beef producing regions in Brazil, was used to characterize Brazilian grass-finished beef.

This carbon footprint study was based on the ISO 14044 standard for Life Cycle Assessment and the ISO 14067 standard for carbon footprinting. Across the three countries, the beef production

systems modelled included one or more of the following phases: cow-calf operations, backgrounding, and finishing. The characterization of the inventory was based on modelling a single calf as a representative animal unit across the different phases. Within this representative animal unit, other cattle (cows, bulls, heifers for replacement) were also included as inputs. A cradle to farm gate system boundary was modelled to include all relevant material inputs, energy inputs, and emissions associated with the three phase such as production of feed inputs, enteric methane and manure-related emissions, energy use for on-farm activities, transportation, and soil organic carbon fluxes resulting from land use change and land management. A functional unit of one kilogram of live weight of cattle intended for slaughter was used and the IPCC 2021 Assessment Report (AR) 6 methodology was used for impact assessment.

Overall, the carbon footprint of Western Canadian beef (8.95 kg CO2-eq.) was the lowest among the three countries considered, while Brazil (22.93 kg CO2-eq.) was the highest per kilogram of live weight of finished beef cattle. The carbon footprint of US beef production (10.96 kg CO2-eq.) was 22.7% higher than that of beef from Western Canada (Figure 2). The carbon footprint of Brazilian beef production was about 157% and 109% higher than Western Canadian and US beef production, respectively. These large differences were primarily driven by soil organic carbon losses and higher enteric methane emissions associated with grass-based diets and longer finishing times.

The majority of the impacts were attributable to the cow-calf phase (67-68%) in Western Canada and the USA, with feedlot finishing (23-25%) and backgrounding (8-10%) having relatively lower impacts. In Brazil, the finishing phase accounted for the largest share of impacts (44%), primarily due to the higher enteric methane emissions resulting from the longer finishing period and forage-based diet. Enteric methane emissions were the single biggest source of impacts, accounting for 79.9% of the overall carbon footprint in Western Canada, 61% in the US, and 49% in Brazil. Feed inputs and manure management were the other major contributors – with almost all of the feed-related impacts in Brazil resulting from land use change. Without considering the impacts of soil carbon fluxes, the carbon footprint of Brazilian beef was still 42.7% and 32.7% higher than Western Canadian and US beef, respectively. Per kilogram of live

weight, the carbon footprint estimates without the inclusion of soil carbon fluxes were 9.44 kg CO_2-eq., 11.09 kg CO_2-eq., and 16.48 kg CO_2-eq. for Western Canada, US, and Brazil respectively.

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1 Introduction

Beef is one of the most important livestock-based food products in Canada, accounting for approximately 24% of per capita meat consumption (Ritchie et al., 2019). Farm receipts from the beef sector in Canada totalled over $10 billion in 2021, with the overall contribution to GDP estimated at ~$22 billion (Canada Beef, 2022). Canada is the 9th largest beef producer in the world (when the European Union is considered a single producer) and accounts for about 2% of the world's beef supply (Canada Beef, 2022). According to the 2021 census of agriculture, Alberta (44%), Saskatchewan (29%), and Manitoba (11%), account for 84% of all beef cattle in Canada, with about 75% of all Canadian beef cattle finished in Western Canada (i.e. Alberta and Saskatchewan) (Canada Beef, 2022).

While domestic consumption accounts for a large proportion of beef production in Canada, 43-49% of Canadian beef is exported (1.1 billion pounds of beef was exported in 2022 from a total production of 3.61 billion pounds). The majority (70.7%) of Canadian beef was exported to the United States of America (USA), with China, Japan, and Mexico representing other major export markets. Canada is the 9th largest beef exporter (including the combined European Union) in the world and Canadian beef exports were valued at over $4.5 billion in 2022 (Canada Beef 2023).While the agri-food sector is economically and socially vital, it is also a key source of resource and environmental impacts. Livestock-based food production alone is considered among the top three contributors to a variety of local and global environmental issues (Steinfeld et al., 2006). Agri-food systems as a whole account for almost one-third of anthropogenic greenhouse gas (GHG) emissions (Crippa et al., 2021). Of this, animal-based food production accounts for 57% – which is approximately twice that of plant-based foods, despite the much smaller production volumes (Xu et al., 2021).

Among livestock-based food products, beef is generally considered the most resource intensive and environmentally impactful (Steinfeld et al., 2006). The production of beef has double the GHG emissions of the food product with the second highest GHG emissions (lamb), and accounts for about 25% of all agri-food GHG emissions (Canada Beef, 2022; Xu et al., 2021). Compared to plant-based protein from beans, beef is estimated to have twenty times the land use and GHG emissions per gram of edible protein (WRI, 2022). The primary drivers of beef's significant carbon footprint are enteric fermentation (producing methane, which has a carbon dioxide equivalency of 25 over a 100 year time horizon and a much higher equivalency over shorter time horizons), nitrous oxide emissions from manure, and feed production (Pelletier et al., 2010; WRI, 2022). On the other hand, grasslands (such as the native prairie grasslands of Western Canada) used in beef production can provide important environmental and societal benefits such as habitat and biodiversity protection, soil retention, water retention, soil carbon sequestration, and community development (Gunn et al., 2018).

However, GHG emissions and other environmental impacts associated with beef production can vary significantly depending on production location and associated soil, climate and management conditions (Pelletier et al., 2010). While the cow-calf stage (i.e. where calves are born and weaned on pastureland) is often common in configuration across different regions, subsequent phases might vary significantly. In some contexts, a transitional backgrounding stage is used in which steers and heifers are managed after weaning on a primarily forage diet. The finishing stage, in which calves fatten and add muscle, can either be done using concentrated feeds in feedlots or using a primarily grass-based diet on pastures (Pelletier et al., 2010; Toor and Hamit-Haggar, 2021). Land use change and associated soil carbon changes can also have a significant influence on the impacts of beef produced in different regions due to the type of land that is converted to pastures or cropland, as well as differences in soil organic carbon storage or losses on rangeland, pasture, or cropland that provides feed inputs (Xu et al., 2021).

Given the competitive nature of international markets in which Western Canadian beef is sold and the growing regulatory and societal pressure for sustainably produced food (Fromm, 2020; WEF, 2023; Zamuz et al., 2021), comparative assessments of the environmental impacts of beef from different production regions and systems is vital to leverage any existing competitive advantages as well as to drive improved sustainability outcomes. Such comparative assessments should ideally be supported using life cycle thinking-based approaches such as Life Cycle Assessment (LCA) or carbon footprinting, based on internationally recognised standards (ISO, 2018, 2006a, 2006b). This allows for transparent and reproducible comparison of the cumulative resource demands and environmental burdens associated with the supply chain of food products.

The Global Institute for Food Security (GIFS) commissioned a study to compare the carbon footprint of the characteristic Western Canadian beef production system against key global competitors (USA, Brazil, Argentina, Australia, New Zealand, and France) on a rigorous and methodologically consistent basis. It is important to note here that the term Western Canada in this report does not include British Columbia, but rather refers exclusively to the provinces of Saskatchewan and Alberta.

This project is divided into two phases:

1. Phase 1 establishes the project methods and focuses on comparing Western Canadian beef production with beef produced in the USA and Brazil.
2. Phase 2 utilizes the methods established in Phase 1 and expands the analysis to include beef production in Argentina, Australia, New Zealand, and France.

The current document represents Deliverable 2 of Phase 1, which details the methods and results of the carbon footprint analysis of beef production systems for countries listed in Phase 1 – including the methods and results for identifying data sources for Phase 1 based on the application of a transparent and consistent set of data quality considerations.

2 Methods

The estimation of the carbon footprint of beef production in each jurisdiction followed a step-wise process. The first step involved characterizing a representative beef production system for each region of interest, followed by a rigorous data mining process to identify credible data sources to support carbon footprint analysis for the systems under consideration. For each region/country, only the production system that accounts for the majority of beef produced for export (excluding beef from culled dairy cows) was considered. The second step involved a data quality assessment to screen and select among available data sources. Deliverable 1 was submitted in April 2024 (and is included in this report under sections 2.2, 2.3, and 2.4). It described the methods and results of the data mining and quality assessment exercise. Finally, modelling of the product systems, the carbon footprint analysis, and comparison of beef production systems in the countries considered was performed. A complete description of the methods used across these three steps is provided below.

2.1 Beef production system characterization

Characteristic beef production practices and supporting supply chains (in particular, related to feed input production and processing) vary both within and between countries of interest. It is infeasible to develop models to characterize all possible variants for beef production in each country considered. Instead, the prevalent system characteristics for beef produced for export from each country of interest, along with representative diets and corresponding feed input production and processing flows, was determined based on a review of literature and expert consultation.

2.1.1 Western Canadian Beef Production System

Western Canada accounts for the majority (~75%) of beef cattle in Canada (CRSB, 2023). In Western Canada, calves are mostly raised on pasture (natural prairie grasslands with a primarily forage-based diet) and finished in feedlots (primarily grain diet). The cow-calf operations in Western Canada are largely concentrated in the provinces of Alberta and Saskatchewan, while feedlot finishing is concentrated primarily in southern Alberta. Within this system, the Canadian Roundtable for Sustainable Beef (CRSB) differentiates between two pathways: The calf-fed (CF) system represents heavy calves weaned at 7-8 months that are sent directly to feedlots for a high energy grain-based finishing diet. The yearling-fed (YF) system represents calves that are backgrounded and put on an intermediate low-energy grass diet in pastures for an extra 4-5 months before being finished in feedlots on a high energy grain-based finishing diet (CRSB, 2023). The CRSB National Beef Sustainability Assessment report (CRSB, 2023) estimates that the CF system represents 45% and the YF system represents 55% of beef calves finished in Canada, with no significant presence of grass-finished herds.

The backgrounding stage in Western Canada generally has two phases – the time before the calves turn one year old and the time they spend in the backgrounding phase as a yearling. As calves, they do not spend much time on pasture and are put on a diet with roughly equal mix of harvested forage and grain. As yearlings however, their primary source of feed is from pasture. As a result, distinction between these two phases of the backgrounding stage is emphasized (CRSB, 2023). Personal communications with the CRSB (CRSB, 2024) indicated that while 45% of calves in beef cattle herds do directly go to feedlot finishing in Western Canada, not all 55% of calves that are backgrounded spend additional time on pasture as yearlings before feedlot finishing. Hence, only 25% of calves were considered to spend time on pasture as yearlings and 30% of calves moving directly to feedlot finishing after backgrounding in Western Canada.

2.1.2 United States Beef Production System

In the United States, a non-trivial level of grass-finishing for cattle was reported in certain regions. For example, eastern USA, which accounts for ~20% of beef produced in the country, had 37% of its cattle finished on grass (Asem-Hiablie et al., 2018). Western USA – which accounts for ~18% of beef herds in the USA – had 34% of its beef cattle finished on grass (Asem-Hiablie et al., 2017). On the other hand, grass-finished cattle made up only 7% of all finished cattle in Kansas, Oklahoma, and Texas – the states which together account for 26% of all beef cattle in the USA (Asem-Hiablie et al., 2015). The Northern Plains and Midwest – representing ~27% of beef produced – also had a very small share of grass-finished cattle (1.1%) (Asem-Hiablie et al., 2016). Given that regions representing over half of all beef produced in the USA have very little grass-finished beef and its share of finished cattle was below 40% in other major beef producing regions, a feed-lot finishing system was modelled to represent beef production in the USA. In the US, cattle that are backgrounded do not appear to have a significant period on pasture during their yearling phase and are instead sent directly to feedlots for finishing.

2.1.3 Brazilian Beef Production System

For Brazil, there is clear evidence that over 80% of all beef produced is from cattle that have an all-forage diet (i.e. they are finished on pasture or harvested forage (ABIEC, 2022). As a result, a grass-finished beef production system was modelled for Brazil.

2.2 Identification of data sources

In order to effectively compare the selected beef production systems for each country, the compilation of high-quality data and use of consistent modelling methods is of paramount importance. Comparative carbon footprint analysis of the beef production systems requires a combination of data and models to characterize the cow-calf, backgrounding (if performed), and feedlot/pasture finishing phases for each country, as determined in Section 2.1. This includes data on aspects such as herd and pasture management, land use and soil carbon changes, feed input production, feed composition, manure management and associated emissions, enteric methane emissions, transportation, and other material and energy inputs (Pelletier et al., 2010). Furthermore, for all major feed inputs to be modelled for each country, data of sufficient quality to characterize crop management practices, soil/climate conditions, inputs, emissions, and yields are similarly required.

Data relevant for this study was sourced from multiple venues. Major sources of data include publicly available or commercial Life Cycle Inventory (LCI) databases, public data that are provided by national or international statistical agencies, peer-reviewed literature, and grey literature (primarily reports from reputable industry groups or government agencies). Data sources can vary in their scope, coverage, and data quality and hence a hierarchy of data sources was defined in order to structure the consideration of potential data sources. The hierarchy of sources to be considered are as follows

1. Life Cycle Inventory databases
2. Peer-reviewed literature
3. Grey literature

Provided data quality is high, complete datasets for beef production systems – including crop production systems for feed ingredients used – were preferentially sourced from life cycle inventory (LCI) databases, if possible, in order to maximize internal consistency among data points with respect to methods and modelling context. LCI databases are private or public sector repositories of data sets characterizing material and energy inputs and emissions for specific economic activities, including documentation of metadata for each data set (LCI data can then be used in a Life Cycle Assessment (LCA) as inputs to models to determine the environmental impacts associated with the product or activity). LCI databases relevant to the agri-food sector specific to the countries considered are available (Fritter, 2020; USDA, 2014). In addition, several other major LCI databases that contain agri-food related datasets were considered. The ecoinvent database, for example, is the most comprehensive and widely utilized database for LCA studies worldwide (Moreno Ruiz et al., 2013). This proprietary database contains datasets covering a wide range of economic activities, including agri-food activities (Weidema et al., 2013). Similarly, the AgriFootprint database hosts agri-food specific data sets related to food and feed products and their intermediaries (Blonk et al., 2023). Finally, the Global Feed LCA Institute (GFLI) database contains LCI data sets characterizing feed ingredients, or groups of ingredients, for use in LCA studies of livestock production systems (GFLI, 2020). All three of these databases provide datasets at varying degrees of spatial resolution, from regional to global.

In each of these databases, only datasets available as unit processes were considered. System processes – a type of aggregate dataset that only includes an inventory of associated elementary flows – are commonly found in LCI databases and were not considered since no individual data points can be sourced from such datasets to characterize the material or energy use in the systems being modelled. Moreover, system processes preclude modifying datasets to better represent the characteristics of the system being modelled and do not allow for any granularity in the assessment of contributing sources to GHG emissions from different parts of the system.

A search of peer-reviewed literature was next undertaken to identify potential data sources with higher quality data compared to LCI databases. Initial searches were carried out in the Web of Science (WoS) database. Three groups of keywords were defined for the search:

1. Type of study: This set of keywords helped in identifying LCA or carbon footprinting literature. Keywords used were “life cycle assessment”, “LCA”, “life cycle analysis”, and “carbon footprint”.
2. Country considered: Keywords used were “Canad*”, “USA”, “United States”, and “Brazil*”.
3. Beef/feed production: Keywords used were “beef” and all major inputs to feed identified (such as barley, corn, soy, hay, etc.)

While several keywords can be used together in an “All fields” search in Web of Science, preliminary trials showed that using complex search queries returned an unmanageable number (often above 10,000) of largely irrelevant results. As a result, multiple searches were undertaken with simpler queries consisting of as few keywords as possible. For example, to identify beef LCA studies in Canada, the search query “life cycle assessment” AND “beef” AND “Canad*” was first used. Then the search was repeated with the keywords “LCA”, “life cycle analysis”, and “carbon footprint” replacing the keyword “life cycle assessment” in each subsequent query.

Some boundaries were applied to this search of peer reviewed literature to ensure efforts were focussed on identifying best available data sources. A temporal boundary of 2010 was applied (studies before this year were not considered) as any data sourced from studies more than 15 years old are likely to have very poor data quality in terms of temporal correlation (see section 2.3). Also, any studies that were based on experimental conditions were excluded. These studies will likely not include data on the entire life cycle as required for this study and will moreover have very poor data quality in terms of geographical correlation and representativeness (see section 2.3). Review papers were only considered for identifying potential sources of data. Conference proceedings, commentary articles, and letters and responses to articles were not considered. The titles and abstracts from the search results were initially screened to determine if the papers were reporting an LCA or carbon footprint analysis of beef production or feed crop production in one of the countries considered.

In addition to the search of literature using the Web of Science database, a secondary search was done using Google Scholar. This was necessary since research has shown that relevant literature can be missed if only one search engine/database is used in a systematic review (Haddaway et al., 2015). The same search parameters used in WoS were employed in Google Scholar. The same process for title and abstract screening and shortlisting for data extraction described above was employed for the search results. The title and abstract screening in Google Scholar was limited to the first 200 results as recommended by Haddaway et al. (2015), since the relevance of the results beyond this point is often questionable. The sources identified were compared against those from Web of Science to remove any duplicates.

Finally, grey literature from government and industry sources were considered as potential sources of high-quality data. These sources were primarily identified through internet searches (using Google) and browsing websites related to each country's major statistical databases, government departments and industry associations. Grey literature sources were primarily considered from Statistics Canada, Agriculture and Agri-food Canada (AAFC), the United States Census Bureau, the United States Department of Agriculture (USDA), the National Agricultural Statistics Service (NASS), the Brazilian Institute of Geography and Statistics (IBGE), and the Brazilian Agricultural Research Corporation (Embrapa). These sources were searched for data related to cattle numbers and herd characterization information, timelines with respect to weaning and time spent in feedlots, grazing patterns, pasture characteristics, pasture management, and composition of supplemental feeds and grain-based diets in feedlots. Similarly, for all major feed crops to be modeled, these sources were search for data related to production volumes and yields, land use, field activities and management practices, irrigation, and inputs of fertilizers and crop protection products. Additional searches of industry organization websites for relevant data and reports included those of the Canadian Roundtable for Sustainable Beef (CRSB), Canadian Roundtable for Sustainable Crops (CRSC), Canada Beef, Canada Cattle Association, Beef Cattle Research Council, the National Cattleman's Beef

Association, United States Cattlemen's Association, and the US Roundtable for Sustainable Beef.

While data for this study was extracted from multiple sources, it is important to note potential methodological inconsistencies between different sources due to varying reporting guidelines, modelling protocols, and submission criteria (Turner et al., 2020). Hence, all data selected for use was extracted and remodelled where necessary using consistent methods to ensure comparability of results.

2.3 Data quality assessment

Once potential data sources were identified, each data point was assessed for data quality using established LCI data quality screening methods. Data quality indicators were defined according to the pedigree matrix from Ciroth et al. (2016) (which is presented in Table 1). The pedigree matrix provides a semi-quantitative method for assessing the quality of individual data points relative to the overall data quality goals of the analysis being performed. The indicators used for data quality assessment were reliability, completeness (representativeness), temporal correlation, geographical correlation, and technological correlation. For each of these indicators, the pedigree matrix provides a 1-5 scale with 1 representing the highest quality of data (lowest uncertainty) and 5 the lowest quality of data (highest uncertainty). For each score in the pedigree matrix, an uncertainty factor is defined in Ciroth et al. (2016), which is provided in Table 2 below. When this uncertainty factor is combined with the base uncertainty factor for each data point (measured as the geometric standard deviation) as per equation 1 in Ciroth et al. (2016), an overall estimate of the uncertainty distribution for the data point is obtained. The use of a pedigree matrix for assessing data quality allows for assessment of parameter uncertainty, an important contributor to uncertainty in LCA and carbon footprint studies (Bamber et al., 2019).

In order to best reflect study-specific goals, modifications were made to the score descriptors for the pedigree matrix where required. These specific modifications are detailed below.

Table 1: Default pedigree matrix for assessing data quality (Ciroth et al., 2016)

Reliability	**Completeness**	**Temporal correlation**	**Geographical correlation**	**Further technological correlation**	**Quality Score**
Verified data based on measurements	Representative data from all sites relevant for the market considered, over and adequate period to even out normal fluctuations	Less than 3 years of difference to the time period of the data set	Data from area under study	Data from enterprises, processes and materials under study	1
Verified data partly based on assumptions or non-verified data based on measurements	Representative data from > 50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Less than 6 years of difference to the time period of the data set	Average data from larger area in which the area under study is included	Data from processes and materials under study (i.e. identical technology) but from different enterprises	2
Non-verified data partly based on qualified estimates	Representative data from only some sites (<< 50%) relevant for the market considered or > 50% of sites but from shorter periods	Less than 10 years of difference to the time period of the data set	Data from area with similar production conditions	Data from processes and materials under study but from different technology	3
Qualified estimate (e.g. by industrial expert)	Representative data from only one site relevant for the market considered or some sites but from shorter periods	Less than 15 years of difference to the time period of the data set	Data from area with slightly similar production conditions	Data on related processes or materials	4
Non-qualified estimates	Representativeness unknown or data from a small number of sites and from shorter periods	Age of data unknown or more than 15 years of difference to the time period of the data set	Data from unknown or distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia)	Data on related processes on laboratory scale or from different technology	5

Table 2: Default pedigree matrix uncertainty factors (Ciroth et al., 2016)

Score	Reliability	Completeness	Temporal Correlation	Geographical Correlation	Technological Correlation
1	1	1	1	1	1
2	1.05	1.02	1.02	1.01	1.05
3	1.1	1.05	1.1	1.02	1.2
4	1.2	1.1	1.2	1.05	1.5
5	1.5	1.2	1.5	1.1	2

First, the definitions for each data quality score under temporal correlation were altered to better represent the potential for inter-annual variability in cattle numbers and data related to characterizing the herd (calving rate, replacement rate, mortality rate). The standard pedigree matrix currently assigns the highest data quality score for temporal correlation if the data is less than 3 years old compared to the time period in which the study is carried out, with the data quality scores decreasing as the data gets older. However, this assumption that representativeness is a function of discreet moments in time is not always accurate. For example, inter-annual variability can be observed from data published in national statistical databases such as NASS and published literature with respect to calving rates, replacement rate of cows in the cow-calf herd, pasture stocking density, and average weight gain (NASS, 2024). To take into account the potential for such variability, the alternate definitions for temporal correlation specified in Table 3 were used in assessing data quality with respect to cattle numbers and herd characterisation data. These alternate definitions for temporal correlation are the same as the definitions developed to assess field crop yield data in (Bamber et al., 2023).These modified definitions are also used in the data quality assessment of yields for all of the crop inputs modelled in the current study.

Table 3: Alternative pedigree matrix definitions for assessment of the quality of herd characterization and yield estimates used in the current analysis.

Temporal correlation – Score definition	Data quality score

5+ year average with last year less than three years prior	1
3 year average with last year less than three years prior OR 5+ year average with last year 3-6 years prior	2
3 year average with last year 3-6 years prior OR 5+ year average more than 6 years prior	3
1 year value less than 6 years prior OR 3+ year average more than 6 years prior	4
1 year value more than 6 years prior	5

As a result of this change in the definitions for temporal correlation data quality, modifications were also made to the completeness score definitions. The default pedigree matrix includes factors associated with time period from which data was collected in its definition of completeness. For example, a completeness score of 1 requires that data from all relevant sites to the market considered are collected over an adequate period to even out fluctuations. Given that variations over time is a temporal factor that has been taken into account in the modified definitions of temporal correlation for those data points subject to influence from such variability, it is removed from the definitions for completeness. The modified definitions for each score under completeness are provided in Table 4 below. Additionally, the definition for a completeness score of 4 was expanded to include data derived from recommendations (i.e., from crop-growing manuals, etc.). Recommendations were assigned a score of 4 because they are not explicitly representative of any of the supply; however, it was assumed that recommendations are based on relevant metrics that inform practices performed by farmers. The GIFS field crops carbon footprint study assigned a completeness score of 3 (the average score) for datasets that did not report representativeness based on the fact that absence of information regarding representativeness of data would likely be the norm (Turner et al., 2020). However, this change is not adopted in this study since it has the potential to underestimate the uncertainty associated with some datasets. As a result, absence of information to enable assessing representativeness of a data point resulted in that data point being assigned a score of 5, as in the default pedigree matrix.

Table 4: Alternative pedigree matrix definitions for assessment of completeness in terms of percentage of supply covered

Completeness – Score definition	**Data quality score**
Representative data from all sites relevant for the market considered	1
Representative data from > 50% of the sites relevant for the market considered	2
Representative data from several sites (<< 50%) relevant for the market considered	3
Representative data from only a small number of sites relevant for the market considered or data derived from recommended practices (i.e., crop growing manuals, etc.)	4
Representativeness unknown or data from a single site	5

The definitions in the pedigree matrix with respect to reliability were also modified in line with those specified in the GIFS field crops study (Bamber et al., 2023). The default pedigree matrix (Ciroth et al., 2016) assigns the highest quality score for reliability to verified data based on measurements and the lowest quality scores to non-verified estimates of data. However, within the context of a carbon footprint study that compares beef production systems representative of large geographical regions (with multiple enterprises operating within that region), verified measurements of farm inputs and outputs should be assigned the highest score for reliability only if the data is based on sufficiently large sample sizes to make it representative of the region or nation. This is not often the case with respect to data such as average daily weight gain (which is not linear across the entire time a calf spends on pasture or in a feedlot) or enteric methane emissions in beef cattle herds. Similarly, when modelling crop production for feed inputs, field-level emissions such as nitrogenous emissions or phosphorus run off associated with fertilizer application are rarely measured at the farm-level. Rather, modeling on a large scale will typically be better supported by use of well defined mathematical models (Yeluripati et al., 2015) that can best represent average emissions over time and space at a given level of resolution (for example, for enteric methane emissions or field-level nitrogenous emissions). Similarly, input data such as average daily weight gain are often extrapolated from weight of calves measured at the beginning and end of the cow-calf or feedlot stage.

A wide range of models may be used to estimate field-level nitrogenous emissions or enteric methane emissions. These models vary in their data requirements, modelling complexity (empirical vs. process-based models), and geographical coverage. For example, the IPCC methods for estimating GHG emissions are widely used. They include either Tier I methods using default emission factors to characterize emissions generically, or Tier II methods that use regionalized emission factors to characterize emissions at the national or sub-national scale. Methods such as the IPCC models are widely accepted, as evidenced by their use in the National Inventory Reports (NIR) of each country included in this analysis (ECCC, 2023; EPA, 2023; MCTI, 2020).

In line with international best practices in estimating carbon footprints, emissions data generating using nationally resolved models such as the IPCC Tier 2 methods were given a reliability score of 1. Generically modeled emissions (such as those calculated with IPCC Tier 1 methods) were given a reliability score of 2. In all cases, reliability scores may be further decreased if the model inputs included in the data set themselves receive lower reliability scores. Finally, measured input and emissions data from a single or a small number of field sites (i.e., <10) were given a score of 4 for reliability, as these measures are not fit for use at the national scale. The modified pedigree matrix scores for reliability are specified in Table 5.

Table 5: Alternative pedigree matrix definitions for assessment of reliability.

Reliability – Score definition	**Score**
Verified data based on measurements from a large number of sites, such as survey data OR	1

nationally-resolved emissions models, such as IPCC Tier 2	
Verified data partly based on assumptions or non-verified data based on measurements OR generic emissions models, such as IPCC Tier 1	2
Non-verified data partly based on qualified estimates	3
Qualified estimate (e.g. by industrial expert) OR measured inputs and emissions from a single or small number of field or experimental sites (i.e., <10)	4
Non-qualified estimates	5

The definition of geographical correlation score 1 was also modified to better align with the nature of this study (Table 6). Since this is a national-level carbon footprint study, the search of data sources was likely to produce data relevant to regions within a country, such as particular states in the USA or provinces in Western Canada. If the standard definitions for geographical correlation are used within the context of this study, such regional data would only be given a score of 3 since they are not representative of the entire region being modelled (Western Canada or USA). This assumes an equal distribution of agricultural activities within each country, which is often not the case. Based on this, the geographical representativeness score of 1 was assigned to data representing smaller regions within the larger region being modelled if they were considered a major producing region for the product considered. Importantly, however, the percentage of supply covered was still considered in assessing completeness, meaning that although data sets may receive higher scores for geographical correlation, they are still scored accordingly based on the percentage of overall supply covered (Table 6).

Table 6: Alternative pedigree matrix definitions for assessment of geographical correlation.

Geographical correlation – Score definition	**Score**
Data from area under study or data from major producing region within area of study.	1
Average data from larger area in which the area under study is included	2

Data from area with similar production conditions	3
Data from area with slightly similar production conditions	4
Data from unknown or distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia)	5

In some cases, additional interpretations of the data quality definitions were needed since the definitions in the pedigree matrix (even after modifications) were not easily applicable to all data points. For example, data sourced from peer reviewed literature or LCI databases were considered to be verified data and were assigned reliability scores of 1 or 2. In cases where older data was extrapolated forward (as often seen in LCI databases), temporal correlation was assessed in accordance with the final year of the original data set date range, plus an additional credit to represent the modifications made to the data set. A data set originally representative of the time period 2000-2005 extrapolated to 2021 would therefore be given a temporal correlation score of 4 rather than 5. Finally, it is also important to note that all of the changes to the pedigree matrix described above are only specific to the definitions of each score. The contributions to data quality uncertainty associated with each data quality score in each category have not been altered from those presented in Table 2 from Ciroth et al. (2016).

2.4 Choice of best fit data for beef production and feed crops

To determine which of the available data points to use in the carbon footprint modelling, a set of inventory categories were defined for the beef production systems. These inventory categories are based on their inclusion in datasets assessed in this report and the expertise of the authors. The inventory categories and the data points associated with each category are listed in Table 7.

Table 7: Inventory categories and associated data points for beef production systems.

Category	**Data points**
Cattle numbers (cow-calf stage)	Number of cows, heifers, and bulls; calving rate; replacement rate; mortality rate.
Cattle numbers (finishing stage)	Number of calves placed; mortality rate.

Cattle performance (separately for cow-calf and finishing stages)	Starting weight, finishing weight, average daily weight gain, and average daily feed consumption, average daily water intake.
Pasture characteristics (cow-calf stage and grass-finishing in Brazil)	Average pasture mix, conversion of other land use types to pasture (if any), pasture utilization rate, fertilizer, irrigation, and crop inputs (if managed pasture is modelled), pasture management practices used.
Feed composition	% share of forage, harvested forage (hay and silage), grain feed inputs, minerals and salts, distiller grains.
Other material and energy inputs	Electricity, natural gas, diesel, gasoline, bedding material
Transportation	Transportation between cow-calf and finishing stages
Enteric methane	Gross energy intake, methane conversion factor
Manure-related emissions	Methane, nitrous oxide, ammonia, nitrate, and NOx emissions associated with manure on pasture and manure storage and application.
Soil carbon	Changes in soil organic carbon from land use change or land management practices

Inventory categories for all feed crops to be modelled were adopted from the GIFS field crops carbon footprint study (Bamber et al., 2023). These categories are:

- Yield
- Seed inputs
- Nutrient inputs including lime, manure, N fertilizers, P fertilizers, K fertilizers, and S fertilizers
- Pesticide inputs including herbicides, fungicides, and insecticides
- Irrigation
- Energy use for field activities
- Transportation
- Post-harvest energy use

- Field level fluxes including direct and indirect N_2O emissions from N inputs, as well as ammonia, nitrate, NOx emissions, CO_2 emissions from lime and urea, and soil carbon changes from land use or land management changes

The total uncertainty associated with each of these data points from each potential source was calculated, taking into account the pedigree matrix score for each data point and associated uncertainty contribution (Tables 1 and 2). According to Ciroth et al. (2016), total uncertainty may be calculated using the equation

$$U_T = exp\left(\sqrt{(lnU_b)^2 + \sum_i (lnU_i)^2}\right)$$

where U_t represents total uncertainty, U_b represents basic uncertainty, and U_i represents the additional uncertainty factors from the pedigree matrix. U_t represents the total geometric standard deviation of the uncertainty distribution of each piece of inventory data, from which Monte Carlo samples would be drawn during uncertainty propagation (Bamber et al., 2019). U_b represents the contribution to total geometric standard deviation that may be derived from the range of collected measurements for a specific data point, such as those collected from a sample of farmers (Turner et al., 2022). U_t therefore represents the contribution to total uncertainty derived from the pedigree matrix entries associated with each data point (Ciroth et al. 2016). Since the raw data used in the calculation of each data point in each source was not available, U_b was assumed to be equal to a base value of 1 for all data points. As a result of this assumption, the U_b term drops out of the total uncertainty calculation because $\ln(1) = 0$. Each value for U_t is therefore representative of contributions to uncertainty related only to the pedigree matrix entries for each data point. Using this method, all calculated uncertainty values were within the boundaries of $1.00 \leq U_t \leq 2.52$, as these values represent the minimum and maximum values of equation 1 (i.e. representing pedigree matrix entries of all ones and all fives, respectively).

Once uncertainty values were calculated for each data point from each identified data source, the calculated uncertainty values for data points representing the same inputs for each beef production system modelled and feed crop production system modelled were compared to identify the data point/source which is of the highest quality (i.e., that will introduce the least amount of uncertainty into the final results).

For the choice of data representing fertilizer and pesticide inputs, two options were possible for use as a data source: the combination of nutrient or total pesticide inputs with the distribution of types of fertilizers or pesticides applied, or the use of data characterizing the amounts of specific fertilizer and pesticide types. Similarly, data on energy use related to field or post-harvest activities may be characterized by the total energy use, or the combination of energy use per activity and activity data (i.e., number of passes, etc.). With respect to fertilizer and pesticide inputs, the data chosen was that which had the lowest overall uncertainty score (i.e., highest overall data quality). For fertilizer inputs, however, highest quality data available for both the total amount of nutrients applied and the types of fertilizers were used to ensure better accuracy and level of resolution in the models.

For field-level emissions and soil carbon changes, the available data points were also compared against a potential scenario of using the best available input data in conjunction with the best practices for emissions modeling. For this study, IPCC Tier 2 methods for modeling direct and indirect N_2O emissions, IPCC Tier 1 methods for modeling CO_2 emissions from lime and urea, and IPCC Tier 2 methods using the data available in the each country's NIR for soil carbon changes were considered to be best practices (IPCC, 2019). These methods are in line with those applied for calculation of GHG inventories in each country's NIR, and are internationally recognized (IPCC, 2019). This choice is also in line with the guidelines for assessment of environmental performance of animal feed supply chains provided by the United Nations Food and Agriculture Organisation Livestock Environmental Assessment and Performance (UN FAO LEAP) Partnership (FAO, 2016a). Where Tier 2 methods are unavailable, Tier 1 methods are used.

In instances of equivalent uncertainty scores for specific data points, data points coming from data sets from which other data points were already sourced were preferentially selected based on the higher likelihood of methodological consistency in the generation of the data points. Such instances were flagged as loci for potential sensitivity analyses.

2.5 Carbon footprint methodology

The carbon footprint analysis undertaken here is based primarily on the ISO 14044 standard for Life Cycle Assessment and the ISO 14067 standard for carbon footprinting. In addition, the LEAP guidelines for modelling environmental performance of large ruminant supply chains (FAO, 2016b) were also consulted to ensure context-specific methodological choices are given adequate consideration and industry-relevant best practices are implemented.

2.5.1 Intended applications, audience, and practitioners

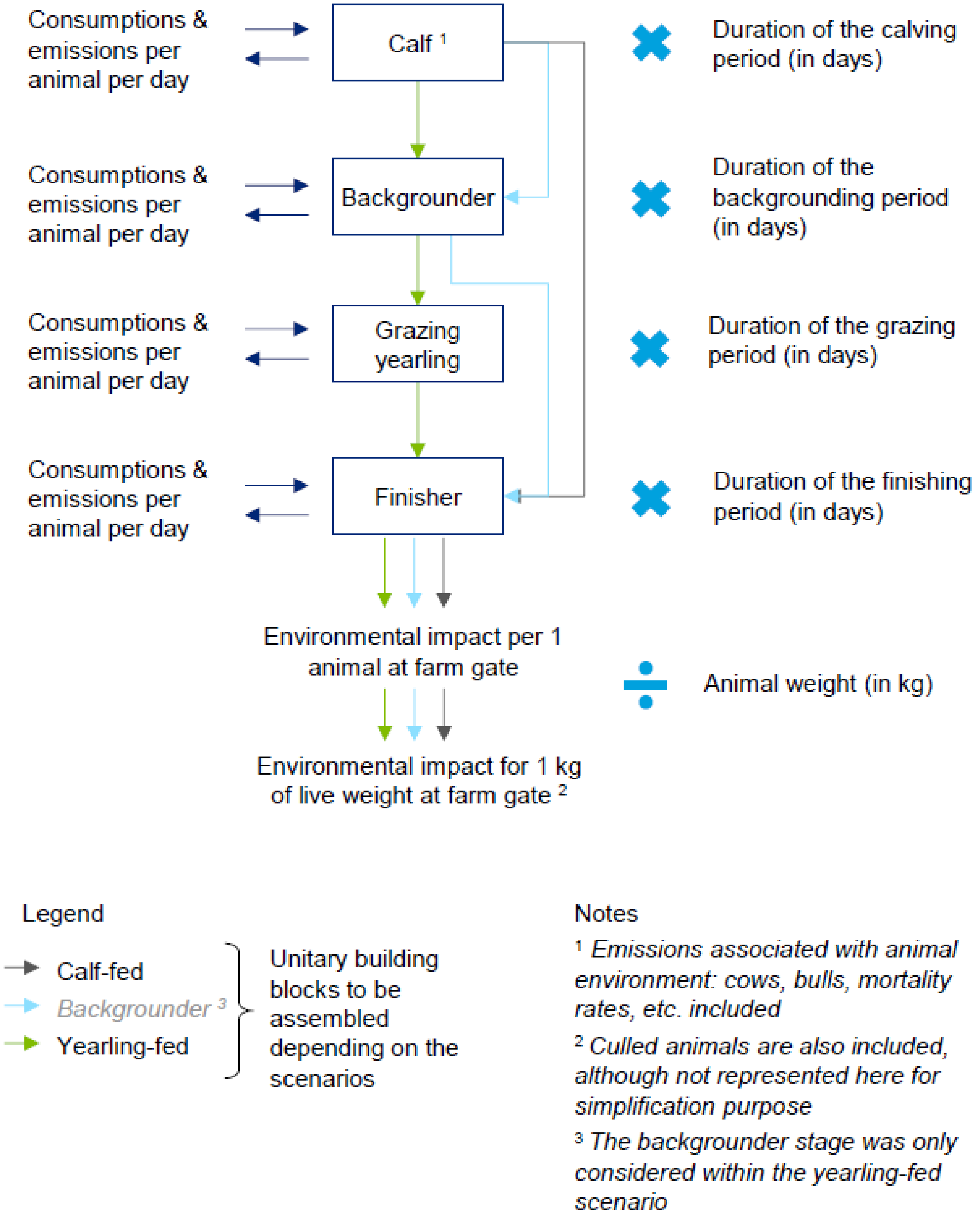
The intended audience of this study includes a number of governmental and industry stakeholders both within Canada, and internationally. These stakeholders include GIFS, the Government of Saskatchewan, as well as relevant representatives of the various countries to which comparisons are made in this report, farmers, traders, retailers, and other interested parties. The results of this study are intended to be used to draw meaningful comparisons between the relative carbon footprints of beef produced within Western Canada, and a subset of countries representing major competitors in international markets. These results may also be used to identify potential hotspots within the beef supply chains modelled that may serve as priority targets for future GHG mitigation efforts.

2.5.2 Functional unit and reference units

The functional unit used to report the beef production carbon footprints in this study was one kilogram of live weight of cattle intended for slaughter. This choice is in line with the functional units used across several beef carbon footprint and life cycle assessments that were reviewed in this study (CRSB, 2023; Rotz et al., 2019). The reference unit used in building the inventories for the beef production systems was one animal unit. However, results per animal unit finished (reported in Table 59) are not used in isolation for direct comparison between regions modelled due to differences in finishing weights. The results are also presented relative to one kilogram of carcass weight and bone free meat in order to account for potential yield differences between beef cattle breeds used in different regions. The reference unit for all feed inputs modelled was 1 kg of grain or forage produced.

2.5.3 Basic framework of inventory characterization and impact assessment

Across the three countries, the beef production systems modelled included one or more of the following phases: cow-calf operations, backgrounding, and finishing. The characteristics of each of these phases modelled in each country varied based on the systems described in section 2.1. For example, the backgrounding phase in Western Canada has both a backgrounding stage and a yearling grazing stage. The finishing phases were feedlot finishing in Western Canada and USA, while Brazil had a forage-based finishing phase. Irrespective of the system modelled, the characterization of the inventory was based on modelling a single calf – which is considered a representative animal unit – across the different phases. Within this representative animal unit, other cattle (cows, bulls, heifers for replacement) were also included as inputs. For all of the types of cattle included in this representative animal model, their material and energy inputs and emissions (differentiated by each phase) were modelled on a single animal-day basis. These were then multiplied by the number of days spent in each phase to obtain a carbon footprint estimate per representative animal unit, which was converted into a carbon footprint estimate per kilogram or tonne of live weight for characterizing the impacts. Due to differences observed in dressing percentages between *Bos taurus* (Western Canada and USA), *Bos indicus* (Brazil), and cross-breed (Brazil) cattle, impacts were also characterised per kilogram of carcass weight. This modelling framework is based on the approach detailed in the Canadian National Beef Sustainability Assessment (CRSB 2023). A representation of this framework for the Western Canadian beef production system is provided in the Figure 1.



Notes

[1] *Emissions associated with animal environment: cows, bulls, mortality rates, etc. included*

[2] *Culled animals are also included, although not represented here for simplification purpose*

[3] *The backgrounder stage was only considered within the yearling-fed scenario*

Figure 1: An example of the modelling framework used, as defined for the Western Canadian beef production system (CRSB 2023)

2.5.4 System boundaries

The system boundaries for this analysis included all relevant material, energy, and emissions flows associated with the beef production systems in each country considered. This includes all of the feed (forage and grain) intake in the cow-calf, backgrounding, and finishing phases, management of manure and associated emissions across the three phases, enteric methane emissions, housing-related energy inputs, and transportation of cattle between phases. For pastures used for grazing, harvested forage and crop production, farm-level inputs of fertilizers, plant protection products, seed, and energy for irrigation, field activities, and post-harvest activities (i.e., product drying) were all included. All on-farm activities related to both beef and feed input production were considered as foreground processes, while all processes occurring upstream of the farm were considered as background processes. Transportation of material inputs to the field in feed production were also included. The geographical, temporal and technological boundaries were intended to be as representative of actual contemporary production conditions in Western Canada, USA, and Brazil as possible. The analysis adopts a cradle-to-farm gate approach, with the supply chain beyond the finishing stage of the beef cattle (such as slaughtering, processing, and distribution phases) not considered. Of particular relevance is that results that are reported relative to one kilogram of carcass weight does not include the impacts of slaughtering (data for the slaughtering phase are often difficult to obtain and there are unlikely to be major differences related to slaughtering due to the similar efficiencies of large-scale industrial processes across countries).

2.5.5 Cut-off criteria and exclusions

Yields from pasture foraged by the cattle were not included since data on this is not often reported in LCAs or carbon footprint studies. Instead, pastures were assumed to meet the feed requirements of the cattle when on pasture (supplemental grain feed and harvested forage were modelled separately and included in the ratio identified for each system), and the total amount of biomass consumed was instead calculated based on the average daily feed intake.

Across all beef and crop production systems modelled, material inputs and associated GHG emissions attributable to production and maintenance of infrastructure (such as buildings or farm machinery) were excluded as they generally make small contributions (i.e., <5%) to life cycle GHG emissions compared to combustion of fuel during use (Biswas et al., 2008; Bortolini et al., 2014; Meisterling et al., 2009). These impacts decrease further when amortized against total production and all emission sources over the lifespan of the infrastructure (Ghamkhar et al., 2022), which may be up to 30 years for some machinery (Lips, 2017).

With respect to feed inputs, any ingredients contributing less than 0.1% of the total feed composition were excluded due to their relatively trivial contribution to the overall carbon footprint. Across countries, impacts associated with the production and administration of growth supplements and medicines (such as antibiotics) were excluded due to the complexity of modelling these inputs and the inability to obtain proprietary data to model their production.

Field level emissions of methane from the application of manure to agricultural soils was also excluded since these are negligible and its calculation is not supported by the IPCC methods (IPCC, 2019). In pastures, manure produced by the cattle are deposited directly onto pastures, with synthetic fertilizer inputs modelled only if specified as being applied in addition to manure deposition in the data sources used. The emissions associated with such direct deposition of manure onto pastures are modelled directly as nutrient inputs. However, inputs of manure collected from feedlots and applied to crop production was not included due to the lack of high-quality data regarding amounts of manure applied and the composition of the manure applied (cattle manure is often mixed with pig and poultry manure when applied to agricultural lands). Instead, nutrient deposition and emissions from the manure that is collected and applied to crops are modelled indirectly. A synthetic fertilizer credit equivalent to the nitrogen amounts contained in the manure after storage and application losses was applied. The synthetic fertilizer credit applied was based on the most commonly used N fertilizer in each country considered. Emissions associated with storage of manure before application to cropland was modelled as described in section 2.5.9.4.

2.5.6 Allocation methods

2.5.6.1 Beef production systems

Since no co-products are considered alongside beef produced, and beef from culled dairy cows are not considered, no allocation procedures were required in the beef production systems.

Similarly, since the manure produced by the beef cattle are considered as inputs to crop production, which in turn produces the feed used in beef production, no allocation procedures were required for manure.

2.5.6.2 Wheat grain and straw

Wheat cultivation results in two co-products – wheat grain and wheat straw. While canola (Iqbal et al., 2016; Karan and Hamelin, 2021; MacWilliam et al., 2014; Rothardt et al., 2021; Umbers and Watson, 2021; Vinzent et al., 2017; Wang et al., 2020) and leguminous crop residues (Bahl and Pasricha, 2000; Marschner et al., 2004; Walley et al., 2007; Wang and Sainju, 2014) are commonly left on fields and/or incorporated into soils, a portion of wheat straw is often harvested and removed from fields to be used in other processes. Therefore, wheat grain and straw are considered to be co-products of wheat (non-durum) production systems. The ISO 14044 standard specifies a hierarchy of options for dealing with processes that produce multiple co-products. First, it is recommended that allocation be avoided by taking a system expansion approach. If such an approach is infeasible and allocation is unavoidable, ISO guidelines dictate that impacts should be allocated between co-products first according to an underlying biophysical relationship between co-products, and, if not possible, according to some other relationship such as relative economic value (ISO, 2006c).

The first step in developing allocation factors for wheat grain and straw was determining the proportion of straw that is removed from agricultural fields – that is, the proportion of above-ground crop residues that is a co-product. Significant difficulty was encountered in finding high-quality, crop specific information detailing amounts of wheat residues baled and removed from fields, with available literature estimates ranging from 15% - 85% of residues removed from an unknown proportion of total production. Given these difficulties, a standardized wheat straw removal rate was applied to Western Canadian and US wheat (there were no wheat inputs for Brazilian beef production) representing 8.3% of non-durum wheat residues removed from field.

Following the identification of the amounts of straw co-produced with grain, it was necessary to choose an allocation method for partitioning impacts between co-products. In line with the GIFS field crops study (Bamber et al., 2023), mass allocation was used with an allocation factor of 95% for wheat grain and 5% for wheat straw applied to wheat production in both USA and Western Canada. This choice was not subject to a sensitivity analysis due to the minimal expected differences in estimated GHG emissions when using a mass- or energy-based allocation approach (Bamber et al., 2023). These allocation factors were not applied for the production of wheat silage that is used in Western Canada beef diets, since the entire crop is harvested for silage production.

2.5.7 Foreground data collection

A large number of potential data sources were identified for modelling both the beef and the feed crop production systems. These sources included complete data sets from LCI databases, as well as individual data points from peer-reviewed literature, and government and industry group publications and statistics. Overall, the identified sources include the majority of all foreground data required for modeling the foreground systems considered in this analysis. The following sections present the best identified data source for modeling each country's beef and feed production processes and associated data quality scores. Complete lists of all sources consulted and their associated data quality scores were provided as separate Excel files as part of deliverable 1 of this project.

2.5.7.1 Western Canada beef production

Data sources for characterizing Western Canadian beef production were generally of very high quality. Data on number of cows, bulls, heifers, and % of calves backgrounded were all obtained from Statistics Canada (Tables 32-10-0130-01 and 32-10-0370-01). Replacement rate and calving rates are calculated as multi-year averages from these cattle numbers and are considered to constitute high quality data. Similarly, data on pasture composition and pasture management practices (e.g. irrigation) were also obtained from Statistics Canada (StatsCan, 2021). Pasture utilization rates and stocking densities were obtained from (Bork et al., 2021) and (Bao et al., 2019) respectively, with both studies reporting the results of farm surveys in the Prairies. All other data to characterize Western Canadian beef production was obtained from the Canadian Roundtable for Sustainable Beef's (CRSB) National Beef Sustainability Assessments (NBSA) from 2016 (CRSB, 2016) and 2023 (CRSB, 2023). The CRSB reports specify that mortality rates were calculated based on a cost of production network survey from 2021 and is considered to have a completeness score of 3 since it is based on less than 50% of the industry. Also, since this data point is based on single year data and, given the potential for inter-annual variability (as discussed in section 2.3), a temporal correlation score of 4 is assigned. Data on number of days spent on pasture obtained from the CRSB reports were based on NBSA surveys for 2014 and 2021. Data on starting and finishing weight and average daily feed consumption were based on expert opinion (i.e. informed by widely accepted models for feed energy intake – (NRC, 2001)) and correlated by personal communications with industry personnel (CRSB, 2024). They hence have average data quality scores for reliability, completeness, and temporal correlation. Feed composition data in the 2023 CRSB report was based on 2014 data adjusted forward in time to 2021 and hence is assigned a temporal correlation score of 2. On farm energy use and transportation data are from 2014 and hence have a temporal correlation score of 3. For all data sourced from the CRSB reports, a completeness score of 3 is given. While the reports do not specify the representativeness of the data, data on number of farms that took part in the survey is provided for each province. Using the number of farms that participated in the NBSA surveys and data on average farm herd sizes from Statistics Canada, a proxy value for representation was obtained for the CRSB data to assign scores for completeness. Enteric methane emissions and emissions from manure management were calculated based on IPCC Tier 2 methods (IPCC, 2019) as applied in the Canadian NIR (ECCC, 2023) submitted to UNFCCC. Soil carbon changes related to pasture is taken directly from the Canadian NIR, which uses the IPCC Tier 1 methods for grassland remaining grassland (Tier 1 is used since no significant conversion of other land use types to grassland is reported in Canada and data on management practices such as tillage and pasture revitalization in existing pastureland is non-existent). Table 8 below provides the data sources and associated data quality scores with respect to each data category. The inventory data extracted from these sources are provided in section 3.3.1.

Table 8: Data sources to model Western Canadian beef production, and their associated pedigree matrix scores

Data point	**Source**	**R***	**C***	**Temp.***	**G***	**Tech.***
Cattle numbers (cow-calf stage)	(StatsCan, 2024)	1	2	1	1	1

Cattle numbers (finishing stage)	(StatsCan, 2024)	1	2	1	1	1
Dressing percentage	(StatsCan, 2024)	1	2	1	1	1
Mortality rate	(CRSB, 2023)	1	3	4	1	1
Calving and replacement rates	Statistics Canada	1	2	1	1	1
Cattle performance (separately for cow-calf and finishing stages)	(CRSB, 2023)	3	3	3	1	1
Pasture type, pasture management practices	(StatsCan, 2024)	1	2	1	1	1
Stocking rate	Bao et al. (2019)	1	3	1	1	1
Pasture utilization rate	Bork et al. (2021)	1	3	1	1	1
Feed composition	(CRSB, 2023)	1	3	2	1	1
Other material and energy inputs	(CRSB, 2023)	1	3	3	1	1
Transportation	(CRSB, 2023)	1	3	3	1	1
Enteric methane	IPCC Tier 2 methods	1	3	1	1	1
Manure-related emissions	IPCC Tier 2 methods	1	3	1	1	1
Soil carbon (for pasture)	NIR – based on IPCC Tier 1 methods	2	1	1	1	1

**R: Reliability; C: Completeness; Temp: Temporal correlation; G: Geographical correlation; Tech: Technological correlation.*

2.5.7.2 United States beef production

Available data to characterize beef production systems in the US was generally of high quality. Data on cattle numbers are multi-year averages obtained through the National Agricultural Statistics Service (NASS) Quick Stats tool (NASS, 2024). Replacement rate, calving rate, and mortalities were all obtained from Rotz et al. (2019), which was based on analysis of NASS data for the years 2013-18. Rotz et al. (2019) was also used to obtain transportation data for calves transported from cow-calf to finishing operations. For all other inventory data points (except emissions), data was sourced from a series of surveys undertaken as part of the US Beef Sustainability Program (funded by the United States Department of Agriculture and the Cattlemen's Beef Board). These surveys (Asem-Hiablie et al., 2018, 2017, 2016, 2015) were undertaken between 2015 and 2018, with each survey covering one of four major beef producing regions in the US. Kansas, Oklahoma, and Texas were considered as one region (these three states account for ~26% of beef cattle in the US), with the other regions being Western USA, Eastern USA, and the Midwest and Northern Plains. The regions covered in these surveys represent ~93% of all beef cattle herds in the USA. This data was used to simulate US beef production in the Integrated Farm Simulation Model (IFSM) – which uses process-based models to simulate cattle growth and feed intake – in Rotz et al. (2019). The resulting average feed intake values are sourced for the current analysis. Data from these surveys were of generally high quality except for completeness and temporal correlation. Across the surveys, reported representativeness of the data ranged between 1-2% for cow-calf operations, and 4-33% for feedlot operations. As a result, these surveys were given a completeness score of 3. The surveys were also given a score of 3 for temporal correlation as per the default pedigree matrix since these data are more than 6 years old, but less than 10 year old. Production weighted averages are calculated from the survey data to estimate US-average numbers. Emissions from manure management were calculated based on IPCC Tier 1 approaches (since the US NIR used Tier 3 models and does not provide country specific emission factors) and soil carbon changes associated with pasture were obtained from the US NIR (EPA, 2023) submitted to UNFCCC. Table 9 below summarizes the data quality scores for the sources used to characterize US beef production. The inventory data extracted from these sources is reported in section 3.2.2.

Table 9: Data sources to model USA beef production, and their associated pedigree matrix scores

Data point	Source	R*	C*	Temp.*	G*	Tech.*
Cattle numbers (cow-calf stage)	(NASS, 2024)	1	2	1	1	1
Cattle numbers (finishing stage)	(NASS, 2024)	1	2	1	1	1
Dressing percentage	(NASS, 2024)	1	2	1	1	1
Mortality rate	Rotz et al. (2019)	1	2	2	1	1
Calving and replacement rates	Rotz et al. (2019)	1	2	2	1	1

Cattle performance (separately for cow-calf and finishing stages)	Rotz et al. (2019)	1	3	2	1	1
Pasture type, pasture management practices	Asem Hiablie et al. (2015, 2016, 2017, 2018)	1	3	3	1	1
Feed composition	Asem Hiablie et al. (2015, 2016, 2017, 2018)	1	3	3	1	1
Other material and energy inputs	Asem Hiablie et al. (2015, 2016, 2017, 2018)	1	3	3	1	1
Transportation	Rotz et al. (2019)	3	4	3	1	1
Enteric methane	IPCC Tier 2 methods	1	3	1	1	1
Manure-related emissions	IPCC Tier 1 methods	2	3	1	1	1
Soil carbon (for pasture)	NIR – based on IPCC Tier 3 and Tier 2 methods	1	1	1	1	1

**R: Reliability; C: Completeness; Temp: Temporal correlation; G: Geographical correlation; Tech: Technological correlation.*

2.5.7.3 Brazil beef production

Data sources used to compile the Brazilian beef production inventories were of relatively lower quality compared to the Western Canadian and US inventory data (Table 10). This was primarily due to the diversity of production characteristics and conditions in different regions of Brazil and the lack of publicly available data to characterize all of these regions to develop a nationally representative model. The highest quality data to characterize Brazilian beef production was sourced primarily from peer-reviewed LCA and carbon footprint studies focussed on the central-west regions of the country, particularly representative of Mato Grosso and Mato Grosso do Sul states (Cardoso et al., 2016; Florindo et al., 2017). These regions represent the largest beef producing regions of the country (ABIEC, 2022). However, specific data gaps were filled using the best-quality data available from sources representative of the Southern region (Dick et al., 2015; Kamali et al., 2016; Pereira et al., 2018; Ruviaro et al., 2015). Beef cattle in Brazil are mostly grown in pasture-based feeding systems with a low level of supplementation with minerals and grains (ABIEC, 2022). Based on Florindo et al. (2017), limestone, fertilizers and herbicides are utilized for land preparation, maintenance, and forage production. Dressing percentages reported for Nellore and Nellore x Angus cross breeds ranged between 50% (Carvalho et al., 2017) and 59% (Fuez et al., 2022). Hence, the dressing percentages reported in Barcellos et al. (2017) – 54% for pure breed Nellore and 55% for Nellore x Angus cattle – were used since it was approximately an average of the values reported across multiple studies. With respect to emissions, as per the Fourth National Communication of Brazil to the UNFCCC (MCTI, 2020), emissions from enteric fermentation and manure management were calculated based on a combination of Tier 2 and Tier 1 methods as used in the Brazilian NIR. In addition, direct and indirect emissions from soil management and emissions from land use and land use change, were obtained from the 4th National Communication – which were estimated based on IPCC Tier 2 methods.

Table 10: Data sources to model Brazilian beef production, and their associated pedigree matrix scores

Data point	**Source**	**R***	**C***	**Temp.***	**G***	**Tech.***
Cattle numbers (cow-calf to finishing phases)	Florindo et al. (2017)	2	3	3	1	1
Dressing percentage	Barcellos et al. (2017)	4	4	3	1	1
Calving rate	Kamali et al. (2016)	3	3	5	1	1
Mortality rate	Florindo et al. (2017)	2	3	3	1	1
Cattle performance	Florindo et al. (2017)	2	3	3	1	1
	Cardoso et al. (2015)	1	2	3	1	1
Pasture yield	Pereira et al. (2018)	1	4	3	1	1
Pasture utilization rate	Dick et al. (2014)	2	2	5	2	1
Time as pasture	Ruviaro et al. (2014)	2	4	3	1	1
Pasture management	Florindo et al. (2017)	2	3	3	1	1
Mineral and protein supplements	Florindo et al. (2017)	2	3	3	1	1
Energy consumption	Florindo et al. (2017)	2	5	5	3	1
Enteric methane	IPCC Tier 2 methods	1	3	1	1	1
Manure-related emissions	IPCC Tier 1 methods	2	3	1	1	1
Soil management emissions	4NC – based on IPCC Tier 1 and Tier 2 methods	2	1	1	1	1

Land use change emissions	4NC - based on IPCC Tier 1 and Tier 2 methods	2	1	1	1	1

**R: Reliability; C: Completeness; Temp: Temporal correlation; G: Geographical correlation; Tech: Technological correlation.*

2.5.7.4 Highest quality data available for feed crop inputs

The major inputs to average feed compositions for both the cow-calf and finishing stages in all of the three countries considered are provided in Table 11. Sections 3.2.1, 3.2.2, and 3.2.3 provide data sources and data quality scores for the inventory data points for the feed crop inputs modelled for Western Canada, USA, and Brazil. Identification of literature sources related to Western Canadian wheat production, Brazilian soy and US wheat production was unnecessary as this was already undertaken as part of the GIFS field crops study (Bamber et al., 2023) and no new literature sources were identified. However, the data quality assessment scores for these sources were verified and modified where necessary according to the goals of the current study (for example, the data quality scores for sources identified for Canadian wheat production was modified to reflect this study's requirements for Western Canadian wheat production data). All yield data collected across the different crops and regions was aggregated to a 5 year average between 2019 and 2023.

Table 11: Major feed ingredients to be modelled for Western Canada, USA, and Brazil

Western Canada		**USA**		**Brazil**	
Cow-calf	**Finishing (including backgrounding)**	**Cow-calf**	**Finishing**	**Cow-calf**	**Finishing**
Forage (pasture)	Harvested forage (barley silage)	Forage (pasture)	Grain (corn)	Forage (pasture)	Forage (pasture)
Harvested forage (Barley, corn, oats, and grass silage)	Grains (barley, corn, wheat, and oats)	Harvested forage (grass and corn silage)	Harvested forage (silage)	Grain supplement (soybean, corn)	Grain supplement (soybean, corn)
Harvested forage (hay)	Supplement (dried distiller grains)	Harvested forage (hay)	Harvested forage (hay)		

Grain supplements (barley, corn, oats)	Other (modelled as soybean meal)	Grain supplements (modelled as corn)	Dried distiller grains		
Minerals and salt pre-mix			Minerals		
			Other (modelled as wheat middlings and bakery waste)		

2.5.7.4.1 Western Canadian barley

Data to characterize barley production in Western Canada (excluding British Columbia) were primarily sourced from the 2022 Canadian Roundtable for Sustainable Crops (CRSC) report for barley ((S&T)2 Consultants, 2022a). To a large extent, this source provided data of high quality for barley production since it reports data at the RU level across Canada, allowing for creating an inventory dataset specific to Western Canada. Within this report, data on fertilizer inputs were sourced from provincial crop insurance surveys from multiple years and averaged. Though representativeness of fertilizer input data is not reported in the CRSC report, the crop insurance surveys in Saskatchewan and Manitoba have good coverage and hence a representativeness score of 3 is given. Data for pesticides had good quality for all indicators since estimates based on Alberta sales data from 2018 were used for Western Canada. The reliability and completeness scores were average or low for irrigation, fuel use for field activities, and post-harvest energy use since data from the Prairie Crop Energy Model or other provinces were used. Transportation distances for crop inputs was taken from the AgriFootprint database – which uses default values based on expert judgement. Transportation data is hence of low quality but this is unlikely to have a significant impact since transportation of crop inputs makes small contributions to GHG emissions of crop production, in general. Estimates of soil carbon changes are from the Canadian NIR (ECCC 2023), as reported in the CRSC report. These are calculated based on IPCC protocols but do not provide crop-specific estimates of soil carbon change, hence resulting in a score of 4 for technological correlation. Direct and indirect N_2O

emissions from the application of nitrogen fertilizers were estimated using IPCC Tier 2 protocols. Further details on the modelling of emissions are provided in section 3.5. Table 12 below provides the sources and data quality scores assigned for each data point to characterize Western Canadian barley production.

Table 12: Data sources to model Western Canadian barley production, and their associated pedigree matrix scores

Data point	**Source**	**R***	**C***	**Temp.***	**G***	**Tech.***
Yield	(StatsCan, 2024).	1	2	1	1	1
Seed	Saskatchewan Crop Planning guide	3	4	1	1	1
All nutrient inputs	CRSC report – Barley^	1	3	2	1	1
All pesticide inputs	CRSC report - Barley^	1	2	2	1	1
Irrigation energy	CRSC report - Barley^	3	3	2	1	1
Fuel use for field activities	CRSC report - Barley^	3	3	2	1	1
Transportation of field inputs	Blonk et al (2023)	4	4	4	1	2
Post-harvest energy use	CRSC report - Barley^	3	4	2	1	1
Direct and indirect N2O emissions	IPCC Tier II methods as specified in the Canadian NIR and reported in the CRSC report - Barley^	1	3	1	1	1
CO2 emissions from lime and urea	Calculated using IPCC methods based on urea inputs from the CRSC Report^	2	3	1	1	2
Soil carbon changes	Canadian NIR and as reported in the CRSC report^	1	1	1	1	4

**R: Reliability; C: Completeness; Temp: Temporal correlation; G: Geographical correlation; Tech: Technological correlation.*
^(S&T)2 Consultants, 2022a

2.5.7.4.2 Western Canadian corn

Life cycle assessments and carbon footprint studies involving corn production (for either grain or biofuels) in Canada were predominantly focussed on eastern Canada since the eastern provinces account for over 80% of corn production in the country. For Western Canadian beef production, all of the feed inputs are assumed to be sourced from the Western provinces. This is reflected in the feed compositions being primarily barley-based (including feed supplements in the cow-calf phase). Due to a lack of any other studies characterizing Western Canadian corn production, most of the data for characterizing corn production was extracted solely from the RU-scale data reported for the Prairie provinces in the 2022 corn CRSC report ((S&T)2 Consultants, 2022b). The only other data source for Canadian corn production identified was the AgriFootprint database but this is representative of production across the country, and not just the Prairies. Seeding rate for Western Canada were based on recommended rates in the Manitoba My Farm Calculator and is hence assigned a reliability and completeness score of 4. Fertilizer input data was of relatively high quality since it was based on surveys undertaken in Manitoba by Fertilizer Canada, and in Saskatchewan by Saskatchewan Crop Insurance. All pesticide input data was based on Ontario application rates from 2014, hence the average scores for reliability and completeness. Similarly, data for fuel use for on-field activities and post-harvest activities are based on estimates for Quebec from 2016. Transportation data is taken from Blonk et al. (2023) and yield data is taken from Statistics Canada (StatsCan, 2024). Modelling of all emissions follow procedures similar to those used for barley (as described in section 3.5). Table 13 below provides the sources and data quality scores assigned for each data point to characterize Western Canadian corn production.

Table 13: Data sources to model Western Canadian corn production, and their associated pedigree matrix scores

Data point	**Source**	**R***	**C***	**Temp.***	**G***	**Tech.***
Yield	(StatsCan 2024)	1	2	1	1	1
Seed	CRSC report-corn^	3	4	2	1	1
All nutrient inputs	CRSC report-corn^	1	3	2	1	1
All pesticide inputs	CRSC report-corn^	3	3	3	2	1
Irrigation energy	CRSC report-corn^	2	3	2	1	1
Fuel use for field activities	CRSC report-corn^	4	4	2	2	1
Transportation of field inputs	Blonk et al. (2023)	4	4	4	1	2
Post-harvest energy use	CRSC report-corn^	3	4	2	1	1

Direct and indirect N2O emissions	IPCC Tier II methods as specified in the Canadian NIR and reported in the CRSC report^	1	3	1	1	1
CO2 emissions from lime and urea	Calculated using IPCC methods based on urea inputs from the CRSC Report^	2	3	1	2	2
Soil carbon changes	Canadian NIR and as reported in the CRSC report^	1	1	1	1	4

**R: Reliability; C: Completeness; Temp: Temporal correlation; G: Geographical correlation; Tech: Technological correlation.*
^(S&T)2 Consultants, 2022b

2.5.7.4.3 Western Canadian wheat

Data for Western Canadian wheat production was largely obtained from the 2022 CRSC report for Canadian wheat ((S&T)2 Consultants, 2022c) and were generally of good quality. Seeding rates in the CRSC report are based on the Saskatchewan crop production guide. Data from the most recent version of this guide was selected for this study. Fertilizer application rates for the Prairie Provinces were reported in the CRSC reports from two sources: Pulse Canada surveys (Alberta) and crop insurance surveys (Saskatchewan and Manitoba). The data for Saskatchewan and Manitoba are multi-year averages, hence nutrient input data is of very good quality except for completeness (the crop insurance surveys are based on surveying multiple farms so they are assumed to have a representativeness below 50%). Pesticide input data for Alberta sourced from 2018 sales data is used across Western Canadian wheat production in the CRSC report, hence has high scores for reliability, geographical, and technological correlation, but average or poor scores for completeness and temporal correlation. Data for energy use associated with on-field activities was taken from the Prairie Crop Energy Model (PCEM), with 2019 tillage data from AAFC and estimates from the 2009 USDA ARMS survey. The irrigation data for Alberta from 2020 is used since only some wheat produced in Alberta is irrigated. Transportation data was taken from Blonk et al. (2023). Modelling of all emissions follow procedures similar to those used for barley (as described in section 3.5). Table 14 below provides the sources and data quality scores assigned for each data point to characterize Western Canadian wheat production.

Table 14: Data sources to model Western Canadian wheat production, and their associated pedigree matrix scores

Data point	**Source**	**R***	**C***	**Temp.***	**G***	**Tech.***
Yield	(StatsCan 2024)	1	2	1	1	1
Seed	Saskatchewan crop production guide	3	4	2	1	1
All nutrient inputs	CRSC report-wheat^	1	3	2	1	1
All pesticide inputs	CRSC report-wheat^	1	2	2	2	1
Irrigation energy	CRSC report-wheat^	2	3	2	1	1
Fuel use for field activities	CRSC report-wheat^	3	3	2	1	1
Transportation of field inputs	Blonk et al. (2023)	4	4	4	1	2
Post-harvest energy use	CRSC report-wheat^	3	4	2	1	1
Direct and indirect N2O emissions	IPCC Tier II methods as specified in the Canadian NIR and reported in the CRSC report ^	1	3	1	1	1
CO2 emissions from lime and urea	Calculated using IPCC methods based on urea inputs from the CRSC Report^	2	3	1	2	1
Soil carbon changes	Canadian NIR and as reported in the CRSC report^	1	1	1	1	4

**R: Reliability; C: Completeness; Temp: Temporal correlation; G: Geographical correlation; Tech: Technological correlation.*
^(S&T)2 Consultants, 2022c

2.5.7.4.4 Western Canadian oats

The 2022 CRSC report were the only significant source of data for Western Canadian oat production ((S&T)2 Consultants, 2022d). The few LCAs or carbon footprint studies found in literature focus on eastern Canada (despite Saskatchewan being the major producer). The datasets found in LCI databases were representative of Canadian production, generally. Seeding rates found in the CRSC reports are recommended amounts from the Saskatchewan crop production guide and the Manitoba CROPPLAN calculator. The nutrient input data found in the CRSC report for oat production is of very good quality since they were based on Saskatchewan crop insurance surveys and a survey undertaken for Fertilizer Canada. The CRSC report used pesticide application rates for Alberta from 2018 across all Western Canadian provinces. Data for energy use associated with on-field activities and irrigation were taken from the Prairie Crop Energy Model (PCEM) and tillage data from the 2009 USDA ARMS survey. Post-harvest energy use data were estimates for Alberta, which were used across all provinces. Modelling of all emissions follow procedures similar to those used for barley (as described in section 3.5). Table 15 below provides the sources and data quality scores assigned for each data point to characterize Western Canadian oat production.

Table 15: Data sources to model Western Canadian oat production, and their associated pedigree matrix scores

Data point	**Source**	**R***	**C***	**Temp.***	**G***	**Tech.***
Yield	(StatsCan 2024)	1	2	1	1	1
Seed	CRSC report-oats^	3	4	2	1	1
All nutrient inputs	CRSC report-oats^	1	3	2	1	1
All pesticide inputs	CRSC report-oats^	1	2	2	1	1
Irrigation energy	CRSC report-oats^	2	3	2	1	1
Fuel use for field activities	CRSC report-oats^	3	3	2	1	1
Transportation of field inputs	Blonk et al. (2023)	4	4	4	1	2
Post-harvest energy use	CRSC report-oats^	3	4	2	1	1
Direct and indirect N2O emissions	IPCC Tier II methods as specified in the Canadian NIR and reported in the CRSC report ^	1	3	1	1	1
CO2 emissions from lime and urea	Calculated using IPCC methods based on urea inputs from the CRSC Report^	2	3	1	2	1
Soil carbon changes	Canadian NIR and as reported in the CRSC report^	1	1	1	1	4

**R: Reliability; C: Completeness; Temp: Temporal correlation; G: Geographical correlation; Tech: Technological correlation.*
^(S&T)2 Consultants, 2022d

2.5.7.4.5 Western Canadian silage

Silage inputs from corn, barley, oats, and wheat are modelled using the same crop models as specified in section 3.2.1.1-3.2.1.4, with yields adjusted as specified in the CRSB study (CRSB, 2023). Data associated with activities such as on-field preparation (chopping) and storage were based on the data sourced for grass silage production (described below in Section 3.2.1.6). No data sources specific to the production of corn, barley, wheat, or oat silage was identified during the literature review.

2.5.7.4.6 Western Canadian grass hay and silage

Data for the production of harvested forage in Western Canada was obtained largely from (Pogue et al., 2023), which characterized the life cycle inventory of Canadian grass hay and silage production. The publicly available data does not include differences between provinces or between eastern and Western Canada. Seeding rates were from provincial crop guidelines and are hence given a score of 4 for completeness (recommendation) and 3 for reliability (non-verified data based on a qualified estimate). Nutrient input data for Manitoba (multi-year averages sourced from Manitoba Agricultural Services Corporation data) were used across the Western provinces and were of good data quality. Pesticide input data and transportation data were obtained from Wiens et al. (2014), which have poor data quality since no representativeness is reported and the data is more than 10 years old. Irrigation data in Pogue et al. (2023) was sourced from Statistics Canada and is of good quality. Fuel estimates for field activities were of poor quality as data was representative of 2011 and was generated using a farm fieldwork simulation model. Hay and silage wastage and losses were taken from Pogue et al. (2023). Modelling of all emissions follow procedures similar to those used for barley (as described in section 3.5). Table 16 below provides the sources and data quality scores assigned for each data point to characterize Western Canadian hay and silage production.

Table 16: Data sources to model Western Canadian hay and silage production, and their associated pedigree matrix scores

Data point	**Source**	**R***	**C***	**Temp.***	**G***	**Tech.***

Yield	(StatsCan, 2024)	1	2	1	1	1
Seed	Pogue et al. (2023)	3	4	2	2	1
All synthetic nutrient inputs	Pogue et al. (2023)	2	2	2	1	1
All pesticide inputs	Wiens et al. (2014)	4	5	4	2	1
Irrigation energy	Pogue et al. (2023)	2	2	2	2	1
Fuel use for field activities	Pogue et al. (2023)	4	4	4	2	1
Transportation of field inputs	Wiens et al. (2014)	4	5	4	1	1
Direct and indirect N2O emissions	IPCC Tier II methods	1	3	1	2	1
Soil carbon changes	Estimated based on IPCC methods in the Canadian NIR and reported in Pogue et al. 2023	1	1	1	1	1
Hay and silage storage losses and wastage	Pogue et al. (2023)	3	5	5	2	1

**R: Reliability; C: Completeness; Temp: Temporal correlation; G: Geographical correlation; Tech: Technological correlation.*

2.5.7.4.7 US corn

The data for US corn production was taken primarily from two different sources – the National Agricultural Statistical Service (NASS) (NASS, 2024), and the AgriFootprint database (Blonk et al., 2023). Yield, fertilizer amounts, and pesticide input data are all sourced from NASS and are based on multi-year averages. However, the NASS data does not differentiate by fertilizer types and, hence, the AgriFootprint database was used for this. The estimates for fertilizer types in Blonk et al. (2023) are based on national-level data distinguished by crop type from the International Fertilizer Association (IFA) and have good data quality overall. Data on energy use for field activities, irrigation, and post-harvest activities in the AgriFootprint database were based on an energy model for crop production and have a low score for completeness since they are considered recommended values. Transportation distances for crop inputs have poor quality due to being a non-verified estimate. Direct and indirect N_2O emissions from the application of nitrogen fertilizers, and emissions associated with the application of lime were estimated using IPCC Tier 2 protocols. Soil carbon change estimates were taken from the US NIR

(EPA, 2023) – as described in further detail in section 3.5. Table 17 provides the sources and data quality scores assigned for each data point to characterize US corn production.

Table 17: Data sources to model US corn production, and their associated pedigree matrix scores

Data point	**Source to be used**	**R***	**C***	**Temp.***	**G***	**Tech.***
Yield	NASS (2024)	1	2	1	1	1
Seed	(Blonk et al., 2023)	2	3	4	2	1
Lime inputs	(Blonk et al., 2023)	4	4	4	2	1
NPK fertilizer amounts	NASS (2024)	1	2	1	1	1
NPK fertilizer types	(Blonk et al., 2023)	1	3	2	1	1
Herbicide, insecticide, and fungicide inputs	NASS (2024)	1	2	1	1	1
Irrigation energy	(Blonk et al., 2023)	2	4	3	2	1
Field activities energy use	(Blonk et al., 2023)	2	4	3	2	1
Transportation	(Blonk et al., 2023)	4	4	4	1	2
Post-harvest	(Blonk et al., 2023)	2	4	3	2	1
Direct and indirect N2O emissions	Calculated using IPCC Tier 2 methods	1	3	2	1	1
CO2 emissions from lime and urea	Calculated using IPCC Tier 2 methods	2	4	4	2	1
Soil carbon changes	EPA (2023)	1	1	1	1	4

**R: Reliability; C: Completeness; Temp: Temporal correlation; G: Geographical correlation; Tech: Technological correlation.*

2.5.7.4.8 US soybean

Yield data for US soy were taken from NASS. Seed input data were obtained from Beal et al. (2021), a peer-reviewed literature source that originally sourced their data from a combination of USDA sources and the GREET model. Lime inputs came from Knoope et al. (2019), whose estimates were based on USDA statistics. Data on the amount of manure applied to US soybeans came from the USDA ERS ARMS survey, with the breakdown of manure types from Blonk et al. (2023). These data have poor quality since they are from 2012 and do not indicate the percent of supply covered. Data on fertilizer types and amounts came from Blonk et al. (2023) and the USDA NASS quick access tool, respectively. The Blonk et al. (2023) data for fertilizer types came from IFA statistics. For pesticides, the amounts of total inputs of active ingredients were sourced from NASS, with the breakdown of types from Blonk et al. (2023). The AgriFootprint data for pesticide types has poor quality due to lack of information on the age of the data. Energy use data came from Beal et al. (2021) and had good data quality except for with respect to completeness. Data for irrigation taken from Blonk et al. (2023) had a poor score for completeness because no information on representativeness is provided and these are considered recommended values. Modelling of all emissions follow procedures similar to those used for corn (as described in section 3.5). Table 18 below provides the sources and data quality scores assigned for each data point to characterize US corn production.

Table 18: Data sources to model US soy production, and their associated pedigree matrix scores

Data point	**Source to be used**	**R***	**C***	**Temp.***	**G***	**Tech.***
Yield	NASS (2024)	1	2	1	1	1
Seed	Beal et al. (2021)	2	3	2	1	1
Lime inputs	Knoope et al. (2019)	1	2	4	1	1
Manure amounts	USDA ERS ARMS Survey	1	3	3	1	1
NPK fertilizer amounts	NASS (2024)	1	2	1	1	1
S fertilizer amount	NASS (2024)	1	2	1	1	1
Herbicide, insecticide, and fungicide input amounts	NASS (2024)	1	2	1	1	1
Irrigation energy	Blonk et al. (2023)	2	4	3	2	1
Field activities energy use	Beal et al. (2021)	2	3	2	1	1
Transportation	Blonk et al. (2023)	4	4	4	1	2
Post-harvest	Beal et al. (2021)	2	3	2	1	1
Direct and indirect N2O emissions	Calculated using IPCC Tier II methods	1	3	3	1	1
Soil carbon changes	EPA (2023)	1	1	1	1	4

**R: Reliability; C: Completeness; Temp: Temporal correlation; G: Geographical correlation; Tech: Technological correlation.*

2.5.7.4.9 US wheat

The main sources for data to characterize wheat production in the US are the AgriFootprint database (Blonk et al., 2023) and the USDA LCA Commons (USDA 2014). Since the data in the AgriFootprint database for US wheat production is based on the USDA dataset, and includes some corrections made to the inventory, the AgriFootprint dataset is alone listed as the source in Table 19 below. For fertilizer inputs, pesticides, and other nutrients, the NASS database (accessed using the NASS quick access tool) is used. However, NASS only includes the total nutrient inputs rather than the amounts by fertilizer type so AgriFootprint data is used to determine the types and distribution of fertilizers applied. Data quality for irrigation energy requirements, field activities, and transportation had poor quality for completeness and temporal correlation since these were based on a crop energy model without any representativeness or age of the data reported. Modelling of all emissions follow procedures similar to those used for corn (as described in section 3.5). Table 19 below provides the sources and data quality scores assigned for each data point to characterize US corn production.

Table 19: Data sources to model US wheat production, and their associated pedigree matrix scores

Data point	**Source**	**R***	**C***	**Temp.***	**G***	**Tech.***
Yield	NASS (2024)	1	2	1	1	1
Seed	(Blonk et al., 2023)	2	3	4	2	1
Lime	(Blonk et al., 2023)	4	4	4	2	1
All fertilizer inputs	NASS (2024)	1	2	1	1	1
Herbicide, fungicide, insecticide inputs	NASS (2024)	1	2	1	1	1
Other agri-chemical inputs	NASS (2024)	1	2	1	1	1
Irrigation energy	(Blonk et al., 2023)	2	4	3	2	1
Field activities energy use	(Blonk et al., 2023)	2	4	3	2	1
Transportation	(Blonk et al., 2023)	4	4	4	1	2
Post-harvest	(Blonk et al., 2023)	2	3	2	3	1
Direct and indirect N2O emissions	Calculated using IPCC Tier II methods	1	3	2	1	1
Soil carbon changes	EPA (2023)	1	1	1	1	4

**R: Reliability; C: Completeness; Temp: Temporal correlation; G: Geographical correlation; Tech: Technological correlation.*

2.5.7.4.10 US corn silage

Corn silage production was characterized using the dataset available in the AgriFootprint database (Blonk et al., 2023), except for yield data. Unlike corn grain production, NASS does not provide any data on nutrient and other inputs to the production of corn silage. Data quality was generally high for most data sourced from the AgriFootprint dataset except for completeness since representativeness was not reported. Fertilizer inputs were based on data from the International Fertilizer Association and were of good quality. Input of pesticides was based on a crop pesticide use model. Similarly, the energy use data for irrigation, field activities, and post-harvest activities were based on a crop energy model. The pesticides and energy use data did not have any representativeness reported and were assumed to be recommended values. Modelling of all emissions follow procedures similar to those used for corn (as described in section 3.5). Table 20 below provides the sources and data quality scores assigned for each data point to characterize US corn silage production.

Table 20: Data sources to model US corn silage production, and their associated pedigree matrix scores

Data point	**Source**	**R***	**C***	**Temp.***	**G***	**Tech.***
Yield	NASS (2024)	1	2	1	1	1
Seed	(Blonk et al., 2023)	2	3	4	2	1
Lime	(Blonk et al., 2023)	4	4	4	2	1
All fertilizer inputs	(Blonk et al., 2023)	1	2	1	1	1
Herbicide, fungicide, insecticide inputs	(Blonk et al., 2023)	2	4	3	2	1
Other agri-chemical inputs	(Blonk et al., 2023)	2	4	3	2	1
Irrigation energy	(Blonk et al., 2023)	2	4	3	2	1
Field activities energy use	(Blonk et al., 2023)	2	4	3	2	1
Transportation	(Blonk et al., 2023)	4	4	4	1	2
Post-harvest	(Blonk et al., 2023)	2	4	3	2	1
Direct and indirect N2O emissions	Calculated using IPCC Tier II methods	2	4	4	2	1
CO2 emissions from lime and urea	Calculated using IPCC Tier II methods	1	1	1	1	4
Soil carbon changes	EPA (2023)	1	2	1	1	1

**R: Reliability; C: Completeness; Temp: Temporal correlation; G: Geographical correlation; Tech: Technological correlation.*

2.5.7.4.11 US Grass hay and silage

Similar to corn silage, there were few life cycle inventory data sources identified for grass hay and silage production in the US. One reason for this is the extensive use of the IFSM tool in US beef and dairy LCAs (this tool provides a process-based approach to modelling forage production based on climate and soil data). The AgriFootprint database (Blonk et al., 2023) was predominantly used for modelling US harvested forage and its data quality scores for each data point are similar to those described in section 3.2.2.4 for corn silage. Table 21 below provides the sources and data quality scores assigned for each data point to characterize US grass hay and silage production.

Table 21: Data sources to model US grass hay and silage production, and their associated pedigree matrix scores

Data point	Source	**R***	**C***	**Temp.***	**G***	**Tech.***
Yield	NASS (2024)	1	2	1	1	1
Seed	(Blonk et al., 2023)	2	3	4	2	1
Lime	(Blonk et al., 2023)	4	4	4	2	1
All fertilizer inputs	(Blonk et al., 2023)	1	2	1	1	1
Herbicide, fungicide, insecticide inputs	(Blonk et al., 2023)	2	4	3	2	1
Irrigation energy	(Blonk et al., 2023)	2	4	3	2	1
Field activities energy use	(Blonk et al., 2023)	2	4	3	2	1
Transportation	(Blonk et al., 2023)	4	4	4	1	2
Post-harvest	(Blonk et al., 2023)	2	4	3	2	1
Direct and indirect N2O emissions	Calculated using IPCC Tier II methods	1	3	2	1	1
CO2 emissions from lime and urea	Calculated using IPCC Tier II methods	2	4	4	2	1
Soil carbon changes	EPA (2023)	1	1	1	1	4

**R: Reliability; C: Completeness; Temp: Temporal correlation; G: Geographical correlation; Tech: Technological correlation.*

2.5.7.4.12 Brazilian soybean

For Brazilian soy, the majority of the inventory data was sourced from Blonk et al. (2023). Some of these data points (transportation and energy use) had poor data quality due to not reporting the age of the data and/or being recommended values. Other data sources included FAOStat for yield, and Nemecek (2007) for lime, other fertilizer inputs (micronutrients other than NPKS), and pesticide types. No sources were identified that directly provided LCI data for inoculant application. However, Santos et al. (2019) indicated that the majority of Brazilian soy was inoculated. This was used in combination with the label rate for a common inoculant (AgTiv, 2023), and the methods for modelling inoculant used by Bamber et al. (2022), originally taken from Alberta Agriculture and Forestry data. Values for N_2O and CO_2 emissions from nutrient inputs were calculated using IPCC Tier II methods. SOC change data were sourced from Blonk et al., (2023) since the Brazilian national communication to the UNFCCC does not provide any estimates for changes in soil carbon for cropland. Emissions associated with land use change were, however, sourced from the Brazilian national communication (MCTI, 2020). The N credit from biological nitrogen fixation was calculated using the equations in Barker (2007), based on research from Western Canada. Table 22 below provides the sources and data quality scores assigned for each data point to characterize Brazilian soy production.

Table 22: Data sources to model Brazil soy production, and their associated pedigree matrix scores

Data point	**Source to be used**	**R***	**C***	**Temp.***	**G***	**Tech.***
Yield (and the inverse, land area)	FAOStat	1	1	1	1	1
Seed	Blonk et al. (2023)	1	3	3	1	1
Inoculant	Santos et al. (2019) and AgTiv label rate	4	4	3	1	4
Lime inputs	Nemecek (2007)	1	3	3	1	1
NPK fertilizers	Blonk et al. (2023)	1	2	1	1	1
Herbicide, insecticide, and fungicide input amounts	Blonk et al. (2023)	1	3	2	1	1
Herbicide, insecticide, and fungicide input types	Nemecek (2007)	1	3	3	1	1
Irrigation energy	Blonk et al. (2023)	2	4	3	2	1
Field activities energy use	Blonk et al. (2023)	2	4	3	2	1
Transportation	Blonk et al. (2023)	4	4	4	1	2
Post-harvest	Nemecek (2007)	2	3	5	2	1

Field level emissions of N_2O	IPCC Tier 2 with inputs from Blonk et al. (2023)	1	3	2	1	1
CO_2 emissions from lime and urea	IPCC Tier 2 with inputs from Blonk et al. (2023)	1	3	2	1	1
Soil carbon changes	Blonk et al. (2023)	1	3	2	1	1
N credit	Barker et al. (2007)	4	4	5	1	4

**R: Reliability; C: Completeness; Temp: Temporal correlation; G: Geographical correlation; Tech: Technological correlation.*

2.5.7.4.13 Brazilian corn

The data to characterize Brazilian corn production was mainly sourced from the AgriFootprint database (Blonk et al., 2023). This inventory was identified as the most representative for Brazilian corn production due to the better quality data sources compared to the available peer-reviewed literature and other LCI databases. Data from crop yields was sourced from FAO stats using a 5-year average from 2018-2022. The amounts of fertilizer inputs were quantified based on information from statistical data from the IFA specific to Brazil. Data on energy use for field activities, irrigation, and post-harvest activities in the AgriFootprint database were based on an energy model for crop production and have a low score for completeness since they are considered to be recommended values. Transportation distances for crop inputs have poor quality due to being a non-verified estimate. Direct and indirect N_2O emissions from the application of nitrogen fertilizers, and emissions associated with the application of lime were estimated using IPCC Tier 2 protocols. SOC change data were sourced from Blonk et al. (2023) since the Brazilian national communication to UNFCCC does not provide any estimates for changes in soil carbon for cropland. Table 23 below provides the sources and data quality scores assigned for each data point to characterize Brazilian corn production.

Table 23: Data sources to model Brazil corn production, and their associated pedigree matrix scores

Data	**Source**	**R***	**C***	**Temp.***	**G***	**Tech.***
Crop yields	FAO statistics	1	1	1	1	1
Fertilizers	Blonk et al. (2023)	2	2	4	1	1
Nutritional input from manure	FAO statistics	1	2	3	1	1

Total water use	(Mekonnen & Hoekstra, 2010)	2	2	5	1	1
Irrigation energy	Blonk et al. (2023)	2	4	3	2	1
Field activities energy use	Blonk et al. (2023)	2	4	3	2	1
Transportation	Blonk et al. (2023)	4	4	4	1	2
Post-harvest	Blonk et al. (2023)	2	4	3	2	1
Field level emissions of N2O	IPCC Tier 2 with inputs from Blonk et al. (2023)	1	3	2	1	1
CO2 emissions from lime and urea	IPCC Tier 2 with inputs from Blonk et al. (2023)	1	3	2	1	1
Soil carbon changes	Blonk et al. (2023)	1	3	2	1	1

**R: Reliability; C: Completeness; Temp: Temporal correlation; G: Geographical correlation; Tech: Technological correlation.*

2.5.8 Background data providers

A single background data source (ecoinvent database version v.3.8) was preferred where possible to ensure methodological consistency for all background data. This database contains background datasets for all relevant data categories at the appropriate levels of regional specificity. It is also one of the most the commonly used background databases for LCA practitioners. When the use of ecoinvent was not possible, other providers (primarily Agrifootprint) were used. Table 24 lists all providers used to model background datasets, as well as any modifications made to make them better fit for the purposes of this study. Table 25 lists all processes used in modifications listed in Table 24 (e.g., regional electricity providers). These tables were split in order to avoid redundancy, as electricity and other regional providers were changed across many of the background processes listed in Table 24. In general, processes were modified to use electricity providers specific to the country or region modelled, unless otherwise indicated in the table. In some cases, production processes representing specific pesticide active ingredients are unavailable in ecoinvent v.3.8. Where possible, active ingredients have been modeled as production of active ingredients of the same chemical family. When these were not available, pesticides were modeled as unspecified.

Table 24: Inventory flows, the processes used to model them from ecoinvent v.3.8 or Agrifootprint 5.0, and any modifications made to those processes.

Data point	**Process (from ecoinvent v.3.8 unless specified otherwise)**	**Modifications**
Fertilizers (including manure modelled as upstream synthetic fertilizer production)		
Urea	urea production | urea | APOS, U – RER or RNA	electricity providers changed for each region for CA, the national average electricity mix was used since urea is produced in many Canadian provinces (Cheminfo Services Inc., 2016)
Ammonia	ammonia production, steam reforming, liquid | ammonia, anhydrous, liquid | APOS, U – RER or RNA	electricity and natural gas providers changed for each region
Ammonium nitrate	ammonium nitrate production | ammonium nitrate | APOS, U – RER or RNA	electricity providers changed for each region for CA, the national average electricity mix was used since ammonium nitrate is produced in many Canadian provinces (Cheminfo Services Inc., 2016) ammonia providers changed to regionalized ammonia providers (modifications described above)
Calcium ammonium nitrate	calcium ammonium nitrate production | calcium ammonium nitrate – RNA or RER	electricity providers changed for each region for CA, the national average electricity mix was used since ammonium nitrate is produced in many Canadian provinces (Cheminfo Services Inc., 2016) ammonia providers changed to regionalized ammonia providers (modifications described above)
Urea ammonium nitrate (UAN)	urea ammonium nitrate production | urea ammonium nitrate mix | APOS, U – RNA or RER	ammonium nitrate provider changed to regionally modified ammonium nitrate process for each region (described above) electricity providers changed for each region for CA, the national average electricity mix was used since urea ammonium nitrate is produced in many Canadian provinces (Cheminfo Services Inc., 2016)
Monoammonium phosphate (MAP)	market for monoammonium phosphate | monoammonium phosphate | APOS, U – RNA or RER	electricity providers changed for each region for CA and SK, process was modelled as taking place in AB since that is the only location of a production facility for MAP (Cheminfo Services Inc., 2016)

Diammonium phosphate (DAP)	diammonium phosphate production | diammonium phosphate | APOS, U – RNA or RER	electricity providers changed for each region ammonia providers changed to regionalized ammonia providers (modifications described above) for CA and SK, process was modelled as taking place in AB since that is the only location of a production facility for MAP (Cheminfo Services Inc., 2016), and no information was provided for production locations for DAP
Single superphosphate	single superphosphate production | single superphosphate | APOS, U – RER	electricity and phosphate rock providers changed for each region for CA and SK, process was modelled as taking place in AB since that is the only location of a production facility for MAP (Cheminfo Services Inc., 2016), and no information was provided for production locations for superphosphate
Triple superphosphate	triple superphosphate production | triple superphosphate | APOS, U – RER	electricity, phosphate rock, and phosphoric acid providers changed for each region for CA and SK, process was modelled as taking place in AB since that is the only location of a production facility for MAP (Cheminfo Services Inc., 2016), and no information was provided for production locations for superphosphate
Phosphate rock	phosphate rock beneficiation | phosphate rock, beneficiated | APOS, U – RER	electricity providers changed for each region
Potassium chloride (potash)	potassium mining and benefication | potassium chloride | APOS, U - CA-SK	electricity providers changed for each region for CA, process was modelled as SK since that is the only location for a production facility of potash, and SK was modelled as SK (Cheminfo Services Inc., 2016)
Potassium chloride (potash)	potassium chloride production | potassium chloride | APOS, U	electricity providers changed for each region
Potassium sulfate	potassium sulfate production | potassium sulfate | APOS, U – RER	electricity providers changed for each region for CA, process was modelled as SK since that is the only location for a production facility of potassium, and SK was modelled as SK (Cheminfo Services Inc., 2016) potassium chloride providers changed for each region (SK for both SK and CA)
Ammonium sulfate	ammonium sulfate production | ammonium sulfate | APOS, U – RER	ammonia providers changed to regionalized ammonia providers (modifications described above) electricity providers changed for each region

		for CA, the national average electricity mix was used since ammonium sulfate is produced in several Canadian provinces (Cheminfo Services Inc., 2016)
Sulfur	natural gas production | sulfur | APOS, U - CA-AB or DE	electricity providers changed for each region for CA and SK, the AB electricity mix was used since sulfur is mainly produced in AB (Prud'homme, 2013)
Zinc	primary zinc production from concentrate | zinc | APOS, U – CA-QC	electricity and urea providers changed for each region for CA, the national average electricity mix was used since zinc is produced in several Canadian provinces, for SK the MB electricity mix was used since SK does not produce zinc and MB is the largest producer (World Atlas, 2022)
Magnesium	magnesium production, electrolysis | magnesium | APOS, U – IL	electricity provider changed to market group for electricity, high voltage | electricity, high voltage | APOS, U - CA
Lime	lime production, milled, loose | lime | APOS, U – CA-QC or CH	electricity providers changed for each region for CA, the national average electricity mix was used since lime is produced in several Canadian provinces, and SK used for SK (Vagt, 2015)
Plant protection products		
Glyphosate	glyphosate production | glyphosate | APOS, U – RER	electricity providers changed for each region US national electricity grids were used for US, CA and SK since the majority of pesticides used in Canada are sourced from the US (Bamber et al., 2022a) ammonia and decarbonised water providers changed for each region
Pyroxasulfone, Metolachlor	acetamide-anillide-compound production, unspecified | acetamide-anillide-compound, unspecified | APOS, U – RER	electricity providers changed for each region US national electricity grids were used for US, CA and SK since the majority of pesticides used in Canada are sourced from the US (Bamber et al., 2022a) ammonia, sulfur and decarbonised water providers changed for each region
Sulfentrazone, propiconazole, prothioconazole, epoxiconazole, tebuconazole, metconazole, Tetraconazole, Carfentrazon-ethyl, metribuzin	triazine-compound production, unspecified | triazine-compound, unspecified | APOS, U – RER	electricity providers changed for each region US national electricity grids were used for US, CA and SK since the majority of pesticides used in Canada are sourced from the US (Bamber et al., 2022a) ammonia and decarbonised water providers changed for each region

Glufosinate, chlorpyrifos, Methidathion	organophosphorus-compound production, unspecified | organophosphorus-compound, unspecified | APOS, U – RER	electricity providers changed for each region US national electricity grids were used for US, CA and SK since the majority of pesticides used in Canada are sourced from the US (Bamber et al., 2022a) ammonia, decarbonised water and sulfur providers changed for each region
MCPA, 2,4-D, Quizalofop-ethyl	phenoxy-compound production | phenoxy-compound | APOS, U – RER	electricity providers changed for each region US national electricity grids were used for US, CA and SK since the majority of pesticides used in Canada are sourced from the US (Bamber et al., 2022a) ammonia and decarbonised water providers changed for each region
Bromoxynil, Azoxystrobin, Dimoxystrobin, chlorothalonil, ethaboxam	nitrile-compound production | nitrile-compound | APOS, U – RER	electricity providers changed for each region US national electricity grids were used for US, CA and SK since the majority of pesticides used in Canada are sourced from the US (Bamber et al., 2022a) ammonia and decarbonised water providers changed for each region
Bentazon	benzo[thia]diazole-compound production | benzo[thia]diazole-compound | APOS, U – RER	electricity providers changed for each region US national electricity grids were used for US, CA and SK since the majority of pesticides used in Canada are sourced from the US (Bamber et al., 2022a) ammonia, sulfur and decarbonised water providers changed for each region
Fluroxypyr, Diflufenican, Boscalid	pyridine-compound production | pyridine-compound | APOS, U – RER	electricity providers changed for each region US national electricity grids were used for US, CA and SK since the majority of pesticides used in Canada are sourced from the US (Bamber et al., 2022a) ammonia and decarbonised water providers changed for each region
Triallate	[thio]carbamate-compound production | [thio]carbamate-compound | APOS, U – RER	electricity providers changed for each region US national electricity grids were used for US, CA and SK since the majority of pesticides used in Canada are sourced from the US (Bamber et al., 2022a) ammonia, sulfur and decarbonised water providers changed for each region
Diquat	bipyridylium-compound production | bipyridylium-compound | APOS, U – RER	electricity providers changed for each region US national electricity grids were used for US, CA and SK since the majority of pesticides used in Canada are sourced from the US (Bamber et al., 2022a)

		ammonia, sulfur and decarbonised water providers changed for each region
Ethalfluralin, Trifluralin, Pendimethalin	dinitroaniline-compound production | dinitroaniline-compound | APOS, U – RER	electricity and ammonia providers changed for each region US national electricity grids were used for US, CA and SK since the majority of pesticides used in Canada are sourced from the US (Bamber et al., 2022a)
Deltamethrin, cyhalothrin-lambda, Bifenthrin, Alpha-cypermethrin, Cypermethrin, Etofenprox, Beta-Cyfluthrin, Permethrin	pyrethroid-compound production | pyrethroid-compound | APOS, U – RER	electricity providers changed for each region US national electricity grids were used for US, CA and SK since the majority of pesticides used in Canada are sourced from the US (Bamber et al., 2022a) ammonia and decarbonised water providers changed for each region
Atrazine	atrazine production | atrazine | APOS, U – RER	electricity and ammonia providers changed for each region
Dimethanamid-P	dimethenamide production | dimethenamide | APOS, U – RER	electricity, ammonia, sulfur and decarbonised water providers changed for each region
Napropamide	napropamide production | napropamide | APOS, U – RER	electricity, sulfur, and decarbonised water providers changed for each region
cyclic N-compound	cyclic N-compound production | cyclic N-compound | APOS, U – RER	electricity, ammonia, sulfur, and decarbonised water providers changed for each region
Metrafenone, dicamba, Propoxycarbazone, fludioxonil	benzoic-compound production | benzoic-compound | APOS, U – RER	electricity, ammonia, sulfur, and decarbonised water providers changed for each region
Flumioxazin	phthalimide-compound production | phthalimide-compound | APOS, U – RER	electricity, ammonia, urea and decarbonised water providers changed for each region
Thiram	dithiocarbamate-compound production | dithiocarbamate-compound | APOS, U – RER	ammonia and electricity providers changed for each region
Benzimidazole compound	benzimidazole-compound production | benzimidazole-compound | APOS, U – RER	ammonia, electricity, and sulfur providers changed for each region

All other active ingredients	pesticide production, unspecified | pesticide, unspecified | APOS, U – RER	electricity providers changed for each region US national electricity grids were used for US, CA and SK since the majority of pesticides used in Canada are sourced from the US (Bamber et al., 2022a) ammonia, urea, sulfur and decarbonised water providers changed for each region
Inoculant		
Peat moss	peat moss production, horticultural use | peat moss | APOS, U – CA-QC	ammonium nitrate and electricity providers changed for each region
Energy providers		
Diesel	diesel, burned in agricultural machinery | diesel, burned in agricultural machinery | APOS, U – GLO	infrastructure and machinery flows removed
Electricity	market for electricity, low voltage | electricity, low voltage | APOS, U (for each region)	processes for each region used without modifications
Natural gas (heat)	heat production, natural gas, at boiler condensing modulating >100kW | heat, district or industrial, natural gas | APOS, U – CA-QC or Europe without Switzerland	electricity and natural gas providers changed for each region
Transportation		
Truck transportation	market for transport, freight, lorry 7.5-16 metric ton, EURO4 | transport, freight, lorry 7.5-16 metric ton, EURO4 | APOS, U – RER	
Fertilizer compounds (Agrifootprint)		
Liquid urea-ammonium nitrate solution (NPK 30-0-0)	Liquid urea-ammonium nitrate solution (NPK 30-0-0), at plant {RNA} Energy, U – RNA	
NPK compound (NPK 15-15-15)	NPK compound (NPK 15-15-15), market mix, at regional storage {RNA} Energy, U – RNA	
PK compound (NPK 0-22-22)	PK compound (NPK 0-22-22), at plant {RER} Energy, U – RER	

Packaging processes for Western Canadian grass hay and silage		
Paper	paper production, woodcontaining, supercalendered | paper, woodcontaining, supercalendered | APOS, U - CA – QC	
Cardboard	carton board box production service, with gravure printing | carton board box production, with gravure printing | APOS, U - CA – QC	
Polypropylene	market for polypropylene, granulate | polypropylene, granulate | APOS, U – GLO	
High density polyethylene	market for polyethylene, high density, granulate | polyethylene, high density, granulate | APOS, U – GLO	
Water inputs		
Tap water	market for tap water | tap water | APOS, S – RoW	
Supplements for cattle		
Mineral supplements	market for mineral supplement, for beef cattle | mineral supplement, for beef cattle | APOS, U – GLO	
Feed crops processing flows (Agrifootprint)		
DDGs	Maize distillers grains dried, at processing {US} Energy, U	Electricity providers changed for each region. Added to corn production system modelled for each region.
Soybean meal	Crude soybean oil (solvent), at processing {US} Energy, U - US Soybean oil and meal, crushing in Brazil, not deforestation, - BR	Added to soybean production system modelled for each region.
Wheat middling	Wheat middlings & feed, proxy market mix, at regional storage {US} Energy, U – US	Added to wheat production system modelled for each region.

Wheat flour	Wheat flour, at processing {US} Energy, U – US	Added to wheat production system modelled for each region.

Table 25: Processes used for modification of background processes.

Modifications	Processes used for modifications
Electricity	- market for electricity, low voltage | electricity, low voltage | APOS, U – Saskatchewan*, - market group for electricity, low voltage | electricity, low voltage | APOS, U – Alberta*, - market for electricity, low voltage | electricity, low voltage | APOS, U – Manitoba* - market group for electricity, low voltage | electricity, low voltage | APOS, U – United States - market for electricity, low voltage | electricity, low voltage | APOS, U – Brazil - market for electricity, low voltage | electricity, low voltage | APOS, U – Brazil -Mid-Western grid

** For Western Canadian crops, the electricity providers from SK, MB, and AB were used based on a production weighted average for each crop*

2.5.9 Emissions modelling

2.5.9.1 Soil organic carbon changes associated with pastures/rangeland

For contributions to GHG emissions due to land use change, pasturelands that were grazed can broadly be classified into two categories: natural grasslands and grasslands that are created from converting other land use types. For natural grasslands, the NIRs of all three countries considered assumed no land use change occurred and as a result, no changes in carbon sequestered in the biomass is considered to have happened. For grasslands that were created from other land use types, the NIRs of all three countries estimated changes in carbon sequestration if the conversion is estimated to have happened within the last 20 years. All three NIRs follow the guidelines specified in the IPCC methods (IPCC 2019) and implement the stock difference method to measure changes in carbon stocks due to land use change. This method involves estimating the amount of area that was converted to grasslands and the difference in biomass stocks between the time of conversion and the year of measurement. The stock difference method equation is as follows:

$$\Delta C_b = \frac{C_{t2} - C_{t1}}{t_2 - t_1}$$

where,

- ΔC_b is the change in carbon stocks of the biomass
- C_{t2} is the total carbon in biomass for previous land use category at time t_2
- C_{t1} is the total carbon in biomass for current land use category at time t_1

where “C” refers to the total carbon in biomass between time t_1 and t_2. This is estimated by the following equation:

$$C = \sum_{i,j} A_{i,j} * V_{i,j} * (1 + R_{i,j}) * CF_{i,j}$$

where,

- A is the area of land remaining in the same land use category in hectares
- V is the volume of biomass growth in m^3/hectare
- R is the ratio of below ground and above ground biomass and
- CF is the carbon fraction of the dry matter in tonnes C/tonne of dry matter
- i is the ecological zone (the number of ecological zones is defined by each country in the NIR)
- j is the climate domain (the number of climate domains is defined by each country in the NIR)

For each country considered, the changes in carbon sequestered due to creating grasslands that were calculated using the equations above were taken directly from the respective NIRs. For Western Canada, no conversion of other land use types to grassland was reported (ECCC 2023). For the US, a Tier 3 approach involving the Daycent model (a process-based model) was used to estimate changes in C stocks for mineral soils that have less than 35% coarse fragments and were converted from cropland to grasslands. For grasslands created from croplands with more than 35% coarse fragments and from other land use types, a Tier 2 approach was used (EPA

2023). Brazil employed a Tier 2 approach with the changes in land use associated with grasslands primarily determined based on multiple spatial maps related to boundaries of biomes, natural vegetation, and land cover for multiple years between 1994 and 2016 (MCTI 2020).

When modelling pastures, the other significant contributor to the carbon footprint was changes in soil organic carbon as a result of management practices. Management practices may include pasture re-establishment, tillage, and application of nutrients and lime. For estimating the impacts of soil organic carbon in grassland remaining grassland, distinction was made between pasturelands that undergo management activities and pasturelands that do not. The IPCC guidelines for estimating these changes follows the same carbon stock difference approach detailed above for C stock changes due to land use change. The only difference to using this approach in this case was that the land use category remains the same (and changes associated with management practices are instead analysed). For each country considered, the changes in soil organic carbon due to grassland management that were calculated using the equations discussed above were taken directly from the respective NIRs (ECCC, 2023; EPA, 2023; MCTI, 2020).

For Canada, natural grasslands with no inputs of nutrients or other land management activities were considered to make up 70% of all pasturelands (CRSB 2023), with re-established or tame pasture making up the rest. Even in tame pastureland, land management activities were reported to be minimal, with the only human activities influencing pasturelands being fire suppression, seeding new plant species, and managing grazing patterns of the cattle. Due to the estimated limited influence of management activities on grasslands, the Canadian NIR used a Tier 1 approach to estimating soil organic carbon changes in managed grasslands. In the US, the share of managed pasture with inputs of nutrients and tillage was also significantly less compared to unmanaged or natural pastureland. However, data on pasture management activities obtained from USDA Agriculture Resource Management Surveys (ARMS) between 1996 and 2020 were included in the estimation of soil organic carbon changes in US grasslands remaining grasslands. As specified before, the US NIR used a combination of Tier 3 (for soils with less than 35% coarse fragments) and Tier 2 approaches. The life cycle impacts of fertilizer application, tillage, and other management activities were also be included in the modelling according to the share of pastureland that is re-established and amortized based on the time period between reestablishment activities. The Brazilian NIR adopted a Tier 2 approach to modelling soil organic carbon changes due to management activities that followed a similar approach to the one described previously for land use change.

2.5.9.2 Soil organic carbon changes associated with feed crop inputs

The estimates of soil carbon change from each country's NIR were used for both cropland and land use change to cropland from other use categories. All the NIRs used the same carbon stock difference method used for grasslands to estimate the soil organic carbon changes in croplands as well. The stock difference method equation is as follows:

$$\Delta C_b = \frac{C_{t2} - C_{t1}}{t_2 - t_1}$$

where,

- ΔC_b is the change in carbon stocks of the biomass
- C_{t2} is the total carbon in biomass for previous land use category at time t_2
- C_{t1} is the total carbon in biomass for current land use category at time t_1

In the above equation, "C" refers to the total carbon in biomass between time t_1 and t_2. This is estimated by the following equation:

$$C = \sum_{i,j} A_{i,j} * V_{i,j} * (1 + R_{i,j}) * CF_{i,j}$$

where,

- A is the area of land remaining in the same land use category in hectares
- V is the volume of biomass growth in m^3/hectare
- R is the ratio of below ground and above ground biomass and

- CF is the carbon fraction of the dry matter in tonnes C/tonne of dry matter
- i is the ecological zone (the number of ecological zones is defined by each country in the NIR)
- j is the climate domain (the number of climate domains is defined by each country in the NIR)

These values were calculated by dividing the total soil carbon change for each country's cropland by the total area of cropland in each country. These area-based estimates were scaled relative to the yield of each crop to give carbon sequestration or emission estimates. Apart from the differences in yield, these values were not crop specific, since the NIR reports these values for all crops. These values were used to ensure methodological consistency between countries, since detailed data were not available for all countries to perform process-based modelling. For estimates of carbon sequestration, these were calculated as inputs of CO_2 to the soil from the atmosphere, and carbon losses were modelled as emissions of CO_2 to the atmosphere from the soil.

All the soil organic carbon fluxes associated with land management and land use change that were obtained from the NIRs of each country considered are provided in Table 26 below.

Table 26: Soil organic carbon (SOC) fluxes per hectare of land use type derived from NIRs of Canada, USA, and Brazil

Source of soil organic carbon (SOC) changes	**SOC flux***	**unit**
Western Canada (2022)		
SOC flux from cropland management (cropland remaining cropland)	-454.093	kg/ha
SOC flux from grassland converted to cropland (prairies)	0.259	kg/ha
Net cropland SOC flux	-453.834	kg/ha
SOC from grassland management (grassland remaining grassland)	0.167	kg/ha
USA (2022)		
SOC flux from cropland management (cropland remaining cropland)	-118.068	kg/ha
SOC flux from conversion to cropland	352.955	kg/ha
Net cropland SOC flux	234.887	kg/ha

SOC flux from grassland management (grassland remaining grassland)	29.499	kg/ha
SOC flux from grassland burning	1.769	kg/ha
SOC flux from conversion to grassland	-72.864	kg/ha
Net grassland SOC flux	-41.5944	kg/ha
Brazil (2020)		
Net cropland SOC flux	1282.817	kg/ha
Net grassland SOC flux	3500.416	kg/ha

*_negative value indicates sequestration of soil organic carbon. Positive value indicates loss of soil organic carbon_

2.5.9.3 Enteric methane

For all of the beef production systems modelled, IPCC Tier II methods were used to estimate enteric methane emissions. These methods require definition of a diverse set of animal categories and the calculation of emission factors for each category defined. Emission factors were defined using Equation 10.21 from IPCC (2019):

$$CH_4 = GE * \frac{Y_m/100}{55.65}$$

where

- CH_4 is the kilogram of methane/head/day for a specific animal category
- GE is the gross energy intake of the animal in MJ/head/day.
- Y_m is the methane conversion factor i.e. the percentage of gross energy of feed converted to methane and
- 55.65 is the energy content of methane in MJ/kg of CH_4

Gross energy values were estimated based on average feed intake values (using GE estimates for all feed rations). Methane conversion factors were taken from the NIRs of each country. The methane emission factors determined for each category (e.g. calves, heifers, cows, bulls) were compared against the emission factors reported in the NIRs for consistency. Once emission factors were determined, total methane emissions was calculated by multiplying the emissions factor for each category with the number of days in the category, which were then aggregated across all categories.

The Y_m values used for each country and their sources are provided in Table 27 below.

Table 27: Methane conversion factors and their sources for modelling enteric methane emissions

Region and source	Cattle type	Y_m (% of GE)
Western Canada (CRSB, 2023)	Calves on grass	6
	Calves on feed	7
	Backgrounders on grass	7
	Backgrounders on feed	7
	Yearlings on grass	7
	Yearlings on feed	7
	Finishers	4
	Cows and bulls on grass	7
	Cows and bulls on feed	7
USA (EPA, 2023)	Beef replacement heifers	6.5
	Beef calves	6.5
	Backgrounders	6.5
	Cows and bulls	6.5
	Feedlot finishers	3.9
Brazil (MCTI, 2020)	Beef cattle on pasture	6.5

2.5.9.4 Manure management

Manure-related emissions occur either on pasture or during manure storage and application. These were calculated using a Tier 2 (and Tier 1 if country-specific emission factors and fractions were not available) approach, as done in the NIRs of the countries considered. Methane emissions from manure application on pasture or storage as a result of anaerobic fermentation were estimated based on a Tier II approach using equation 10.23 of the IPCC (2019) guidelines as follows

$$CH_{4,methane} = VS * B_0 * MCF * 0.67$$

where

- $CH_{4,methane}$ is the manure-related methane emissions in kg CH_4/head/day
- VS refers to the volatile solids excreted in manure (kg/head/day), differentiated by categories (calves, cows, bulls, heifers) and stage of production (cow-calf, backgrounding, feedlot).
- B_0 is the maximum methane producing capacity of the manure produced by each animal category (CH_4/kg of volatile solids) and
- 0.67 is the conversion factor of volume to mass (kg/m^3)

Volatile organic solids were estimated using Equation 10.24 of the IPCC (2019) guidelines.

$$VS = \left(GE\ \left(1 - \frac{TDN}{100}\right) + 0.04GE\right) * \frac{1 - \frac{ASH}{100}}{18.45}$$

where

- VS refers to the volatile solids excreted in manure (kg/head/day), differentiated by categories (calves, cows, bulls, heifers) and stage of production (cow-calf, backgrounding, feedlot)
- GE is the gross energy intake in MJ/day
- TDN is the total digestible nutrients in feed (represented as a % of feed)
- ASH is the ash content of the feed calculated as a % of dry matter intake and
- 18.45 is a conversion factor for dietary gross energy per kilogram of dry matter intake (MJ/kg) and is used as a default due to being relatively constant across a range of forage and grain-based diets used in cattle operations.

Direct N2O emissions from manure deposited in pastures and manure management were calculated using a Tier II approach based on equation 10.25 of IPCC (2019) which is simplified as follows.

$$N_2O - N_{direct,manure} = N_{ex} * EF_{dir}$$

where

- $N_2O - N_{direct,manure}$ is the direct manure management related emission rate in kg N/head/day
- N_{ex} is the nitrogen excretion rate in manure (kg N/head/day) and
- EF_{dir} is the emission factor for direct N_2O emissions

Indirect nitrogenous emissions from manure deposited on pastures and manure management include volatilization of nitrogen as ammonia and nitrous oxide, and nitrate leaching. Equation 10.26 of the IPCC (2019) guidelines were used to calculate indirect nitrous oxide emissions from volatization, which is simplified below as

$$N_2O - N_{manure,volatization} = N_{ex} * Frac_{vol} * EF_{vol}$$

where

- $N_2O - N_{manure,volatization}$ is the amount of manure lost to volatization of ammonia and nitrous oxide (kg N/head/day)
- EF_{vol} is the emission factor for volatization and
- $Frac_{vol}$ is the fraction of managed manure that volatizes as ammonia or nitrous oxide.

For calculating the amount of nitrogen lost due to leaching, equation 10.27 of IPCC (2019) was used.

$$N_2O - N_{manure,leaching} = N_{ex} * Frac_{leach} * EF_{leach}$$

where

- $N_2O - N_{manure,leaching}$ is the amount of manure lost to leaching of ammonia and nitrous oxide (kg N/head/day)
- EF_{leach} is the emission factor for leaching and
- $Frac_{leach}$ is the fraction of managed manure that gets leached.

The data used for calculating volatile excreted solids is provided in Table 28 below. All these values are sourced from a single source (Feedipedia, 2024) for consistency and are combined with feed composition data reported for each country in Section 3.1 to determine volatile excreted solid amounts.

Table 28: Data used for estimating volatile organic solids excreted

Ingredient	**Dry matter (%)**	**GE (MJ/kg of DM)**	**TDN (%)**	**Ash (%)**
Grass - forage	31.3	18	58.4	9.5
Corn-grain	87.2	18.7	89	1.4
Hay	91.5	18.3	53.5	8.3
DDGS (corn)	89	21.4	83.3	5.4
Grass silage	30.8	18.2	64.2	8.2
Corn silage	30	18.9	71.1	3.9
Minerals	-	-	-	-
Soy meal	88	19.7	91.1	7.3
Wheat middlings	87.9	19.2	78.9	4.3
Bakery waste	90.7	19.1	93	2.8

2.5.9.5 N2O emissions from feed crops

Modelling of N2O emissions for all crops followed the methods detailed in each country's NIR, which were all based on IPCC methods (IPCC 2019). Direct field-level N2O emissions were calculated using equation 11.2 of IPCC (2019) as follows

$$N_2O_{direct} - N = \sum\nolimits_i (F_{SN} + F_{ON})_i \times EF_{1i} + (F_{CR} + F_{SOM}) \times EF_1 + N_2O - N_{OS} + N_2O - N_{PRP}$$

where

- $N_2O_{direct} - N$ represents the annual direct N_2O–N emissions produced from managed soils in kg N_2O–N year^{-1}
- F_{SN} represents the amount of synthetic fertilizer N applied to soils in kg N year^{-1}
- F_{ON} represents the annual amount of animal manure, compost, sewage sludge, and other organic N additions applied to soils in kg N year^{-1}
- EF_{1i} represents emissions factors developed for N_2O emissions from synthetic fertilizers, organic N application, N inputs from crop residues, and mineralization of N due to losses of soil organic matter in kg N_2O-N (kg N input)$^{-1}$
- F_{CR} represents the annual amount of N in above and belowground crop residues, including N-fixing crops, and from forage/pasture renewal, returned to soils in kg N/year
- F_{SOM} represents the annual amount of N in mineral soils that is mineralised, in association with loss of soil C from soil organic matter as a result of changes to land use or management, in kg N year^{-1}

Indirect N2O emissions from volatization of ammonia and nitrogen oxides were estimated according to equation 11.11 of IPCC (2019) as follows

$$N_2O_{(ATD)} - N = \left\{ \sum_i \left(F_{SN_i} \times Frac_{GASF_i} \right) + \left[(F_{ON} + F_{PRP}) \times Frac_{GASM} \right] \right\} \times EF_4$$

where

- $N_2O_{(ATD)}$ – N represents the annual amount of N_2O – N produced from atmospheric deposition of N volatilised from managed soils in kg N_2O–N /year
- F_{SN} represents the annual amount of synthetic fertilizer N applied to soils in kg N year^{-1}

- $Frac_{GASF}$ represents the fraction of synthetic fertilizer N that volatilises as NH_3 and NO_x in kg N volatilised (kg of N applied)$^{-1}$
- F_{ON} represents the annual amount of managed animal manure, compost, sewage sludge and other organic N additions applied to soils in kg N /year
- $Frac_{GASM}$ represents the fraction of applied organic N fertilizer materials (F_{ON}) that volatilises as NH_3 and NO_x, in kg N volatilised (kg of N applied or deposited)$^{-1}$
- EF_4 represents emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces, in [kg N–N_2O (kg NH_3–N + NO_x–N volatilised)$^{-1}$]

Indirect emissions from nitrate leaching were calculated using equation 11.10 of IPCC (2019) as follows

$$N_2O_{(L)} - N = (F_{SN} + F_{ON} + F_{PRP} + F_{CR} + F_{SOM}) \times Frac_{Leach-(H)} \times EF_5$$

where

- $N_2O_{(L)}$–N represents the annual amount of N_2O–N produced from leaching and runoff of N additions to managed soils in regions where leaching/runoff occurs, in kg N_2O–N/year
- F_{SN} represents the annual amount of synthetic fertilizer N applied to soils in regions where leaching/runoff occurs, in kg N/year
- F_{ON} represents the annual amount of managed animal manure, compost, sewage sludge and other organic N additions applied to soils in regions where leaching/runoff occurs, in kg N/year
- F_{CR} represents the amount of N in crop residues (above- and below-ground), including N-fixing crops, and from forage/pasture renewal, returned to soils annually in regions where leaching/runoff occurs, in kg N/year
- F_{SOM} represents the annual amount of N mineralised in mineral soils associated with loss of soil C from soil organic matter as a result of changes to land use or management in regions where leaching/runoff occurs, in kg N/year

- $Frac_{Leach}$ represents the fraction of all N added to/mineralised in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff, in kg N (kg of N additions)$^{-1}$
- EF_5 represents the emission factor for N_2O emissions from N leaching and runoff, in kg N_2O–N (kg N leached and runoff)$^{-1}$

2.5.9.6 CO_2 emissions from urea and liming

Carbon dioxide emissions as a result of adding carbonate limes and urea to soils were estimated using Equation 11.12 of IPCC (2019) as follows

$$CO_2 - C = M * \ EF_{lime\ or\ urea}$$

where,

- CO_2-C is the C emissions from lime or urea application in tonnes of C/year
- M is the amount of limestone or urea applied in tonnes/year
- $EF_{lime\ or\ urea}$ is the emissions factor in tonnes of C/tonne of limestone and urea

Table 29 below summarizes all of the emission factors and fractions used for modelling emissions across all three countries considered.

Table 29: Emission factors and fractions used in calculating manure management and field-level crop-related emissions

Emission factors and fractions*	Western Canada	USA	Brazil
Manure management			
B_o (Ch4/kg of VS)	0.19	0.17	0.1
MCF	0.029 for backgrounders and finishers, 0.01 for cow-calf phase	0.015 for backgrounders and finishers, 0.0047 for cow-calf phase	0.02
EF_{dir} (non pasture)	0.0074	0.02	-

EF_{dir} (pasture)	0.00064	0.02	0.02
EF_{vol} (non pasture)	0.005	0.01	-
EF_{vol} (pasture)	0.005	0.01	0.01
EF_{leach} (non pasture)	0.0075	0.0075	-
EF_{leach} (pasture)	0.0075	0.011	0.0075
$FRAC_{vol}$ (non pasture)	0.318	0.23	-
$FRAC_{vol}$ (pasture)	0.2	0.21	0.2
$FRAC_{leach}$ (non pasture)	0.215	0.3	-
$FRAC_{leach}$ (pasture)	0.215	0.24	0.3
Crop field-level emissions			
EF_1 – synthetic N application	0.008	0.0021	0.01
EF_1- crop residues	0.007	0.0021	0.01
$FRAC_{GASF}$	0.061	0.11	0.1
$FRAC_{GASM}$	0.21	0.21	0.2
EF_4 – indirect N volatization	0.01	0.01	0.01
$FRAC_{LEACH}$	See supplementary information Section 6.1	0.24	0.3
EF_5 – indirect N leaching	0.011	0.011	0.0075
Urea emissions factor	0.2	0.2	0.2
Lime emission factor	0.12	0.12	0.12

2.5.10 Impact assessment method

The carbon footprint of each crop-country model was calculated using the IPCC 2021 Assessment Report (AR) 6 methodology (Cilleruelo, 2022). This method is based on the most recent AR6 released by the IPCC (IPCC, 2022), which reports all characterization factor values used in calculation of global warming impacts.

2.5.11 Data quality and uncertainty assessment

Data quality indicators were computed for each LCI data point based on the pedigree matrix scores assigned during the data quality assessment stage (reported in Tables 8-23). These pedigree matrix scores were entered into openLCA for each flow. The openLCA software was used to calculate the total uncertainty (geometric standard deviation) associated with the data quality indicators. In addition to data quality uncertainty, the other source of uncertainty that was accounted for was the parameter uncertainty, known as the base uncertainty in openLCA. This represents the stochastic uncertainty associated with the variability in the value for each data point, rather than the quality of the data (Bamber et al., 2019). These uncertainty values were sourced from Frischknecht et al., (2005), which provides generic base uncertainty factors specific to sector or type flow (supplementary information section 6.2). These generic factors were used since data were collected from various sources and it was not possible to consistently calculate the variability of the data values. The uncertainty of the impact assessment results was calculated using Monte Carlo simulation, which propagates the uncertainty in the inventory data to the results to determine the overall uncertainty of the model. Each Monte Carlo simulation was performed with a total of 1000 runs, which is the most common method of uncertainty propagation for agricultural LCAs (Bamber et al., 2019).

2.5.12 Sensitivity analysis

Sensitivity analyses were performed to determine the sensitivity of the final results to any changes in methodological choices and to inventory data points that made significant contributions to the overall carbon footprint results. The first sensitivity analysis focussed on using an alternate methane conversion factor (MCF) for cattle consuming grass diets (in the cow-calf and yearling phases). The Western Canadian MCF of 7% was higher than the US and Brazilian MCFs (6.5%) for grass diets – with 6.5% also being the default IPCC Tier 1 MCF. Given the significant role of enteric methane emissions and the cow-calf herd (which are on pastures and hence a grass diet) to the overall carbon footprint, a sensitivity analysis using the 6.5% MCF for cattle on grass diets in Western Canada was performed.

The second sensitivity analysis focussed on manure management emissions since the emission factors for direct and indirect N_2O emissions for manure deposited on pastures was significantly different between Western Canada and the other two countries (and contributing strongly to the difference in carbon footprint results of the two countries as seen in section 3.3). The IPCC Tier 1 emission factors for direct and indirect N_2O emissions from manure deposited on pastures used in the Brazilian and US models were also applied to the Western Canadian model.

The third sensitivity analysis also focussed on manure management and involved applying IPCC Tier 1 default manure excretion rates (as done in the Brazilian model) to the Western Canadian and US beef models (the IPCC manure excretion rates for North America are different from South America). The nitrogen excretion rates influence all manure-related emissions specified in section 2.5.9.4.

The fourth sensitivity analysis substituted all Western Canadian corn inputs with US corn. This was due to suggestions by industry experts that a significant proportion of corn used in Alberta feedlots is sourced from the US since much of Canadian corn production is concentrated in Ontario. Due to the lack of any reliable literature to back this claim or an estimate from the experts consulted, a 100% substitution was considered to determine the sensitivity of the results.

Finally, due to the lack of any regional breakdown of land use change-related SOC estimates in the Brazilian NIR and the regional differences in land use patterns that exists between states, an alternate estimate of SOC fluxes from land use changes obtained from the BRLUC online tool (https://brluc.cnpma.embrapa.br/) and weighted by state production data (ABIEC, 2022) was used to test the sensitivity of the carbon footprint estimate of Brazilian beef production. The data used to calculate this alternate SOC estimate is provided in supplementary section 6.5.

3 Results and Discussion

3.1 Inventory data for beef production systems

Table 30 below represents a simplified comparative inventory for the cow-calf, backgrounding, and finishing phases of beef production in each of the regions being analysed. Additional inventory data specific to each of the regions modelled are reported separately in sections 3.1.1-3.1.3.

Calving rates were comparable in Western Canada (91%) and USA (88%) but considerably lower in Brazil (70%). Replacement rates (11-15%), mortality rates (1-3%), and cows to bull ratio (19-25) in the cow-calf phase were similar across all three regions. Stocking rates were highest in Western Canada (1.8 animal units/hectare) among the three countries. Brazilian stocking rates (1.23 AU/hectare) were comparable to Western Canada but stocking rates in the US were considerably lower (0.18 AU/hectare). This was largely due to the very low stocking rates seen in Western USA (13-17 hectares per cow-calf pair), with only south eastern USA reporting relatively high stocking densities (1 hectare per cow-calf pair).

Weights at the end of the cow-calf phase in Western Canada was 260.8 kilograms for calves going directly to feedlot and 226.8 kilograms for calves going to backgrounding. This was comparable to the weight at the end of the cow-calf phase in Brazil (220 kilograms). The data source used for modelling US beef production did not report weights at the end of the cow-calf and backgrounding phase and instead reported all material and energy inputs (e.g. feed intake) during each phase relative to a kilogram of carcass weight. Similarly, the Brazilian data source did not report feed intakes separately across the three phases since all three phases were primarily grass-based diets from foraging on pasture – with minor changes in grain supplements included in each phase. Hence the feed intake values for Brazil are reported cumulatively for all three phases in Table 30. Overall feed intake for Brazilian beef production was higher than in Western Canada and the US. This can be attributed to the higher number of days spent on a grass-based diet and the low calving rates in Brazil, which resulted in a higher proportion of cows in the modelled herd being attributed to each animal unit.

Reported finishing weights were much higher in Western Canada (~650-680 kilograms per calf) compared to USA (586 kilograms) and Brazil (570 kilograms). This resulted in considerable variations with respect to estimate feed intake, enteric methane emissions, and nitrous oxide emissions from manure management (the latter two are modelled based on dry matter intake). This was the primary reason for not presenting the results in section 3.3 relative to the animal unit modelled for each country. Instead, carbon footprint results in section 3.3 are presented relative to live and carcass weights.

Table 30: Simplified inventory table for cow-calf, backgrounding, and finishing phases of beef production in the regions compared

Data point	Western Canada	USA	Brazil	Unit
Cow calf phase				
Calving rate	91	88	70	%
Replacement rate	14	11	15	%
Mortality rate	Calves -3.3%; Cows 1.5%; Bulls-1.2%;	2	1.6	%
Cows to bull ratio	19	19.22	25	number of cows per bull
Start weight	44.9	-	30	kg
End weight	226.8 for calves going to backgrounding, 260.8 for calves going to feedlot	-	220	kg
Duration of cow calf phase	205	221	240	days
Feed intake	6713.49	5734.28	Reported cumulatively in finishing phase	kilograms/animal unit
Water consumption	22854.16	19288.91	-	kilograms/animal unit
Stocking rate	1.8	0.18	1.23	cow-calf pair/hectare
Enteric methane	4,307.59	3,447.60	Reported cumulatively in finishing phase	kg CO2-eq./animal unit
Manure management	278.27	966.74	Reported cumulatively in finishing phase	kg CO2-eq./animal unit

Backgrounding				
Start weight	226.8	-	220	kg
End weight	358.96 for calves going direct to feedlot, 453.59 for calves put on pasture as yearlings	289.78	350	kg
Duration	151 days backgrounding, 108 yearling phase	88	360	days
Feed intake	857.89	870.76	Reported cumulatively in finishing phase	kilograms/animal unit
Water consumption	3726.29	3144.99	-	kilograms/animal unit
Enteric methane	558.92	523.4	Reported cumulatively in finishing phase	kg CO2-eq./animal unit
Manure management	51.49	57.45	Reported cumulatively in finishing phase	kg CO2-eq./animal unit
Finishing feedlot				
Start weight	260.8 for calves from cow-calf, 358.96 for calves from backgrounding, 453.51 for calves after time on pasture as yearlings	289.78	350	kg
End weight	653 for calves direct from cow-calf, 680 for calves after backgrounding and yearling phases	586.04	570.00	kg
Duration	270 for calves from cow-calf, 214 for calves from backgrounding, 140 for calves after time on pasture as yearlings	149	480	days
Feed intake	1831.795	1313.22	29747 (across all three phases)	kilograms/animal unit
Water consumption	7800.41	6583.55	-	kilograms/animal unit

Enteric methane	1,004.68	473.74	7799.96	kg CO2-eq./animal unit
Manure management	252.76	295.98	3448.05	kg CO2-eq./animal unit
Dressing percentage	60	60.4	55	%

3.1.1 Western Canada

As described in section 2.1, 45% of calves were sent directly to feedlots for finishing and 55% go through a backgrounding phase. The direct to feed lot system is referenced as the calf-fed (CF) system and the backgrounding system is referenced as the yearling-fed (YF) system, based on the description of these systems in the CRSB report (CRSB 2023). Managed pasture was considered minimal in Western Canada, with ~1% of pasture land irrigated and no significant inputs of fertilizers. Yields from pasture foraged by the cattle were not included since this data is not often reported in LCAs or carbon footprint studies. Instead, pasture is assumed to meet the feed requirements of the cattle on the days designated as pasture days (this assumption was applied for USA and Brazil as well), and the total amount of biomass consumed is calculated based on the average daily feed intake. No nutrient inputs, plant protection products, or irrigation was modelled for pastures used for beef production in Western Canada. Information on how pasture-related emissions such as those associated with land use changes, soil organic carbon, and manure deposited on pastures are all described in Section 3.5.

The CRSB report (CRSB 2023) provided feed rations separately for the cow-calf, backgrounding, and feedlot operation (Table 31). For the days estimated for the animals to be on pasture, the only feed intake considered was the grass foraged by the animals. For the days estimated to be on feed, the animals were assumed to consume a combination of harvested forage and grain (ratios vary depending on the stage). This, combined with the daily dry matter intake (calculated as a % of body weight), was used to determine the total feed consumption.

Table 31: Feed composition data for different cattle types and different stages of Western Canadian beef production

Data point	Calves (CF)	Finishers (CF)	Calves (YF)	Backgrounders (YF)	Yearlings (YF)	Finishers (YF)	Cows	Bulls
On pasture (days)	188	0	188	38	100	0	290	287
On feed (days)	17	270	17	113	8	140	75	78
Barley (%)	15.6	71.4	15.6	22		71.4	0.6	0.6
Corn (%)	1.9	1.3	1.9			1.3	9.3	8.8
Wheat (%)		4.65				4.65		
Oats (%)	0.6		0.6	4.5			1.8	1.9
Barley silage (%)	19.2	8.5	19.2	27.5	35.3	8.5	4.1	4.1
Corn silage (%)	8.3		8.3	1.5			0.6	0.7
Grass silage (%)	7.5		7.5	4.6	6.5		0.9	1
Hay (%)	44		44	20	45.3		71.2	72
Straw (%)	1.3		1.3				7.9	6.9
Oat silage (%)	1.2		1.2				2.2	2.8
DDGS* (%)		10.3		19	8	10.3	0.2	0.2
Minerals and salt (%)	0.1		0.1				0.9	0.9
Other (%)		2.8		1	4.5	2.8		

**Dried distiller grains*

All other material and energy inputs to characterize the beef production system in Western Canada is provided in the Table 32 below. The energy consumption data was provided in the CRSB report as amount per head of cattle per day – without differentiation between the cow-calf, backgrounding, and feedlot stages. Given the relatively minor contribution to the carbon footprint expected from the energy inputs (CRSB 2023), these inputs were divided among the three stages based on the ratio of number of days spent in each stage (from Table 30).

Table 32: Energy use data for the Western Canadian beef production system

Data point	Unit	Value
Electricity	kWh/head/day	0.04
Natural gas	Cubic feet/head/day	0.05
Diesel	Litres/head/day	0.02
Gasoline	Litres/head/day	0.003
Feed transportation	kilometres	15
Cow-calf to feedlots or backgrounding	kilometres	300
Backgrounding to feedlots	kilometres	300
Water consumption		
Calves	Litres/head/day	8
Cows	Litres/head/day	41.5
Bulls	Litres/head/day	45
Backgrounders	Litres/head/day	20.5 (calves), 32 (yearlings)
Finishers	Litres/head/day	38

The enteric methane emissions for the different cattle types and diet types across different phases of the Western Canadian beef production process are provided in Table 33 below. These values were combined with the proportion of each cattle type in a reference animal unit and number of days spent in each phase to determine the enteric methane emissions reported in Table 30.

Table 33: Enteric methane emissions for each cattle type in Western Canada in kg CH4/head/day

	Yearling fed	Calf fed
Calves on grass diet	0.07	0.08
Calves on grain diet	0.08	0.09
Backgrounders	0.09	0.00

Yearlings	0.22	0.00
Finishers	0.18	0.14
Cows	0.27	0.27
Bulls	0.36	0.36

Table 34 below represents the composition of manure management strategies used in Canadian backgrounding and feedlots.

Table 34: Manure storage strategies used in Western Canadian backgrounding and feedlots

Manure storage practices	% share of storage practice
Liquid or slurry	7.4
Solid stockpile	46.8
Manure piles on field	18.9
Anaerobic lagoon/digester	6.8
Composting	16.8

Table 35 below represents the manure management-related emissions estimated for each cattle type in Western Canada. These values were combined with the proportion of each cattle type in a reference animal unit and number of days spent in each phase to determine the manure-related emissions reported in Table 30.

Table 35: Manure related emissions for each cattle type in Western Canada in kg emission/head/day

	CH4 (kg/head/day)-YF system	CH4 (kg/head/day)-CF system	Direct N_2O (kg/head/day)	N_2O volatized (kg/head/day)	N_2O leached (kg/head/day)
Calves on grass	1.53E-03	1.78E-03	7.43E-05	1.16E-04	1.87E-04
Calves on feed	1.53E-03	1.78E-03	8.59E-04	1.85E-04	1.87E-04
Backgrounders on pasture	3.18E-03	0	7.43E-05	1.16E-04	1.87E-04
Backgrounders in feedlot	8.12E-03	0	8.59E-04	1.85E-04	1.87E-04
Yearlings	4.96E-03	0	1.86E-04	2.90E-04	4.68E-04

Finishers	1.07E-02	8.86E-03	2.15E-03	4.62E-04	4.68E-04
Cows	6.62E-03	6.62E-03	2.04E-04	3.18E-04	5.13E-04
Bulls	9.04E-03	9.04E-03	3.06E-04	4.77E-04	7.70E-04

3.1.2 United States

As described in section 3.1.2, data to characterize the beef production system in the US was obtained largely from a series of surveys (Asem-Hiablie et al., 2018, 2017, 2016, 2015) and the National Agricultural Statistical Service, or from Rotz et al. (2019), which used data from those two sources to simulate beef production in the IFSM tool. For all data points for which the Asem-Hiablie et al. (2018, 2017, 2016, 2015) surveys were used as the source, production weighted averages were calculated. The Asem-Hiablie et al. (2018, 2017, 2016, 2015) surveys covered regions that account for 93% of beef production in the USA. The factors used to calculate production weighted averages for these regions are provided in the Table 36.

Table 36: Share of beef production for major producing regions modelled in the USA

Region	**Production weighted average factor**
Texas, Kansas, Oklahoma	0.28
Northern provinces	0.15
Midwest	0.15
Northwest	0.11
Southwest	0.10
Northeast	0.04
Southeast	0.18

Inventory data characterizing US beef production (in addition to those reported in Table 30) are provided below in Table 37. This includes data on energy consumption across phases, the feed intake data relative to carcass weight that were used to calculated feed intake per animal unit (as reported in Table 30), and pasture fertilization data (% of pasture land that is fertilized and fertilization rate).

Table 37: Preliminary inventory table characterizing the beef production system in USA

Data point	Unit	Value
Cow-calf operations		
Fuel inputs	Litres of diesel per animal	50.68
Electricity use	kWh/animal	75.90
Average daily feed intake - grazing	Kg dry matter/ kg of CW*	12.3
Average daily feed intake – harvested forage	Kg dry matter/ kg of CW*	3.2
Average daily feed intake – grain supplement	Kg dry matter/ kg of CW*	0.7
Equipment – pickup truck	Cattle number per equipment	270-724
Equipment – tractors and all terrain vehicles	Cattle number per equipment	400
Pasture characteristics in cow-calf operations		
Proportion of pasture receiving synthetic N fertilizer inputs	%	8.52
Proportion of pasture receiving P fertilizer inputs	%	4.68
Proportion of pasture receiving K fertilizer inputs	%	5.3
Nitrogen fertilizer application**	Kg N/ha	86.36
Phosphorus fertilizer application**	Kg N/ha	44.16
Potash fertilizer application**	Kg N/ha	51.29
Backgrounding		
Average daily feed intake - grazing	Kg dry matter/ kg of CW*	0.89
Average daily feed intake – harvested forage	Kg dry matter/ kg of CW*	1.3
Average daily feed intake – grain supplement	Kg dry matter/ kg of CW*	0.27
Feedlot finishing		

Fuel inputs (including backgrounding)	Litres/animal	8.2
Electricity use (including backgrounding)	kWh/animal	31.24
Natural gas	M3/animal	14.34
Average daily feed intake - grazing	Kg dry matter/ kg of CW*	0
Average daily feed intake – harvested forage	Kg dry matter/ kg of CW*	0.62
Average daily feed intake – grain supplement	Kg dry matter/ kg of CW*	3.09

**Carcass weight based on assumed dressing percentage of 60.4%.*
***Rate of application only for proportion of grazing land fertilized, not all grazing land*

The average feed compositions used in the backgrounding and finishing phases for each region is provided in Tables 38 and 39, respectively. One issue identified with these feed composition numbers in the Asem-Hiablie et al. (2018, 2017, 2016, 2015) surveys was the lack of granularity. For example, the feed composition data only specified how much silage was included in the feed, but did not mention whether the silage was from grass or crops (corn or wheat). As a result, silage was modelled as a combination of grass and corn silage, with their respective contributions being based on the data modelled for Western Canada. Similarly, the feed composition data did not specify what the relative contributions of ingredients listed as 'other' were. Since the three commonly reported other feed ingredients in Asem-Hiablie et al. (2018, 2017, 2016, 2015) were soy meal, wheat middlings, and bakery waste, they were assumed to account for equal shares within the 'other' feed ingredients classification.

Table 38: Feed composition for the backgrounding phase in each production region for US beef

Region	**Production weighted average factor**	**Corn**	**Hay**	**Silage**	**Minerals**	**Other**	**DDGS**
Texas, Kansas, Oklahoma	0.28	26.8	17.3	14.8	2.7	2	37.1
Northern provinces	0.15	19.1	22.7	17.1	2.7	8.8	29.5
Midwest	0.15	26.6	21.6	22.2	2	11.8	15.7
Northwest	0.11	19	10	48	1.8	5	15

Southwest	0.10	21	43	12	2	18	5.4
Northeast	0.04	19	25	44	1.1	4	6
Southeast	0.18	14	37	10	2.1	23	14

Table 39: Feed composition for the feedlot finishing phase in each production region for US beef

Region	Production weighted average factor	Corn	Hay	Silage	Minerals	Other	DDGS
Texas, Kansas, Oklahoma	0.28	68.8	4.7	6.2	3.7	7.1	9.1
Northern provinces	0.15	49.7	8.2	5.4	2.4	7.8	26.4
Midwest	0.15	51.1	3.9	11.4	2.2	11.4	19.9
Northwest	0.11	43	14	12	1	20	10
Southwest	0.10	64	9	4	2.9	10	9
Northeast	0.04	45	6	29	1.5	13	6
Southeast	0.18	18	38	13	2.4	12	17

The enteric methane emissions for the different cattle types and diet types across different phases of the US beef production process are provided in Table 40 below. These values were combined with the proportion of each cattle type in a reference animal unit, average feed intake, and time spent in each phase to convert the emissions relative to one animal unit as reported in Table 30.

Table 40: Enteric methane emissions for each cattle type in USA in kg CH4/kg of CW

Cattle type	Enteric methane (kg CH4/kg of CW)
Calves-forage	0.038
Calves-feed	0.001
Backgrounders-forage	0.047
Backgrounders-feed	0.006
Finishers	0.048
Cows	0.292
Bulls	0.019

Table 41 represents the manure management-related emissions estimated for each cattle type in the US. These values were combined with the proportion of each cattle type in a reference animal unit, average feed intake, and time spent in each phase to convert the emissions relative to one animal unit as reported in Table 30. In the US, dry lot storage of manure is assumed to be the only manure storage strategy.

Table 41: Manure related emissions for each cattle type in US in kg emission/head/day

	CH4 (kg/kg of CW)	Direct N2O (kg/head/day)	N2O volatized (kg/head/day)	N2O leached (kg/head/day)
Calves-forage	9.61E-05	3.78E-03	3.97E-04	4.99E-04
Calves-feed	1.58E-05	3.78E-03	4.35E-04	4.26E-04
Backgrounders-forage	4.81E-04	3.78E-03	3.97E-04	4.99E-04
Backgrounders-feed	7.82E-05	3.78E-03	4.35E-04	4.26E-04
Finishers	1.50E-03	5.65E-03	6.49E-04	6.35E-04
Cows	1.16E-03	6.14E-03	6.45E-04	8.11E-04
Bulls	1.54E-03	7.01E-03	7.36E-04	9.26E-04

3.1.3 Brazil

Most of the data used to build the Brazilian beef production system inventory model (i.e. cattle numbers and cattle performance) were sourced from Florindo et al. (2017), which is based on primary data from a farm based on Mato Grosso do Sul - a representative state from the Central-West region, with additional data from Cardoso et al. (2015) that were sourced from relatively high-quality sources, such as Empraba reports or the Brazilian livestock yearbook (ANUALPA/FNP, 2008). During the cow-calf phase, calves received grain supplements containing 30% corn meal and 51% soybean meal. The cattle also receive mineral supplementation during the backgrounding and finishing phases (Florindo et al. 2017). No additional mineral or protein supplements are provided during cattle finishing. Table 42 contains additional inventory data to those presented in Table 30 related to Brazilian beef production such as volume of grain and mineral supplements, energy use, and fertilizer application in pastures.

Table 42: Additional inventory data for Brazilian beef production

Input	Amount	Unit
Cow-calf stage		
Mineral supplements	19.84	Kg/animal unit
Grain supplements	33.86	Kg/animal unit
Backgrounding and Finishing		
Mineral supplements	55.29	Kg/animal unit
Electricity	21.48	kWh/animal unit
Pasture establishment		
Limestone	2237.037	Kg/hectare
Seeds	15	Kg/hectare
Herbicide	1	Kg/hectare
Fertilizer	8.889	Kg/hectare
Diesel	11.852	L/hectare
Pasture maintenance		
Herbicide	4.5	Kg/hectare
Fertilizer	64	Kg/hectare

No separate methane conversion factors were found for different cattle types (cows, bulls, heifers, etc.) in Brazil. Given that the entire beef production process has a grass-based diet (which has a default Ym values of 6.5%), a standard enteric methane emission rate of 0.491 kilogram of CH_4/kilogram of carcass weight was calculated and used to determine the enteric methane emissions reported in Table 30. Table 43 provides the emissions related to manure deposited on pasture that was used to calculate the cumulative manure management related emissions in Table 30.

Table 43: Manure related emissions for Brazilian beef cattle in kg emission/kg of CW

Emission	Beef cattle
CH4 (kg/kg of CW)	1.23E-02
Direct N2O (kg/head/day)	9.34E-03
N2O volatized (kg/head/day)	9.34E-04
N2O leached (kg/head/day)	1.05E-03

3.2 Inventory data for feed crop inputs

This section provides inventory tables for all feed crop inputs (Tables 44 to 57). These inventory tables are based on data extracted from the data sources specified in section 2.5 for each crop in each region.

3.2.1 Western Canada

The inventory data tables for all major feed crop inputs to Western Canadian beef production are provided below.

3.2.1.1 Barley

Table 44: Inventory data for 1 kilogram of barley production in Western Canada

Flow	Amount	Unit
Inputs		
Yield	1.00	kg
Seed	0.04	kg
N fertilizer	0.02	kg
P fertilizer	0.01	kg
K fertilizer	0.003	kg
S fertilizer	0.002	kg
Ammonia	0.005	kg
Urea	0.014	kg
Urea ammonium nitrate (UAN)	0.003	kg
Ammonium sulfate	0.002	kg
Mono ammonium phosphate (MAP)	0.0004	kg
Mono ammonium phosphate (MAP)	0.015	kg
Potassium chloride	0.006	kg
Agricultural chemicals (pesticides)	0.0004	kg

Irrigation energy	0.001	kWh
Energy use for field activities	0.34	MJ
Transportation of crop inputs	50	kg*km
Post-harvest energy use	0.003	kWh
Output		
Barley	1.00	kg
Carbon dioxide - SOC flux	-0.13	kg
Carbon dioxide from lime and urea application	0.02	kg
Dinitrogen monoxide	0.001	kg

3.2.1.2 Corn

Table 45: Inventory data for 1 kilogram of corn production in Western Canada

Flow	Amount	Unit
Inputs		
Seed	0.002	kg
N fertilizer	0.02	kg
P fertilizer	0.01	kg
K fertilizer	0.004	kg
S fertilizer	0.001	kg
Ammonia	0.003	kg
Urea	0.009	kg
Urea ammonium nitrate (UAN)	0.002	kg
Ammonium sulfate	0.001	kg
Mono ammonium phosphate (MAP)	0.0002	kg
Mono ammonium phosphate (MAP)	0.007	kg
Potassium chloride	0.006	kg
Agricultural chemicals (pesticides)	0.0002	kg
Irrigation energy (for Alberta only)	0.002	kWh
Energy use for field activities	0.23	MJ
Transportation of crop inputs	50	kg*km
Post-harvest energy use	0.24	MJ
Output		
Corn	1.00	kg
Corn stover	0.15	kg

Carbon dioxide - SOC flux	-0.05	Kg
Carbon dioxide from lime and urea application	0.01	kg
Dinitrogen monoxide	0.0004	kg

3.2.1.3 Wheat

Table 46: Inventory data for 1 kilogram of wheat production in Western Canada

Flow	Amount	Unit
Inputs		
Seed	0.04	kg
N fertilizer	0.03	kg
P fertilizer	0.01	kg
K fertilizer	0.003	kg
S fertilizer	0.002	kg
Ammonia	0.007	kg
Urea	0.018	kg
Urea ammonium nitrate (UAN)	0.004	kg
Ammonium sulfate	0.007	kg
Mono ammonium phosphate (MAP)	0.0005	kg
Mono ammonium phosphate (MAP)	0.015	kg
Potassium chloride	0.006	kg
Agricultural chemicals (pesticides)	0.0004	kg
Irrigation energy (Alberta only)	0.001	kWh
Energy use for field activities	0.32	MJ
Transportation of crop inputs	50	kg*km
Post-harvest energy use	0.003	kWh
Output		
Wheat	1	kg
Wheat straw	0.12	kg
Carbon dioxide - SOC flux	-0.15	kg
Carbon dioxide from lime and urea application	0.03	Kg
Dinitrogen monoxide	0.001	kg

3.2.1.4 Oats

Table 47: Inventory data for 1 kilogram of oat production in Western Canada

Flow	Amount	Unit
Inputs		
Seed	0.04	kg
N fertilizer	0.02	kg
P fertilizer	0.01	kg
K fertilizer	0.003	kg
S fertilizer	0.001	kg
Ammonia	0.006	kg
Urea	0.013	kg
Urea ammonium nitrate (UAN)	0.003	kg
Ammonium sulfate	0.006	kg
Mono ammonium phosphate (MAP)	0.0004	kg
Mono ammonium phosphate (MAP)	0.013	kg
Potassium chloride	0.006	kg
Agricultural chemicals (pesticides)	0.0004	kg
Irrigation energy (Alberta only)	0.001	kWh
Energy use for field activities	0.30	MJ
Transportation of crop inputs	50	kg*km
Post-harvest energy use	0.003	kWh
Output		
Oats	1	kg
Carbon dioxide - SOC flux	-0.14	kg
Carbon dioxide from lime and urea application	0.01	kg
Dinitrogen monoxide	0.001	kg

3.2.1.5 Grass hay and silage

Table 48: Inventory data for 1 kilogram of grass hay and silage production in Western Canada

Flow	Amount	Unit
Inputs		
Seed	0.0004	kg
N fertilizer	0.005	kg

P fertilizer	0.01	kg
K fertilizer	0.005	kg
S fertilizer	0.004	kg
Ammonia	0.001	kg
Urea	0.003	kg
Urea ammonium nitrate (UAN)	0.001	kg
Ammonium sulfate	0.0004	kg
Mono ammonium phosphate (MAP)	0.0001	kg
Mono ammonium phosphate (MAP)	0.014	kg
Potassium chloride	0.005	kg
Ammonia sulfate	0.004	kg
Agricultural chemicals (herbicide-Glyphosate)	0.0004	kg
Irrigation energy (only for 1% of forage land in Saskatchewan)	0.05	kWh
Energy use for field activities	0.29	MJ
Paper	3.0E-05	kg
Cardboard	3.0E-05	kg
Polypropylene	2.1E-05	kg
High density polyethylene	2.1E-05	kg
Output		
Harvested forage	1.00	kg
Dry matter loss during storage	0.05	kg
Carbon dioxide - SOC flux	4.6E-05	kg
Carbon dioxide from lime and urea application	0.005	kg
Dinitrogen monoxide	0.0002	kg

3.2.1.6 Other silage

For barley, corn, wheat, and oat silage production in Western Canada, all inventory data specified in the respective crop tables above (Tables 44-47) were used without change with the only exception being the yields. Table 49 below specifies the yield multiplication factor applied for silage production for each of these crops in Western Canada.

Table 49: Yield multiplication factors for non-grass silage production in Western Canada

Crop	Yield multiplication factor for silage
Wheat	3.2
Barley	2.3
Oats	1.8
Corn	3.11

3.2.1.7 Plant protection products composition for Western Canada

Since the CRSC reports from which data for feed crop production in Western Canada was gathered did not specify the specific types and amounts of plant protection products used, a default composition (Table 50) based on the Alberta pesticide sales data was created and applied across all crop products.

Table 50: Default pesticide composition for feed crops in Western Canada

Active ingredient	% of total applied
Glyphosate	49.506%
Glufosinate	5.678%
MCPA	5.526%
Surfactant blend	4.507%
2,4-D	3.828%
Petroleum hydrocarbon blend	2.377%
Bromoxynil	2.196%
Bentazon	1.581%
Fluroxypyr	1.560%
Triallate	1.329%
Diquat	1.037%
Ethalfluralin	1.022%
Polyoxyalkylated alkyl phosphate ester	0.841%
Paraffin Base Petroleum Oil	0.835%
Prothioconazole	0.797%
Azoxystrobin	0.900%
Propiconazole	1.200%
Boscalid	0.900%
Chlorothalonil	0.020%
Fluorpyram	0.200%

Fluxapyroxad	0.020%
Pyraclostrobin	0.400%
Other fungicides	1.363%
Other Herbicide	6.560%
Other Ajuvant	3.916%
Other Insecticide	1.900%

3.2.2 USA

3.2.2.1 Corn

Table 51: Inventory data for 1 kilogram of corn production in the US

Flow	Amount	Unit
Inputs		
Seed	0.003	kg
Lime	0.04	kg
N fertilizers	0.007	kg
P fertilizers	0.005	kg
K fertilizers	0.006	kg
S fertilizers	0.001	kg
Ammonia	0.002	kg
Ammonium nitrate	0.0001	kg
Ammonia sulfate	0.0002	kg
Di ammonium phosphate	0.0007	kg
Urea ammonium nitrate (UAN)	0.0019	kg
NPK compound (NPK 15-15-15)	0.0005	kg
Urea	0.0017	kg
Di ammonium phosphate	0.0034	kg
NPK compound (NPK 15-15-15)	0.0035	kg
PK compound (NPK 0-22-22)	0.0001	kg
Single superphosphate	1.4E-05	kg
Triple superphosphate	0.0001	kg
NPK compound (NPK 15-15-15)	0.0016	kg
PK compound (NPK 0-22-22)	8.3E-05	kg
Potassium chloride	0.0048	kg
Potassium sulfate	0.0002	kg
Ammonia sulfate	0.0042	kg
Agricultural chemicals (pesticides)	0.002	kg
Irrigation energy	0.08	MJ
Field activities energy	0.27	MJ

Flow	Amount	Unit
Post-harvest energy	0.11	MJ
Transportation	52.13	kg*km
Output		
Corn	1	kg
Corn stover	0.15	kg
Carbon dioxide - SOC flux	0.05	kg
Carbon dioxide from lime and urea application	0.02	kg
Dinitrogen monoxide	0.0001	kg

3.2.2.2 Soy

Table 52: Inventory data for 1 kilogram of soy production in the US

Flow	Amount	Unit
Inputs		
Seed	0.03	kg
Lime	0.14	kg
N fertilizers	0.005	kg
P fertilizers	0.04	kg
K fertilizers	0.05	kg
S fertilizers	0.004	kg
Ammonium nitrate	0.0005	kg
Urea	0.001	kg
Urea ammonium nitrate	0.003	kg
Di ammonium phosphate	0.015	kg
Single superphosphate	0.002	kg
Triple superphosphate	0.020	kg
Potassium chloride	0.027	kg
Potassium sulfate	0.021	kg
Ammonia sulfate	0.004	kg
Agricultural chemicals (pesticides)	0.001	kg
Irrigation energy	2.1E-06	MJ
Field activities energy	0.80	MJ
Post-harvest energy	0.02	MJ
Transportation	34.20	kg*km
Output		
Soybean	1	kg
Carbon dioxide - SOC flux	0.07	kg

Flow	Amount	Unit
Carbon dioxide from lime and urea application	0.09	kg
Dinitrogen monoxide	0.0001	kg

3.2.2.3 Wheat

Table 53: Inventory data for 1 kilogram of wheat production in the USA

Flow	Amount	Unit
Inputs		
Seed	0.05	kg
Lime	0.12	kg
N fertilizers	0.05	kg
P fertilizers	0.02	kg
K fertilizers	0.01	kg
Ammonia	0.009	kg
Ammonium sulfate	0.003	kg
Mono ammonium phosphate	0.001	kg
Urea	0.025	kg
Urea ammonium nitrate	0.006	kg
Mono ammonium phosphate	0.017	kg
Potassium chloride	0.006	kg
Total pesticides	0.0003	kg
Irrigation energy	2.9E-09	MJ
Field activities energy	1.29	MJ
Post-harvest energy	0.53	kWh
Transportation	20.90	kg*km
Output		
Wheat	1	kg
Wheat straw	0.123	kg
Carbon dioxide - SOC flux	0.07	kg
Carbon dioxide from lime and urea application	0.06	kg

3.2.2.4 Corn silage

Table 54: Inventory data for 1 kilogram of corn silage production in the US

Flow	Amount	Unit
Inputs		
Yield	1.00	kg
Seed	0.01	kg
Lime	0.40	kg
Fertilizer mix	0.004	kg
Ammonium sulfate	0.0002	kg
Calcium ammonium nitrate	0.0001	kg
Di ammonium phosphate	0.0003	kg
Liquid urea-ammonium nitrate	0.0016	kg
NPK compound (NPK 15-15-15)	0.0003	kg
PK compound (NPK 0-22-22)	1.3E-05	kg
Potassium chloride	0.0005	kg
Potassium sulfate	2.73E-05	kg
Single superphosphate	2.54E-06	kg
Triple superphosphate	9.78E-06	kg
Urea	0.0009	kg
Total pesticides	2.6E-06	kg
Field activities energy	0.06	MJ
Transportation	53.86	kg/km
Output		
Corn silage	1	kg
Carbon dioxide - SOC flux	0.01	kg
Carbon dioxide from lime and urea application	0.004	kg
Dinitrogen monoxide	6.4E-05	kg

3.2.2.5 Grass hay and silage

Table 55: Inventory data for 1 kilogram of grass hay and silage production in the US

Flow	Amount	Unit
Inputs		
Seed	0.01	kg
Lime	0.40	kg
Fertilizer mix	0.004	kg
Ammonium nitrate	0.0001	kg
Ammonium sulfate	0.0002	kg
Di ammonium phosphate	0.0003	kg
Liquid urea-ammonium nitrate	0.0016	kg
NPK compound (NPK 15-15-15)	0.0003	kg
PK compound (NPK 0-22-22)	1.3E-05	kg
Potassium chloride	0.0005	kg
Potassium sulfate	2.7E-05	kg
Single superphosphate	2.5E-06	kg
Triple superphosphate	9.8E-06	kg
Urea	0.0009	kg
Total pesticides	2.6E-06	kg
Field activities energy	0.06	MJ
Transportation	53.86	kg*km
Output		
Harvested forage	1	kg
SOC flux	-0.001	kg
Carbon dioxide from lime and urea application	0.006	kg
Dinitrogen monoxide	6.3E-05	kg

3.2.3 Brazil

The data inventories presented in Tables 56 and 57 represent the production of Brazilian soybean and corn, which serve as the primary ingredients in the mineral creep feed utilized in calf supplementation feeding within the Brazilian beef production system.

3.2.3.1 Soybean

Table 56: Inventory data for 1 kilogram of soy production in Brazil

Input	Amount	Unit
Seed	0.019615	kg
Lime	0.08	kg
N fertilizers	0.004	kg
P fertilizers	0.087	kg
K fertilizers	0.049	kg
S fertilizers	0.001	kg
Ammonium nitrate	0.0009	kg
Calcium ammonium nitrate	0.0002	kg
Urea	0.0031	kg
Di ammonium phosphate	0.0016	kg
Phosphate rock, beneficiated	0.0026	kg
Single superphosphate	0.0608	kg
Triple superphosphate	0.0215	kg
Potassium chloride	0.0485	kg
Potassium sulfate	0.0001	kg
Ammonium sulfate	0.001	kg
Field activities	0.938	MJ
Irrigation energy	9.16E-04	MJ
peat moss	1.12E-07	m3
Plant protection consumption	0.0016	kg
Post-harvest energy	9.76E-06	kWh
Transportation	20.5	kg*km
Output		
Soybean	1	kg
Carbon dioxide - SOC flux	0.39	kg
Carbon dioxide from lime and urea application	0.04	kg
Dinitrogen monoxide	0.0002	kg

3.2.3.2 Corn

Table 57: Inventory data for 1 kilogram of corn production in Brazil

Input	Amount	Unit
Seed	0.04	kg
Fertilizer mix	0.31	kg
Ammonium nitrate	0.022	kg
Ammonium sulfate	0.034	kg
Calcium ammonium nitrate (CAN)	0.008	kg
Di ammonium phosphate	0.033	kg
Lime	0.400	kg
NPK compound (NPK 15-15-15)	0.012	kg
Phosphate rock	0.001	kg
PK compound (NPK 0-22-22)	0.000	kg
Potassium chloride (NPK 0-0-60)	0.061	kg
Potassium sulfate (NPK 0-0-50)	0.0002	kg
Single superphosphate	0.038	kg
Triple superphosphate	0.013	kg
Urea	0.085	kg
Electricity use for irrigation	0.001	MJ
Diesel use for irrigation	3.55	MJ
Diesel use for on field activities	0.003	MJ
Plant protection consumption	0.003	kg
Lime	0.40	kg
Transportation	0.07	Kg*km
Water-irrigation	0.0005	m3
Output		
Corn	1	kg
Carbon dioxide - SOC flux	0.24	kg
Carbon dioxide from lime and urea application	0.04	kg
Dinitrogen monoxide	0.34	kg

3.3 Impact assessment

3.3.1 Beef production systems

Overall, the carbon footprint of Western Canadian beef (8.95 kg CO2-eq.) was the lowest among the three countries considered, while Brazil (22.93 kg CO2-eq.) was the highest per kilogram of live weight of finished beef cattle. The carbon footprint of US beef production (10.96 kg CO2-eq.) was 22.7% higher than that of beef from Western Canada (Figure 2). The carbon footprint of Brazilian beef production was about 157% and 109% higher than Western Canadian and US beef production, respectively, on a live weight basis. These large differences were primarily driven by the soil organic losses associated with land conversion to grasslands and higher enteric methane emissions associated with finishing cattle on grass in Brazil. With enteric methane emissions in Brazil, grass finished beef is impacted by both the higher methane conversion factor (Y_m) of grass-based diets and the increased number of days it takes to achieve finishing weights.

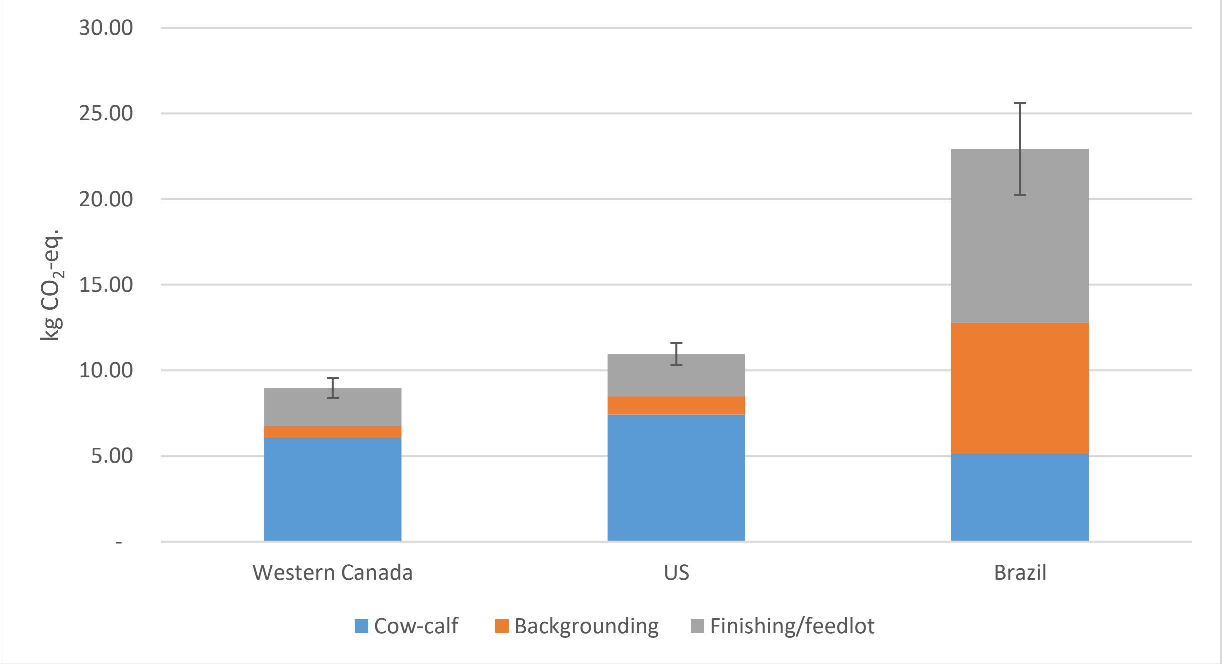


Figure 2: Carbon footprint of 1 kg of live weight beef produced – contributions by phase of production. Error bars represent one standard deviation from the mean.

The contributions of the different stages of the beef production process were similar for both Western Canada and US (Figure 2). The majority of the impacts were attributable to the cow-calf phase in both countries (67-68%), with feedlot finishing (23-25%) and backgrounding (8-10%) having relatively lower impacts. In Brazil, the finishing phase accounted for the largest share of impacts (44%), followed by backgrounding (33%) and the cow-calf phase (22%). The higher share of impacts associated with the finishing phase in Brazil was due to the higher enteric methane emissions resulting from the longer finishing period, and the soil organic carbon losses from converting forestland into pastures and rangeland for beef production.

Looking at the sources of impacts across the different phases (Figure 3), enteric methane emissions accounted for 79.9% of the overall carbon footprint in Western Canada, 61% in US, and 49% in Brazil. While the difference in the respective share of enteric methane to overall impacts was quite large between Western Canada and the US, the actual enteric methane emissions per kilogram of live weight was only 7% higher in the US. The primary drivers of differences in enteric methane emissions between Western Canada and US were the higher methane conversion factor for the cows and bulls in the cow-calf phase in Western Canada (7% vs 6.5%), and the presence of a yearling phase after backgrounding for about 25% of calves, during which they are on a primarily grass-based diet. Per kilogram of live weight, the enteric methane emissions were 7.15 kg CO_2-eq., 6.68 kg CO_2-eq., and 11.38 kg CO_2-eq. for Western Canada, US, and Brazil respectively. The results of a sensitivity analysis performed by using the default 6.5% methane conversion factor for Western Canadian beef cattle on grass-based diets in the cow-calf and yearling phases is shown in section 3.3.2.

Feed consumption was the second highest source of impacts in Western Canada (11.5%) and the third highest contributor in the USA (12%). In Brazil, the contribution of feed inputs is relatively minor (0.3%) since this only takes into account impacts from harvested forage and feed supplementation. The impacts associated with cattle foraging in pastures and rangeland is not accounted for in this category. If all of the impacts associated with pastures and rangeland is considered – including soil organic carbon fluxes due to land use change – the share of feed consumption in the overall carbon footprint of beef production was the highest in Brazil (29.3%).

The carbon footprints of all grain and harvested forage inputs to the feed compositions of beef production in each country are provided in Table 58 relative to one kilogram of yield for the respective crop. A detailed breakdown of the LCIA results of crop inputs are provided in the supplementary information section 6.3

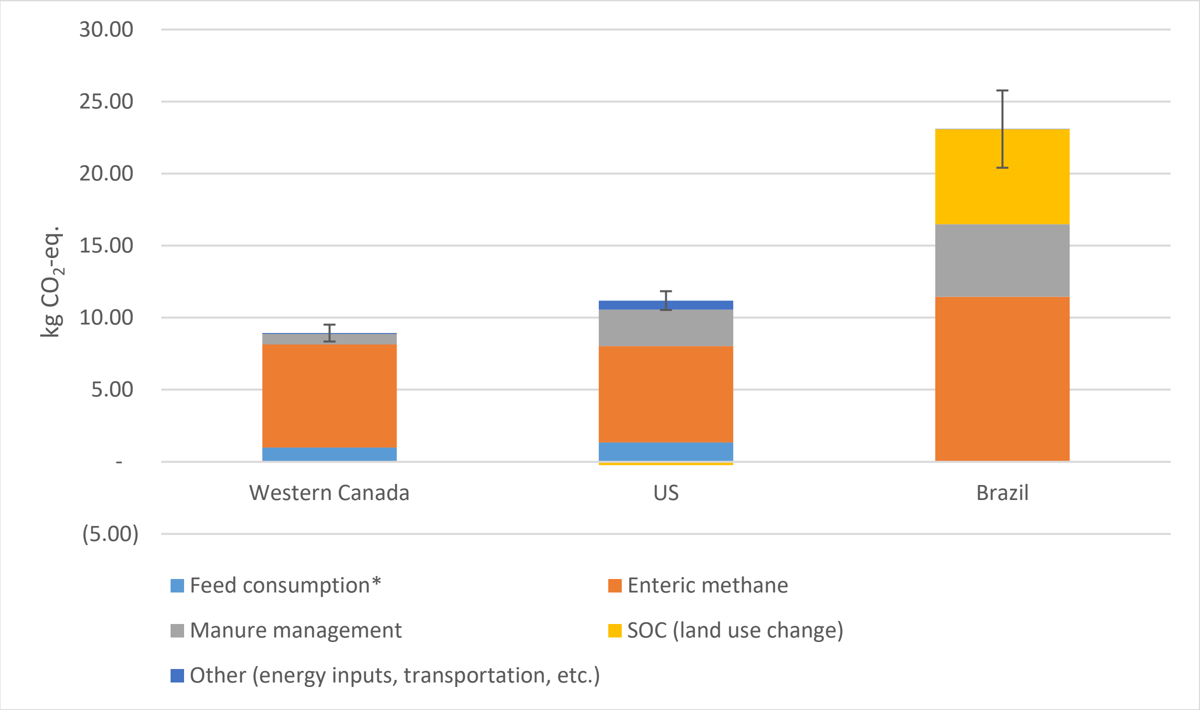


Figure 3: Carbon footprint of 1 kg of live weight beef produced – contributions by source of impacts. Error bars represent one standard deviation from the mean.

Table 58: Carbon footprints of crops for grain and harvested forage inputs per kilogram of yield

Crop	Western Canada	US	Brazil
Barley	0.1485	-	-
Corn	0.1302	0.1651	0.9365
Grass (for hay and silage)	0.1612	0.0736	-
Oats	0.1144	-	-
Soybean	-	0.3591	0.676
Wheat	0.1574	0.6523	-
Corn silage	0.0041	0.056	-
Barley silage	0.0148	-	-
Oat silage	0.2375	-	-
Wheat silage	0.0455	-	-

Impacts associated with manure management – including the deposition of manure on pastures and rangeland by cattle while grazing – was the other major contributor to the carbon footprint across the three regions, and was by far the biggest source of difference between the carbon footprints of Western Canadian and US beef. Manure management impacts were considerably lower in Western Canada (0.73 kg CO_2-eq. per kg of live weight) compared to USA (2.53 kg CO_2-eq.) and Brazil (5.03 kg CO_2-eq.). This was primarily down to using country-specific Tier 2 emission factors from the Western Canadian NIR, including a detailed breakdown of manure management practices that included a significant share of anaerobic digestion. The US NIR (EPA, 2023) does not provide a detailed breakdown of manure management practices (with dry lot stockpiling assumed to be the common practice across the country) and does not provide country-specific emissions factors for modelling N_2O emissions due to adopting a Tier 3 process-based modelling approach for field-level N_2O emissions. Given that N_2O is 273 times a more potent greenhouse gas than CO_2, the difference in manure-related emission factors related to both direct and indirect N_2O emissions contributed overwhelmingly to the difference in carbon footprint between the two North American regions modelled. The results of a sensitivity analysis performed by using Tier 1 emission factors for manure management in Western Canada is presented in section 3.3.2.

Soil organic carbon fluxes resulting from land use change was a significant contributor to the overall carbon footprint only in Brazil (3.63 kg CO_2-eq. per kg of live weight), accounting for 29% of the impacts. These impacts were primarily a result of forest land being converted to pastures and rangeland for beef production. Based on the Brazilian NIR, there was a net soil organic carbon loss of ~3500 kg CO_2-eq. per hectare of grassland in Brazil, with Brazilian beef production having a stocking rate of 1.23 hectares per animal unit. Land use change also made a non-trivial contribution to US beef production emissions, resulting from conversion of cropland into grassland (pastures or rangeland). Grasslands are considered to sequester more carbon than croplands and, as a result, US beef production had a net carbon sequestration of 150.53 kg CO_2-eq. per kg of live weight (~2% reduction in carbon footprint). In contrast, since the majority of pasture and rangeland used for beef production in Western Canada is natural prairie grassland with very little conversion of other land use types to grassland, no significant changes in soil organic carbon composition associated with land use change is modelled in the Canadian NIR. Energy inputs and transportation contributed relatively trivial amounts (< 1%) to the overall carbon footprint across all three regions.

Figures 4 and 5 present the carbon footprint of beef production in the three regions considered relative to one kilogram of carcass weight. It is important to note again that this does not include any of the impacts associated with the slaughtering process (reasons for excluding this were already discussed in section 2.5.4) or transportation from finishing to slaughter. The primary reason for presenting results relative to carcass weights is due to the reported differences in dressing percentages between *Bos taurus* (US and Western Canada) and *Bos indicus* (Brazil) cattle. Due to the lower dressing percentage of Brazilian beef cattle (55%) compared to the other two countries (60%), the carbon footprint of Brazilian beef per kilogram of carcass weight (41.68 kg CO_2-eq.) was 180% and 130% higher than Western Canadian (14.88 kg CO_2-eq.) and US (18.15 kg CO_2-eq.) beef production, respectively.

Table 59 below presents the carbon footprint of beef production characterised per animal unit finished, one kilogram of live weight, one kilogram of carcass weight, and one kilogram of boneless beef. As with the calculation of impacts per kilogram of carcass weight described previously, the impacts per kilogram of boneless beef are calculated based on the fraction of animal weight that is considered boneless and does not include any impacts associated with the processes required to transform live finished beef cattle at the farm gate into boneless beef products, nor any allocation to beef processing co-products. For Western Canada and the US, a conversion factor of 1.4 (AAFC, 2021) was used to convert impacts per kilogram of carcass weight to impacts per kilogram of boneless meat. For Brazil, 17.7% of the animal weight is assumed to be bone (Barcellos et al., 2017).

Table 59: Carbon footprint (kg CO_2-eq.) of beef produced characterized relative to different reference units.

Reference unit	Western Canada	USA	Brazil
1 Animal unit	7061.4 (788.98 kg finishing weight)	7293.0 (665.42 kg finishing weight)	15822.2 (685.24 kg finishing weight)

1 kg of live weight	8.95	10.96	22.93
1 kg of carcass weight	14.88	18.15	41.68
1 kg of boneless meat	20.84	25.42	60.30

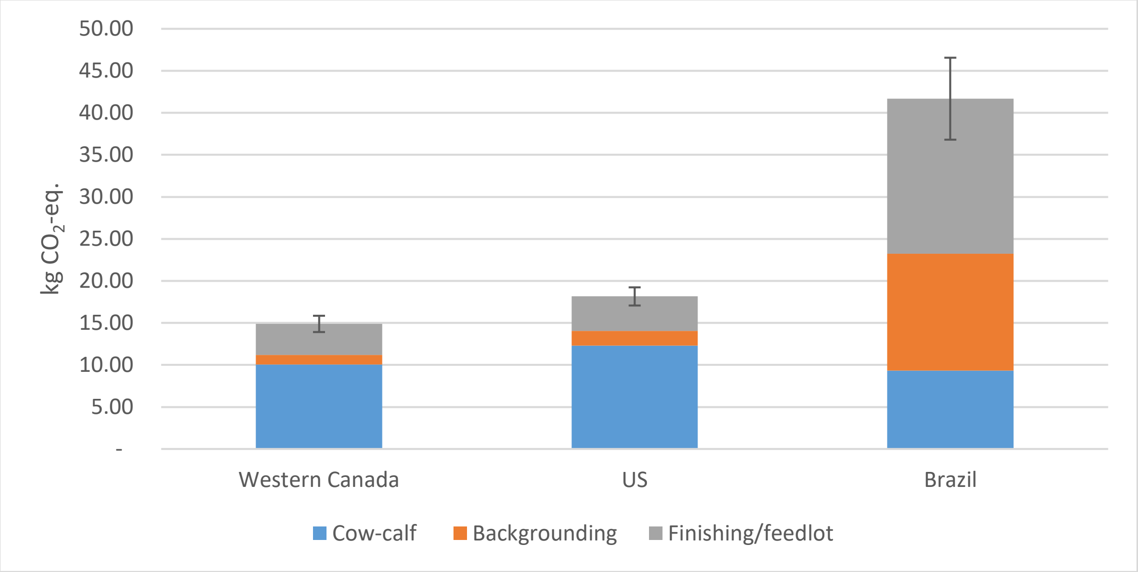


Figure 4: Carbon footprint of 1 kg of carcass weight beef produced – contributions by phase of production. Error bars represent one standard deviation from the mean.

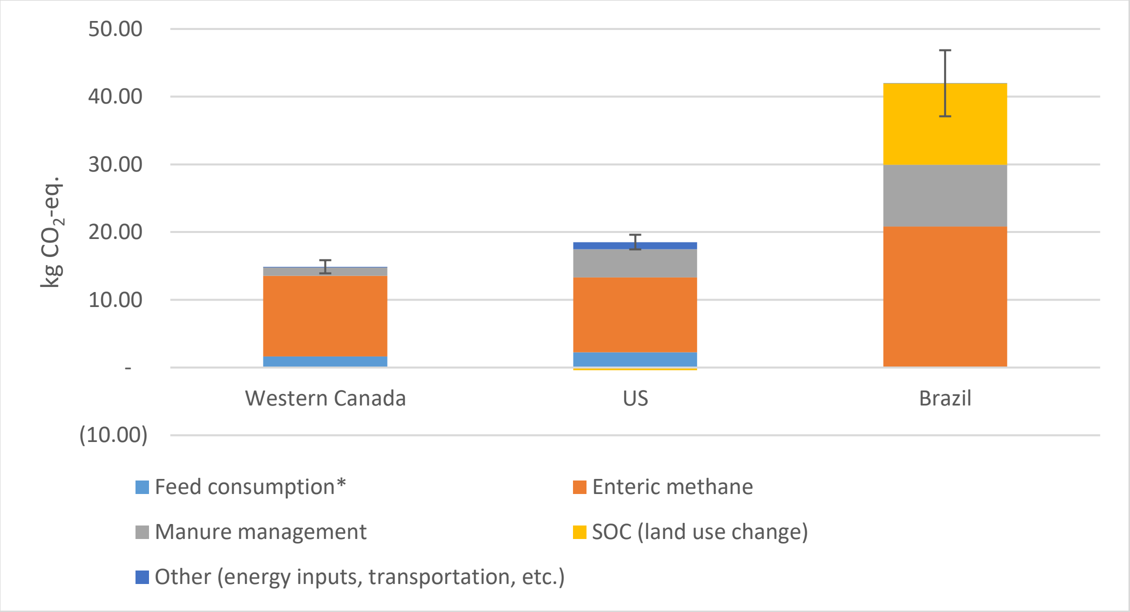


Figure 5: Carbon footprint of 1 kg of carcass weight beef produced – contributions by source of impacts. Error bars represent one standard deviation from the mean.

Finally, Figure 6 represents the carbon footprint of producing beef per kilogram of live weight without the contributions of soil organic carbon fluxes. Both the Western Canadian (6%) and US (1%) impacts increase slightly due to the removal of carbon sequestered in feed inputs and carbon sequestered from converting cropland to grasslands respectively. The carbon footprint of Brazilian beef production reduced considerably (29%) when soil organic carbon losses due to land use change were excluded. However, the carbon footprint of Brazilian beef was still 42.7% and 32.7% higher than Western Canadian and US beef, respectively. Per kilogram of live weight, the carbon footprint estimates without the inclusion of soil carbon fluxes were 9.44 kg CO_2-eq., 11.09 kg CO_2-eq., and 16.48 kg CO_2-eq. for Western Canada, US, and Brazil respectively.

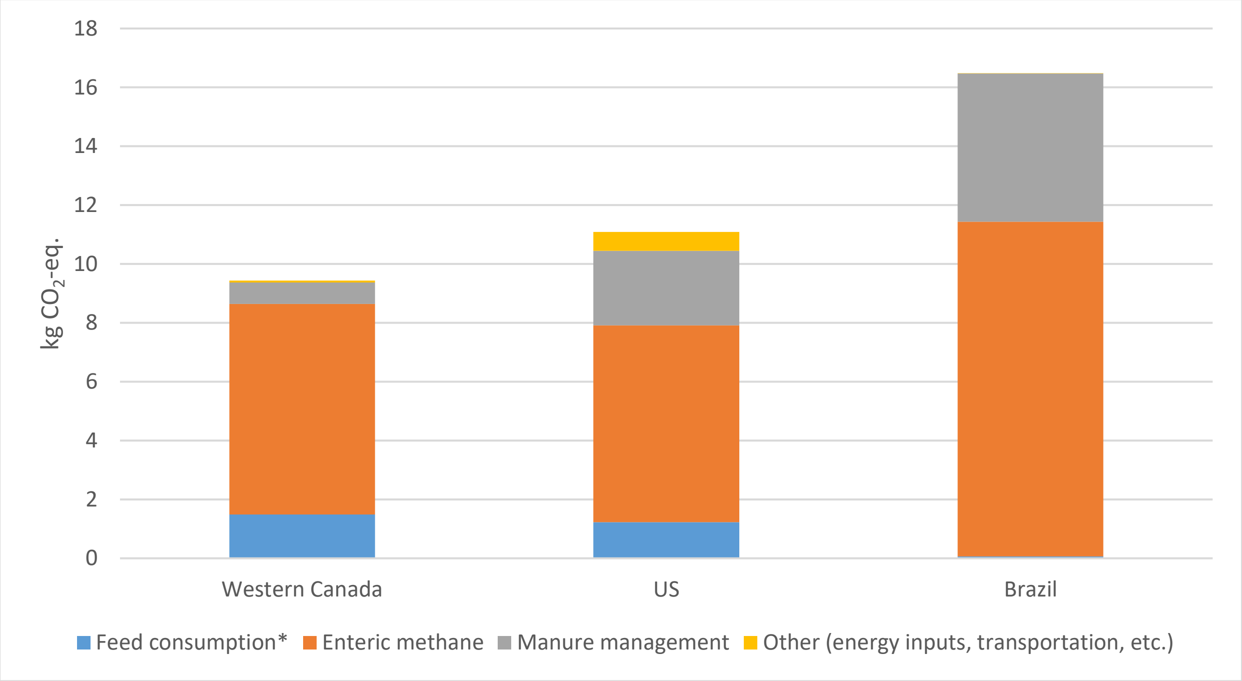


Figure 6: Carbon footprint of 1 kilogram of live weight beef produced without SOC contributions

The impact assessment results represented in Figures 2-6 and discussed in section 3.3 are provided in the supplementary information section 6.4.

3.3.2 Uncertainty and sensitivity analysis

The results of the Monte Carlo simulations showed that uncertainty was higher in Brazil compared to Western Canada and the USA. This was largely due to the inventory data for the

Brazilian beef production system modelled being of comparatively poorer quality – in particular with respect to temporal correlation and completeness.

T-tests were performed comparing the Western Canadian beef production system against the US and Brazilian systems using the results of the Monte Carlo simulation. In both, the P-values were less than 0.001, indicating strong statistical significance of the observed differences between these systems. An ANOVA comparing all three systems also resulted in a P-value less than 0.001 and the statistical significance of the differences was further validated by the F-value being higher than the F critical value (at $\alpha = 0.05$). The 95% confidence interval of the Monte Carlo Simulation results were +/- 0.043, 0.045, and 0.20 from the respective means for Western Canada, USA, and Brazil. The results table for the T-test are provided in supplementary information section 6.4 and are presented relative to one representative animal unit. The error bars used in figures 2-5 represent one standard deviation from the mean and not the 95% confidence intervals for the 1000 Monte Carlo simulated values for each region.

Sensitivity analysis

When the default 6.5% MCF for cattle on grass diets was used in the Western Canadian model instead of the country-specific 7% value, a 4.6% reduction in enteric methane emissions per kilogram of live weight beef was observed. This resulted in a non-trivial change (3%) to the overall carbon footprint estimates for Western Canada. This highlighted the importance of selecting appropriate MCFs in estimating carbon footprints, but the sensitivity analysis showed that the relative differences seen between the regions compared did not change significantly when using default Tier 1 emission factors.

The carbon footprint estimates for Western Canadian beef production were found to be highly sensitive to the emission factors used for direct and indirect N_2O emissions from manure deposited on pastures. The use of default IPCC Tier 1 emission factors increased the manure-management related impacts per kilogram of live weight by almost 3 times, resulting in a carbon footprint estimate (10.41 kg CO_2-eq.) that was 16.5% higher for Western Canada. Despite this increase, Western Canadian beef still had the lowest carbon footprint – albeit with a smaller (5% vs. 22.7%) difference – compared to the US estimate.

The use of default manure excretion rates for Western Canada and the US (similar to Brazil) resulted in small differences in the overall carbon footprint estimates for both countries. Western Canadian carbon footprint estimates increased by 0.3% and the US estimate decreased by 4.9%. These small changes, however, did not result in any significant changes to the relative impacts of the beef production systems compared in the three countries. Overall, the sensitivity analyses performed showed that, while methodological choices made – especially those related to emission factors – were important to the carbon footprint estimates for each region modelled, Western Canadian beef still had the lowest impacts, followed by the USA, and Brazil.

Replacing corn grain inputs in Western Canadian beef production with corn produced in the US resulted in a 0.9% increase in the carbon footprint per kilogram of live weight. Similarly, the use of an alternate regionally-weighted estimate of SOC fluxes only produced a small (1%) increase in the carbon footprint estimate per kilogram of Brazilian live weight beef. This is likely because the Brazilian NIR – from which SOC fluxes related to land use changes was sourced – likely uses (but not explicitly reported) a regionally-weighted land use change model to calculate SOC changes.

3.3.3 Comparison of results to other studies

The carbon footprint estimated for Western Canadian beef in this study (8.93 kg CO_2-eq. per kilogram of live weight) was comparable to values reported in CRSB (2023) for Western Canada (10.5 kg CO_2-eq.). This study used newer feed crop models based on the data sources described in section 2.5.7.4 compared to CRSB (2023) and this accounted for a significant share of the difference in overall estimates. Feed related impacts in this study were 0.98 kg CO_2-eq. per kilogram of live weight as compared to 2.1 kg CO_2-eq. in CRSB (2023). In addition, the CRSB study did not take into account soil carbon changes associated with land use, used a different emission factor for direct N_2O emissions associated with manure deposited in pastures, and did not take into account the beef produced from replaced cows in the cow-calf herd. The estimates for enteric methane (6.68 kg CO_2-eq. in this study vs. 6.5 kg CO_2-eq. in the CRSB study) were very similar between the two studies.

The carbon footprint estimate for US beef production in this study (18.15 kg CO_2-eq. per kg of carcass weight) was comparable (up to ~16% difference) to the most recently published beef LCA studies for US beef production. Castaño-Sánchez et al. (2023) estimated the carbon footprint of beef produced in Southwest USA to be 17.2 kg CO_2-eq. The carbon footprint estimates at the farm-gate for US beef developed using aggregation of individual farm models in the Integrated Farm Simulation Model (IFSM) by Rotz et al. (2019) and Putman et al.(2023) were 21.0 kg CO_2-eq. and 21.3 kg CO_2-eq. per kilogram of carcass weight, respectively. These differences are likely due to IFSM using a process-based model to estimate cattle growth, feed consumption, emissions from manure management, and productivity and emissions associated with feed crop production.

Comparison of the estimated carbon footprints of Brazilian beef across studies is not easy given that studies are often focussed on a particular region, often model a small number of farms, and may or may not include land use-related impacts. Dick et al. (2015) estimated the carbon footprint to be 22.5 kg CO_2-eq. per kilogram of live weight beef in extensive grazing systems. A report by the Centre for Sustainable Studies at Fundação Getulio Vargas's Sao Paulo School of Business Administration (FGV EAESP) reported the carbon footprint of Brazilian beef to be 28-47 kg CO_2-eq. per kilogram of packaged boneless beef (FGVces, 2019). Morais et al. (2023)reported that carbon footprint estimates for Brazil ranged between 18.3 kg CO_2-eq. per kilogram of live weight at the farm gate and 42.6 kg CO_2-eq. per kg of packaged beef. Cederberg et al. (2011) reported that Brazilian beef had a carbon footprint of 28 kg CO_2-eq. per kilogram of carcass without the inclusion of land use related impacts. All these values are in a comparable range to the carbon footprint estimate for Brazilian beef in this study (22.93 kg CO_2-eq. per kilogram of live weight). Taking into account impacts associated with slaughter, processing, and packaging, the carbon footprint estimate per kilogram of carcass weight is also comparable to the estimate in this study (41.68 kg CO_2-eq.) Overall, the carbon footprint estimates for all three regions modelled were found to be quite similar – and when different, largely within a ~15% range – to other studies in literature.

4 Conclusion

Overall, the carbon footprint of Western Canadian beef production was lower by 22.7% and 157% compared to US and Brazilian beef production. Enteric methane was found to be the largest source of GHG emissions across the three countries, with manure management and feed use also being significant contributors. In Western Canada and the USA, the majority of the enteric methane and manure-related emissions were attributable to the cow-calf phase whereas. in Brazil, the impacts were highest in the finishing phase (due to a prolonged grass-based finishing period). Impacts associated with land use change represented a significant proportion (29%) of the overall impacts for Brazil. Without the impacts of soil carbon fluxes included, impact of Brazilian beef was still 43% and 33% higher than Western Canadian and US beef respectively.

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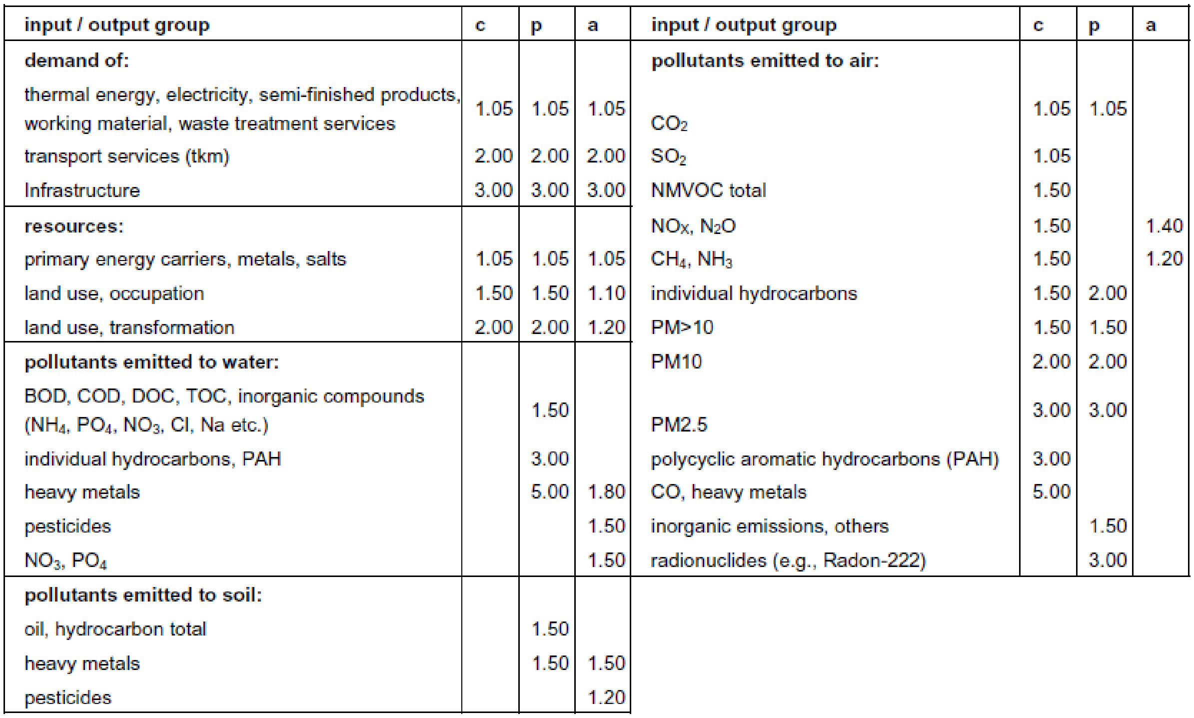
6 Supplementary Information

6.1 Leaching and run-off fractions for indirect N_2O emissions associated with fertilizer application in feed crop production in Western Canada

RU	$FRAC_{LEACH}$
22	0.2489
23	0.2019
24	0.1858
28	0.1745
29	0.1667
30	0.1539
34	0.1119
35	0.183
37	0.1689

6.2 Basic uncertainty factors from Frischknecht et al. (2005)



input / output group	c	p	a
demand of:			
thermal energy, electricity, semi-finished products, working material, waste treatment services	1.05	1.05	1.05
transport services (tkm)	2.00	2.00	2.00
Infrastructure	3.00	3.00	3.00
resources:			
primary energy carriers, metals, salts	1.05	1.05	1.05
land use, occupation	1.50	1.50	1.10
land use, transformation	2.00	2.00	1.20
pollutants emitted to water:			
BOD, COD, DOC, TOC, inorganic compounds (NH_4, PO_4, NO_3, Cl, Na etc.)		1.50	
individual hydrocarbons, PAH		3.00	
heavy metals		5.00	1.80
pesticides			1.50
NO_3, PO_4			1.50
pollutants emitted to soil:			
oil, hydrocarbon total		1.50	
heavy metals		1.50	1.50
pesticides			1.20

input / output group	c	p	a
pollutants emitted to air:			
CO_2	1.05	1.05	
SO_2	1.05		
NMVOC total	1.50		
NO_X, N_2O	1.50		1.40
CH_4, NH_3	1.50		1.20
individual hydrocarbons	1.50	2.00	
PM>10	1.50	1.50	
PM10	2.00	2.00	
PM2.5	3.00	3.00	
polycyclic aromatic hydrocarbons (PAH)	3.00		
CO, heavy metals	5.00		
inorganic emissions, others		1.50	
radionuclides (e.g., Radon-222)		3.00	

6.3 Breakdown of the carbon footprint of all feed inputs modelled (per kilogram of yield)

Western Canada	Barley	Corn	Oats	Wheat	Grass hay
Seed	0.0048	0.0002	0.0044	0.0053	0.0001
Fertilizer consumption	0.0512	0.0258	0.0530	0.0604	0.0251
Plant protection	0.0036	0.0019	0.0038	0.0038	0.0038
Field activities	0.0274	0.0169	0.0241	0.0246	0.0234
Irrigation energy	0.0005	0.0014	0.0002	0.0010	0.0378
Post-harvest consumption	0.0014	0.0161	0.0004	0.0013	
Transportation	0.0106	0.0092	0.0106	0.0100	
Field-level CO2	0.0226	0.0197	0.0067	0.0279	0.0048
Field-level N2O	0.1444	0.0873	0.1499	0.1627	0.0536
Land use change	-0.1331	-0.0404	-0.1384	-0.1395	4.6E-05
Total	0.1334	0.1381	0.1146	0.1576	0.1487

Western Canada	Barley silage	Corn silage	Oats silage	Wheat silage	Grass hay silage
Seed	0.0071	0.0008	0.0080	0.005412	6.15E-05
Fertilizer consumption	0.0680	0.0297	0.0729	0.050724	0.025139
Plant protection	0.0054	0.0070	0.0069	0.003858	0.003764
Field activities	0.0407	0.0349	0.0439	0.025055	0.023406
Irrigation energy	0.0007	0.0051	0.0003	0.001056	0.037826
Post-harvest consumption	0.0014	0.0185	0.0004	0.001348	
Transportation	0.0106	0.0106	0.0106	0.010571	
Packaging					0.005102
Field-level CO2	0.0226	0.0136	0.0067	0.029331	0.004797
Field-level N2O	0.0552	0.0299	0.0883	0.060159	0.053613
Land use change	-0.1973	-0.1459	-0.2521	-0.14182	4.59E-05
Total	0.0143	0.0039	-0.01429	0.04569	0.153754

USA	Corn	Soybean	Wheat	Corn silage	Grass hay and silage
Seed	0.0004	0.0101	0.0299	0.0003	0.0004
Fertilizer consumption	0.0246	0.0667	0.0828	0.0137	0.0137
Peat moss		0.0000			
Plant protection	0.0212	0.0064	0.0031	0.0000	0.0000
Field activities	0.0190	0.0774	0.0991	0.0046	0.0046

Irrigation energy	0.0056	0.0000	0.0000		0.0248
Post-harvest consumption	0.0110	0.0010	0.2572		
Transportation	0.0096	0.0072	0.0000	0.0114	0.0114
Field-level CO2	0.0162	0.0902	0.0539	0.0038	0.0055
Field-level N2O	0.0272	0.0287	0.1292	0.0174	0.0173
Land use change	0.0464	0.0698	0.0693	0.0062	-0.0011
Total	0.1813	0.3573	0.7245	0.0574	0.0766

Brazil	**Corn**	**Soybean**
Seed	0.0057	0.0130
Peat moss		0.0000
Fertilizers	0.2657	0.0540
Plant protection	0.0350	0.0144
Field activities energy	0.3034	0.0759
Irrigation energy	0.0001	0.0001
Post-harvest activities		0.0000
Transportation	0.0133	0.0043
Field-level CO2	0.0337	0.0398
Field-level N2O'	0.0795	0.0641
Land use change	0.2111	0.3948
Total	0.9476	0.6603

6.4 Impact assessment results of the beef production systems modelled per kilogram of live weight (LW)/carcass weight (CW) and MC simulation results per representative animal unit

Phase	**Western Canada-LW**	**Western Canada-CW**	**US=LW**	**US-CW**	**Brazil-LW**	**Brazil-CW**
Cow-calf	6.05	10.04	7.42	12.29	5.12	9.32
Backgrounding	0.70	1.16	1.07	1.77	7.65	13.91
Finishing/feedlot	2.22	3.68	2.48	4.10	10.15	18.46

Source	**Western Canada-LW**	**Western Canada-CW**	**US=LW**	**US-CW**	**Brazil-LW**	**Brazil-CW**
Feed consumption	0.983	1.637	1.348	2.233	0.068	0.124
Enteric methane	7.152	11.915	6.680	11.061	11.383	20.694
Manure management	0.734	1.223	2.534	4.196	5.032	9.148

SOC (land use change)	0.0001	0.0002	-0.226	-0.375	6.602	12.003
Other (energy inputs, transportation, etc.)	0.065	0.108	0.627	1.039	0.006	0.011

Per representative animal unit	**Western Canada**	**US**	**Brazil**
Impact category	IPCC 2021 GWP 100	IPCC 2021 GWP 100	IPCC 2021 GWP 100
Reference unit	kg CO2 eq	kg CO2 eq	kg CO2 eq
Mean	7138.40	7211.70	16205.41
Standard deviation	461.28	433.28	1838.11
Standard error	14.59	13.70	58.13
Minimum	5905.56	5859.67	11822.52
Maximum	8803.58	8701.29	25104.13
Median	7117.75	7174.31	16022.79
5% Percentile	6404.16	6511.77	13584.84
95% Percentile	7926.06	7973.39	19354.24
95% Confidence interval (+/- mean)	28.59	26.85	113.93
p-value	<0.001 (ANOVA)	0.00026	0.00

6.5 Data used to estimate alternate land use-related SOC values for Brazil.

State	**Beef produced (thousand tonnes) - 2019**	**% share of Brazilian beef production**	**SOC estimate for creation of pastures – 2019 (kg/ha)**	**Land use related SOC estimate for pastures weighted by beef**

				production (kg/ha)
Rondônia	5639	0.054	10.77	0.583
Acre	1312	0.013	13.33	0.168
Amazonas	719	0.007	21.87	0.151
Roraima	412	0.004	15.34	0.061
Pará	8628	0.083	13.71	1.135
Amapá	25	0.000	16.88	0.004
Tocantins	3840	0.037	2.55	0.094
Maranhão	3382	0.032	8.26	0.268
Piauí	895	0.009	0.67	0.006
Ceará	1316	0.013	0.43	0.005
Rio Grande do Norte	590	0.006	0.07	0.000
Paraíba	855	0.008	0.19	0.002
Pernambuco	1046	0.010	0.19	0.002
Alagoas	527	0.005	0.02	0.000
Sergipe	707	0.007	0.28	0.002
Bahia	5327	0.051	1.01	0.052
Minas Gerais	11208	0.108	0.55	0.059
Espírito Santo	1026	0.010	0.47	0.005
Rio de Janeiro	1137	0.011	0.18	0.002
São Paulo	4736	0.045	0.19	0.009
Paraná	4805	0.046	0.38	0.018
Santa Catarina	2077	0.020	0.38	0.008
Rio Grande do Sul	7262	0.070	-0.1	-0.007
Mato Grosso do Sul	11547	0.111	0.83	0.092
Mato Grosso	14849	0.142	5.84	0.832
Goiás	10319	0.099	0.77	0.076

Distrito Federal	37	0.000	0.44	0.000
Total	104223	1		**3.625**